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The Presidential Address of

H.R.H. the Duke of Kent, G.C.M.G., G.C.V.O., F.I.E.R.E.

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Introduction

I suppose there are few more challenging and at the same time daunting situations than to be elected to high office in a great and famous institution. As far as I am concerned, it is above all an immense honour to succeed to the chair of such men as Sir Louis Sterling who created one of our greatest and most famous electronics groups which has gone from strength to strength; or Leslie Bedford whose contributions to the development of television and radar were of such fundamental importance and led on to work on guided weapons; or of Professor Eric Zepler, one of the pioneers of modern radio receiver design and the first man to be appointed to a chair of electronics in a British University—and many others.

To the honour of following such distinguished predecessors is of course added a very special sort of responsibility in that 1975 is the Golden Jubilee Year of the Institution of Electronic and Radio Engineers. I like the idea of celebrating 50 years of existence—it has the distinction of being well within a man's lifespan, unlike the 100th or 150th anniversaries. Which of course is part of the reason why we feel such pride that our Institution has travelled so far and grown to such maturity in its comparatively short life. For think what amazing things our founder members have seen in these fifty years.

The great changes that have swept over the world during this last half century are without question the widest and deepest that have taken place in any equivalent period of history. That this extraordinary epoch of social, political and economic revolution should have coincided with the growth of the new science of electronics is not, I am sure, an accident—although attribution of cause and effect is something for historians of the 20th century to argue over, not me. The fact is that throughout this period, electronics has evolved from the fledgling of 'wireless' to a great, and in many cases dominant, industry spanning a huge field from communications to data management, transport to process control, and medicine to entertainment. It was the belief in the great future that lay ahead that stirred our founding fathers—not that even they could have foreseen what was to come—to establish our Institution, in spite of some cynicism from the older institutions of that day.

Now we are proudly celebrating the first fifty years of this Institution's history and it is right that we should do so. Many people have contributed to this and their names include some of the greatest and most far-sighted of the many brilliantly inventive minds produced by this fertile nation of ours. These men, some of whom I have mentioned, despite many differences of approach, had at least one thing in common: vision. Not always practical vision perhaps, but an ability to glimpse possibilities however remote, and work towards them. Some may suggest that it is the besetting sin of scientists that they are always searching for the 'new improved model' before the current one has been properly developed, but surely that is inherent in all scientific exploration. Without vision we stagnate; without proper development of new ideas we shall soon not be able to afford the vision. There needs to be a delicate balance between research, which is never-ending, and development, which should have a finite objective.

ELECTRONICS TODAY

Having reached this milestone in our Institution's progress it is perhaps a convenient time to ponder on the shape of things to come and with your indulgence I propose to devote some moments to this. Not that what has happened since 1925 is in any sense unimportant, but I want to concentrate on looking ahead, rather than back. I have in the past few years had the advantage of visiting many establishments concerned with research and development as well as production and have had some illuminating discussions (at least they were illuminating for me!) with many of my colleagues within our Institution. From these experiences I would like to

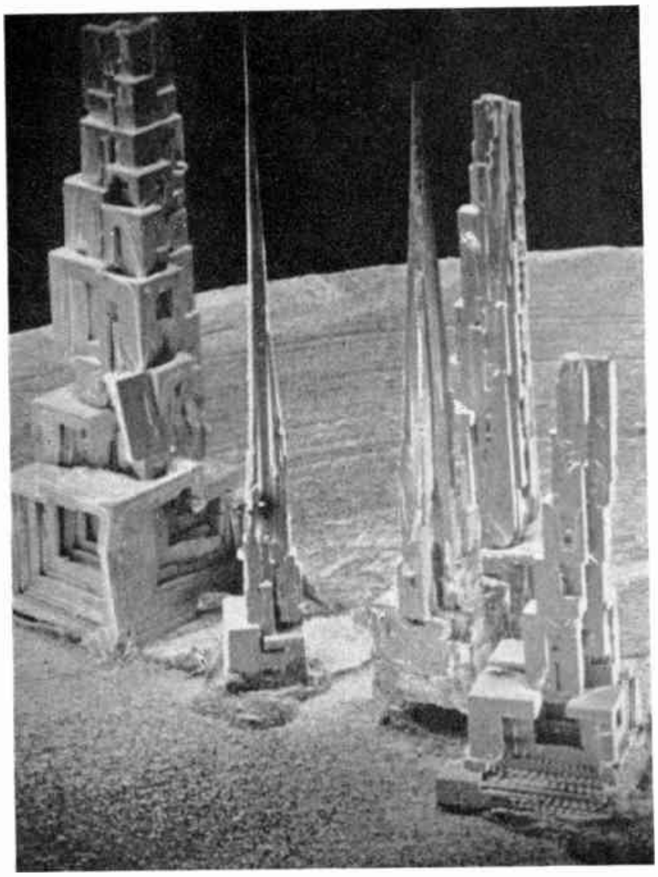


Fig. 1. The Stereoscan is a scanning electron microscope which shows a great improvement on either optical or conventional electron machines. Its presentation and clarity are far better, giving a three-dimensional appearance, and it has a range of magnification from ×30 to ×50,000. This photograph shows crystals of lead tin telluride magnified ×60.

polish the crystal ball and try to cast ahead into the future. In doing this, I cannot help wondering how the Institution's first President might have felt if he had been asked to predict what might come about in the next 50 years.

Is it conceivable that in the days when the crystal set held sway and radio transmissions were measured in wavelengths of kilometres, he would have predicted that, within 50 years:

it would be commonplace to deal in wavelengths of millimetres or even fractions of these;

full colour television of high definition would be available over nearly the whole of the globe;

aircraft and ships would be navigating to great accuracy wholly by the use of electronics;

radar would emerge as a powerful means of accurately locating remote objects;

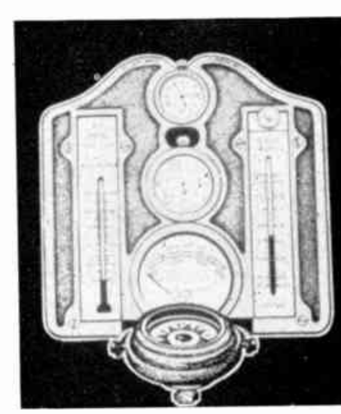
men walking on the surface of the Moon would communicate two-ways to the Earth and that pictures in colour from the Moon would be transmitted simultaneously to millions of homes in all continents;

the computer would arrive and fundamentally change the way we gather information, analyse it and act upon it;

electronic instrumentation and control would have deeply influenced the majority of our industries;

or above all, that his gigantic equipment of iron-cored chokes and transformers, sturdy condenser blocks and handsome glass bottles usually glowing brightly, standing like sentinels on a massive steel chassis, would have dwindled to tiny pieces of jewellery invisible except under the microscope where their elegant filigree can be seen;

Fig. 2. (a) Flight deck display on *Concorde* 002—the first British prototype. This is a striking example of the use of electronics to absorb a mass of information, analyse and present it.



(b) Compare a World War I aircraft instrument panel! (Made by Elliott Brothers (London) Ltd. for Army aircraft in 1912). The instruments include: (*left*) airspeed indicator, (*centre, top to bottom*) clock, barometer/altimeter, engine revolutions indicator, compass, (*right*) angle of inclination indicator.

or further, that these microcircuits would form the heart of computers and control systems of literally pocket-sized dimensions?

I am quite sure my predecessor would not have ventured to predict any of this; indeed he would have been thought pretty eccentric if he had done so. Why then should I dare to make predictions now? The main reason of course is that we now have over fifty years' experience behind us, we have a much clearer idea of the possibilities and limitations and perhaps because I have gained confidence as a result of the many bold forecasts made to me during my visits to various highly reputable factories and research centres. But before embarking on an expedition into the future, I feel I should pitch a firm base camp, first to establish what we expect of our science of electronics, and secondly, to consider what kind of world might emerge during the rest of this century and the first quarter of the next.

I believe the role of electronics to be fourfold:

First: extension of the human senses to see, hear and observe—in distance, at speed, in quality, in complexity and under all conditions. (Fig. 1).

Secondly: extension of the human intellect to absorb information, to manipulate it and to present it. (Fig. 2).

Thirdly: to enable large numbers of people to be simultaneously informed or entertained and conversely for large numbers to communicate to and influence a single point of decision—for example the referendum.

Lastly: by performing complex, repetitive or unpleasant tasks, to take drudgery out of work and make many jobs more acceptable.

Now, what about the world of the future? Can we make any sensible assumptions about its future shape and the environment in which its peoples will live? I believe we can reasonably state a few. Perhaps the best place to start is with people.

It is difficult to get experts to agree on population trends but Fig. 3 is based on United Nations reports. Even if this estimate is only partially realized then the population factor must dominate all our planning considerations in the future. It is worth noting that within the next 25 years there will be *added* 2,000M people—*twice* the total population living on earth in the year 1800. Following from this will spring the urgent need to harness the Earth's limited resources (minerals, energy, food) more efficiently by cutting out waste, by sorting and recycling or even by reducing the over-all demand in order to feed, employ and satisfy the needs of these immense multitudes.

The growing numbers will intensify many problems and the control of crime and delinquency, the reduction of nuisance (noise and pollution) the maintenance of safety at home, while travelling and at work will all demand increased vigilance. On the other hand, there is likely to be more leisure and rising living standards. As more and more goods and services are provided by machines, time spent not working will increase in both the developed and undeveloped countries.

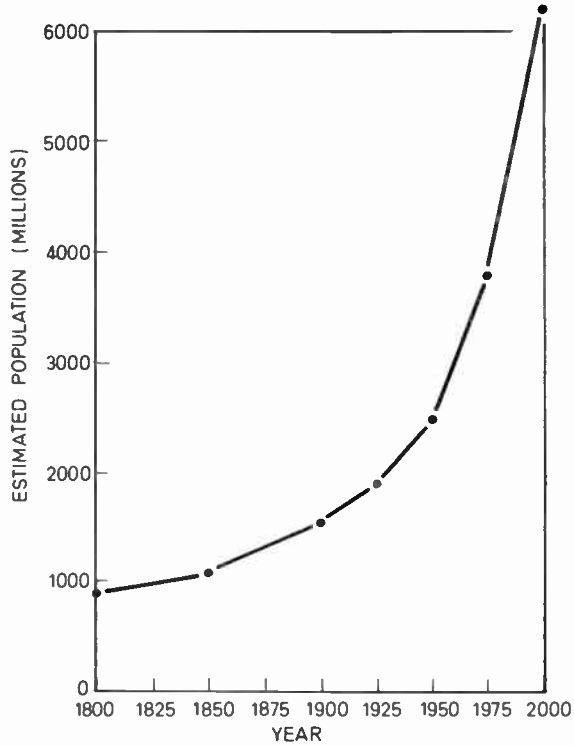


Fig. 3. Estimated population of the world. (Mainly from UN Report—'Future Growth of World Population'.)

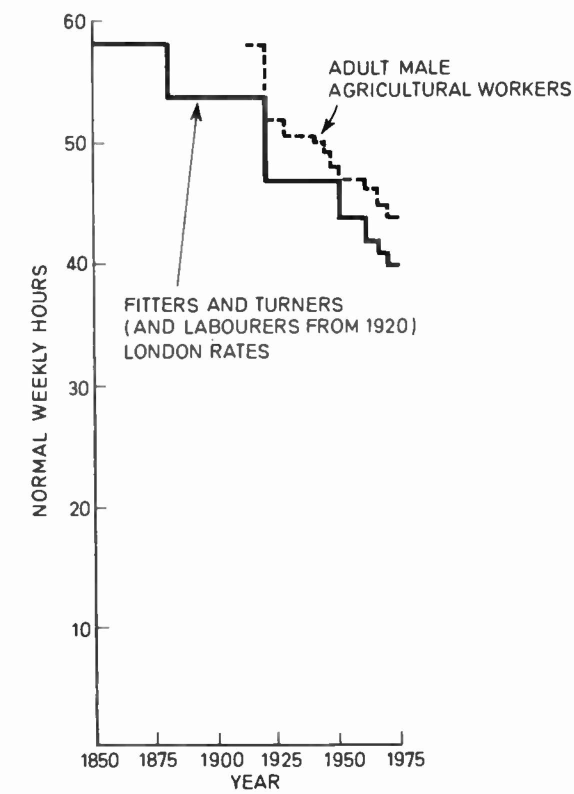
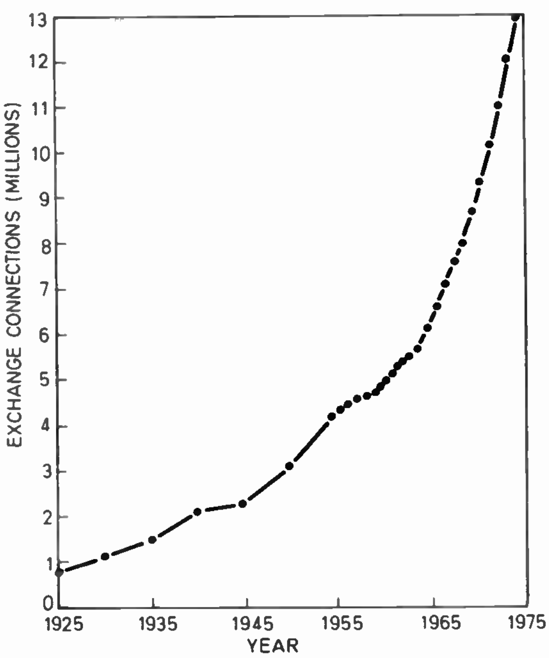


Fig. 4. Normal weekly hours of work over the past 125 years. (British Labour Statistics: Historical Abstract 1886–1968).

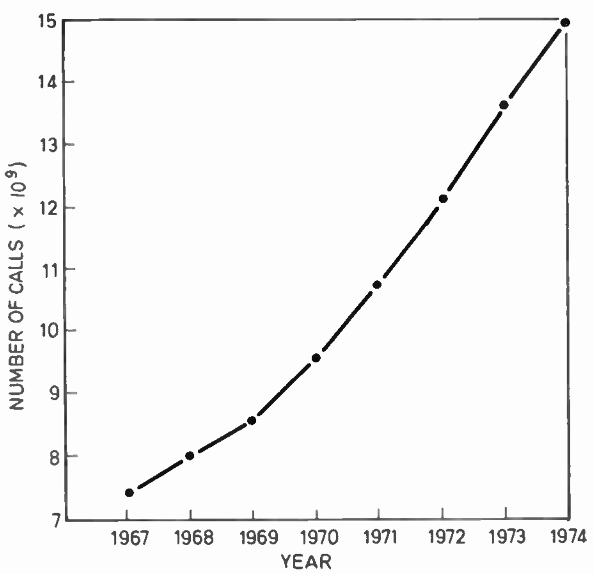
Figure 4 illustrates how the weekly working hours for two categories of workers have reduced since 1850 and this is indicative of similar trends for shop assistants, transport operators and indeed for the majority of us. I would predict that this trend is likely to continue, perhaps not reducing as dramatically, but there will be a tendency for the ratio of working to leisure time to fall (from an extension of the graph it looks as though we all knock off for good in about 2025!); more time being left free for sport, travel, the arts and for recreation generally and the enjoyments of pursuits that are not necessarily remunerative.

And this vastly greater number of people are going to want to communicate with one another. Already we are experiencing a communications explosion. The graphs in Fig. 5 show what has happened in this country over the last few years and the same is true for most other developed countries. The Post Office forecasts that over the next five years traffic will increase by about 20% per annum, that is, doubling in less than 4 years. What changes in demographic groupings and structures might result from this communications explosion is impossible to predict, but what is certain is that its shape and evolution will be determined almost entirely by advances in electronic technology.

My base camp is now established and I am now ready to set forth into the unknown. But time is limited so I can only head into some of those fields where I expect the role of electronics to be a powerful one.



(a) British Post Office exchange connections (P.O. Telecommunications Statistics 1974).



(b) Growth of calls in the UK. Telephone traffic has increased by 50% in five years.

Fig. 5.

ELECTRONICS IN THE NEXT HALF-CENTURY

Communications

I have briefly mentioned communications as being one of the significant areas, and we have seen how telephone connections have been expanding. Can further use be found for them, beyond ordinary speech? I would predict much more use of the telephone system will be made to transfer data; this could be to or from computers or in the form of facsimile. Facsimile machines of course already exist, but their potential has hardly begun to be exploited.

Let us imagine the average home of the future. All services to the house (gas, electricity, water) could be remotely metered, marking the demise of the man with a torch coming to read the meters. Instead, in his place will stand a facsimile machine. Among the documents that arrive by this machine will be the bills and statements of account for these and other services. A quick instruction will pass these bills to the bank for payment, then back over the machine will arrive the up-dated bank statement: that's a less attractive thought—instant overdrafts! I suppose this also spells the end of letters and letter-writing for good—but by then their cost will surely be prohibitive anyhow!

The television set is now an established piece of domestic equipment and already we take for granted the near global inter-connection of the world's television networks to give us full, high-definition reception in colour. The next development is likely to be direct transmission by satellite into the home. Already this is being done on an experimental basis to provide education to remote and isolated peoples. There will be problems to solve, such as the language barrier and the time variations throughout the world, but I feel confident these will be overcome.

A new by-product of the television networks which is going to become very important is the ability to provide data in alphanumeric form. This is already being used experimentally—as witness Teletext in this country, and although development of the technique is still in its infancy I foresee great potential here.

At present the television networks are under-utilized for substantial periods, long enough for vast amounts of data and information to be transferred, linked and made available to multitudes of people. Within the next few years we should be able to receive the news, shopping catalogues, company reports, entertainment guides and so on in the home as 'hard copy' (i.e. the printed word) through attachments to the domestic television receiver. Extension of this principle to provide a dialogue between the viewer, in his home or office, and the information source is quite feasible. So we have the prospect of two-way communication using both the television and telephone networks.

As any radio and communications engineer is only too well aware, bandwidth shortage is already a major constraint and the advent of a new technology which enables transmission of signals in the form of *light* waves rather than radio waves offers exciting possibilities. The development of optical technology opens up the prospects of greatly increasing the number of separate channels which can travel along a line and offers new opportunities for a vast increase in the size and variety of services which can be provided. Every development which will free us from the requirement of transmitting within the electromagnetic spectrum is urgently needed. Already we are beginning to experience overcrowding within some of the bandwidths in which we are transmitting.

As an example I would instance the 30–1000 MHz spectrum, as being the most practically usable range at the present time. About 60% of this spectrum is devoted to broadcasting and about 30% to defence applications. This leaves only about 10%, or a bandwidth of about 100 MHz, available for other uses and for future expansion. Quite obviously we have either got to find more spectrum to use, or develop techniques which use less of what is available. As time goes on it will become an extravagance to convey, for example, television pictures by filling up a large proportion of any available spectrum with high-powered signals and we can expect that much greater use will be made of transmission by other means such as cable. We must recognize, however, that any change of this kind is likely to be gradual, due to cost and to natural reluctance to change domestic broadcasting receivers so that for the most part efforts will need to be concentrated on *using* the bandwidths more efficiently. Mobile radio occupies about 3% of the 30–1000 MHz spectrum. Figure 6 gives a prediction of the number of mobile radio sets likely to be in use up to the year 2000: six times as many as today! This illustrates a challenge to produce economically-priced equipment which will operate efficiently in every part of the radio frequency spectrum.

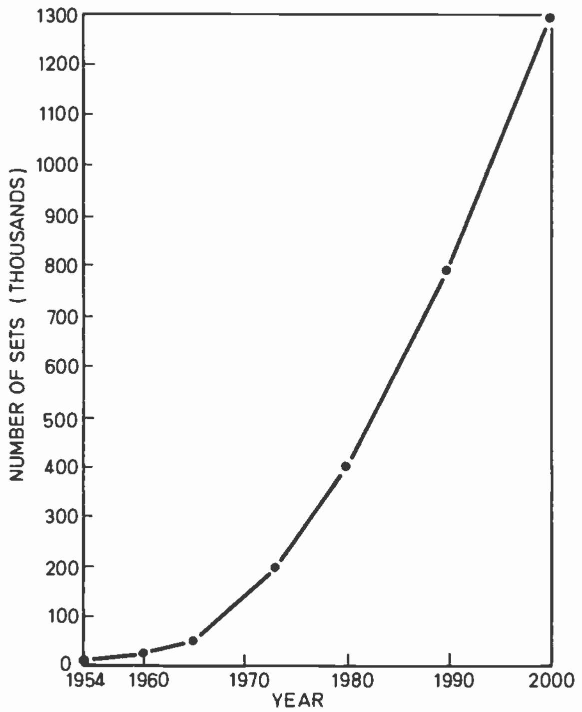


Fig. 6. Mobile radio sets—estimated number in use in the UK.

Advances in Manufacturing Processes

I would now like to talk for a moment about manufacturing processes. I don't think we can seriously doubt that manufacturing will continue to be a dominating feature of the economic life of the country, but I expect there to be some significant changes in its form. In the first place it is plainly going to be necessary to consume less human effort, both physically and psychologically in the manufacturing process. Secondly, we are going to require that industry makes much smaller intrusions into the environment. And above all, I am quite certain that manufacturing processes which involve the consumption of large amounts of resources, whether energy or materials, will become less and less acceptable; men and women will be increasingly disinclined to perform jobs that are boring, menial and unrewarding in anything except cash terms; while at the same time the value of finished products will become proportionately higher as their quality and durability show marked improvement. Some of these requirements are of course conflicting—but that will be nothing new to industrialists. At least they now have a more precise tool than ever before, in the shape of electronics, to help them make these adjustments.

Our own electronics industry is a remarkable example of evolution in a particular industry towards what has been described as technology with a human face. The early factories making electrical and electronic components were noisy, frequently dirty, malodorous and disagreeable to work in—their products generally large, heavy and crude. We have now reached the stage where the factories are compact, almost clinical in their cleanliness and illumination, the material and energy input is small and in real terms the products are made at only a fraction of the earlier costs whilst their quality and reliability have improved out of all recognition.

Already many industrial processes are largely controlled automatically by electronics, and many manufacturing operations are performed under human supervision only. In time many more continuous processes will become automated and some will be *entirely* controlled by electronic equipment. A similar trend will also apply to the mechanical engineering industry. I think we can confidently predict that within the next 50 years the fully automatic factory will arrive (it is already a technical possibility), where all the operations between feeding the basic materials into one end and the delivery of the fully inspected final product at the other are under the control of electronic systems. This prospect clearly brings in its train some important social implications which ought to be taken into account in our education and training system. This is a large and important subject and although outside the scope of my talk today, I think it worth mentioning that one of the fields that the National Electronics Council, with which I am proud to be associated, concerns itself with is the whole question of the impact of electronics on society and on our social and political institutions.

But to revert to our topic, there is in my view no question that electronics holds the key to the new revolution in industry, the beginnings of which we can already see—indeed only electronics can bring it about. Take as one example the demand for better quality and reliability, which offers a special challenge. The scope for inspection and control systems such as 'in-process gauging' where the performance of the *product* rather than the *tool* is assessed, will be enormous and the ability to reject or correct a faulty item early in its production history so as to eliminate waste will be vital.

The Future of Computers

These work-reducing, simplifying principles operate at a humbler level too. A very few years ago, electronic process control was synonymous with giant computers. The conventional wisdom used such phrases as 'time shared remote access real time processing' and other equally mind-bending concepts.

Already the scene has changed. The remarkable progress of the giant integrated circuits (g.i.c.s) which have outstripped the expectation of half a decade ago, has enabled us to think of 'dedicated' *low* cost computers devoted to a particular task. These may range from the control of fairly simple processes such as baking, to component part manufacture or medical diagnostic aids or domestic appliance control (e.g. washing machines).

Yet even the advance of this super-miniaturization technique is in its infancy. Already the pocket calculator sold in our supermarkets is beginning to vie with the giant computer occupying several rooms in the universities two decades ago. For about £50 now you can buy as much computing power as would have cost thousands a few years ago. The ability to register information, subject it to complex mathematical processing and submit meaningful conclusions, is rapidly becoming a simple and low cost process, and this greatly widens the ability of men to analyse and control. The electronically controlled motorcar, pathological laboratory, warehouse or even kitchen is in sight. Computer peripherals are rapidly ceasing to be morons enslaved to their computer masters and are becoming independent machines able to analyse, decide and inform in their own right.

Where this will lead in the future is difficult to decide but it is clear that our inherited concept of the computer as a single 'machine' will have to give way to the concept of an 'intelligent system' where each part has a logic and autonomy of its own. In case we get conceited about this line of progress, we must remind ourselves that nature has anticipated us by many millions of years in the way that the nervous and intelligence systems work in animals and man.

Aerospace and Maritime Applications

But to go back to our earlier theme of industry, probably no area places a higher premium on quality and reliability than aviation, and the avionics industry has achieved remarkable standards while successfully combatting the constraints of weight saving and safety, two attributes which are seldom compatible. Aeronautical engineers have to combine many disciplines; structural, mechanical, electronic, chemical, physics, etc. and their products are prime examples of systems engineering. Here is an area where electronics has come to be *the* pace-setting technology—with avionics in a modern aircraft representing as much as 30% of its value. It may well be that the broad requirements of aircraft will change little during the next 50 years or so, but two things I think we may safely predict: (1) The pressures on our engineers to produce ever more sophisticated and reliable systems to highly demanding specifications will stay with us and increase with each successive generation of manned aircraft—and spacecraft. (2) The systems and instruments which today equip only the 'jumbos,' *Concordes* and MRCAs will eventually filter down to much more commonplace aeroplanes, even to light aircraft.

Perhaps for one moment I might digress into another element that is receiving increasing attention these days —the sea. What possibilities does it hold for us? Can we make use of its resources more intelligently? Can we farm the seas? Are they an energy and materials source? People are now asking these questions, but the incentive to answer them has not so far been very great. I suggest it is going to become so. Deep-sea exploration may not have the same glamorous appeal as space travel, yet to my mind more benefit is likely to be gained by sending a probe to the deep sea-bed than by sending one to Mars. The plunge into sea-bed exploration will surely come and I have no doubt when it does that the skills of our industry will be urgently needed. The initial task will presumably be done by unmanned probes and pretty marvellous vessels they will need to be. The navigation and communication problems will be at least as demanding as those in outer space. There are control problems too: the Research Vessel *Sealab* uses a dynamic mooring system whereby a computer controls thrusters which maintain the ship in a constant position relative to the sea-bed.

The vehicles will need to be self-sufficient in energy—no chance of solar energy here. The darkness will have to be penetrated to give good resolution pictures. Extensive scientific readings and samples will be needed for analysis before it can be considered safe to send manned vehicles to such depths in order to carry out worthwhile functions. Within the next fifty years it would be surprising if we did not have manned laboratories and workshops on the sea-bed and at varying stages beneath the surface. If energy is abundant, can we find a way to process and convert it to other forms on the spot? Will there be any need for the expensive pipelines that we build at the moment? How we shall exploit the sea's resources, I would not care to predict, but I have a feeling that in time the sea could become almost as familiar a medium to us as the atmosphere, since we cannot for much longer afford to ignore its potential; yet the whole process of sea-bed exploration will be impossible, as was the exploration of space, without our omnipresent electronic techniques.

Electronics and the Human Being

When I was setting up my base camp I mentioned one of the roles of electronics as being to take the drudgery out of working life. Perhaps I should have broadened my brief to the social benefits to be gained by means of electronics. My thoughts are prompted by the contribution electronics has made to the science of medicine. We have already seen the beginning of the dramatic effect which electronic means of measurement has had upon medical diagnosis. The replacement of infrequent and not very accurate measurement of body temperature by continuous recording, the electro-cardiograph for the measurement of heart performance, and now the revolutionary detection and identification of abnormalities achieved by X-ray tomography, are but early steps in the business of accurate and rapid diagnosis of illness so that it may be remedied by what one might call conventional medical and surgical practice. But now we also see the possibility of electronics being used to remedy defects, as well as to identify them.

The term 'prosthetics' is coming into more common usage, and we can now confidently foresee mechanical access to the human brain. We shall expect to see a television 'eye' connected to the human optical nerves to restore sight to the blind, something similar to restore hearing to the deaf, and so on.

These achievements, while most praiseworthy in alleviating the handicap of a few, have little effect on the majority of healthy human beings; but if access and connection to the brain becomes a matter of standard practice, what dramatic developments might not ensue? If one can feed a vision signal into a brain, may it not also be possible to feed in logic—knowledge—understanding? Shall we one day see the laborious and haphazard system for implanting useful knowledge into a child's mind over a period of many years, being replaced by plugging into an educational data bank one afternoon? Of course we are trespassing here onto some very tricky ground. The thought may be appalling and one can imagine there might well be a public outcry but it is essential that we recognize such possibilities even if for one reason or another they have eventually to be rejected. If man imagines a possibility, history shows that it very often becomes reality in due course.

This electronic access to the brain may turn out to be a two-way street—if we can feed signals *in*, should we not be able to feed them *out* also? In the first instance there would be popular support for a development which enabled a paralysed person to operate machinery for a 'living by think' control. In due course, however, this might be extended and we can extrapolate other possibilities from this medical idea.

What great results might not be achieved by 'thinking' information and commands into a computer controlling a machine, later perhaps an industrial system, without the loss of efficiency in having the human eye or hand or voice in the control loop? Mind you, we should need to build in some fairly thorough safeguards against the thoughts being wrong!

It may not even be necessary to have a connection to the brain to achieve this end. It is well established that the human brain, whilst thinking, radiates electromagnetic energy and this must surely be in a pattern associated with the control of the thought. The remarkable progress in the increasing sensitivity of electronic receivers and the application of pattern recognition techniques to be able to read signals below noise level, may well lead to the production of a practical 'think control' helmet, not only for astronauts engaged on extra-vehicular operations, but also for run-of-the-mill factory process workers. Already I understand experiments are being carried out into pilots' control of aircraft by means of thought—though I don't think volunteer passengers have yet been called for!

Safety and Reliability

Talking of medicine and aircraft passengers inevitably reminds one of the paramount need for safety, and of the part electronics can play in helping to ensure it. Modern aviation would be totally impossible without electronic methods of air traffic control and navigation aids. The nuclear reactors of today rely almost wholly on electronic instrumentation and control to ensure safety and efficient running. Giant tankers navigate and steer by electronic devices whilst on the roads, on the railways and in our industries safety increasingly depends on sensors, signalling and alarm systems.

But as industries become more complex and have higher hazards associated with them (look at Flixborough for example), and as the insatiable appetite for transportation grows with its ever attendant risks, so will the problems of safety. Greater calls will be made on our expertise to provide electronic automatic control, early warning and collision avoidance systems with even greater sophistication and extreme reliability. This will be another growing role for electronics and I predict that within the next 50 years it will become a rarity to find men carrying out tasks which are recognized as being hazardous; where it is unavoidable that they should do so, they will be elaborately protected by electronics. Without doubt, 'Safety through Electronics' will become a major wing of the industry during the next half century.

Yet behind all these engineering achievements, the tendency to more automation and removal of human error, there will still be somewhere a man or woman in control and it is an inevitable corollary to progress that the problems of management become more intractable. Whether it is the small shopkeeper or the giant manufacturing organization, the armed forces or the national government, the scale and complexity of management systems will grow. (This trend will continue as our activities become more trans-national and global in character.) Here the role of electronics will be paramount. The community of the future will rely on the ability to communicate between individuals or large groups of people, to record, sift and analyse data, to encapsulate accumulated wisdom and experience (i.e. in computer data banks) and present a series of options for final human judgement. Yet there are inherent dangers. I stress that it is the human element that is all important, for it will be our task, together with the planners of management systems, to ensure that the privacy of the individual is preserved, that he or she is not reduced to the status of a 'human terminal' in a central management complex. I see great strides in the whole field of 'management' by electronic devices in the future but I also hope to see an industry profoundly concerned with ensuring preservation of the essential human liberties. The almost limitless scope for extending 'management by electronics' must be accompanied by rigorous safeguards against deliberate or accidental abuse.

Conclusion

Our expedition into the future has touched on many diverse and important fields of human activity. It has not attempted, as it could not, to be all-inclusive. If one lesson has been learned in the half-century that the practice of electronics has been institutionalized, it is that the limits to what can be achieved are set only by the boundaries of human ingenuity. In my necessarily very brief excursion I have tried, relying on the best available advice, to project forward some ideas which are either now in the pipeline or else are embryonic gleams in some engineer's eye. Throughout this exercise I have been conscious that the momentum of technological progress in electronics, although unpredictable, will almost certainly overtake and far outstrip anything that we are now able to imagine.

Nevertheless, I think it would be bold to imagine that the rate of technical advance that we have seen in the last fifty years, which generally has been an accelerating one, would be maintained. Advance there must and surely will be, but I believe that we are embarking now on an era where the emphasis is on consolidation and refinement, when the great discoveries are harnessed, applied and developed to their utmost. Already the science and techniques of electronics have reached a level where in many fields they exert an influence that is dominant, or is rapidly becoming so; and as means of managing and controlling at low cost with the minimum of human intervention are extended into further and wider realms, I expect to see this tendency increasing. More industrial processes, more businesses, more leisure activities will depend for their success and efficient operation on automatic systems—in fact more people all over the world will come to rely on electronics to lighten their work load and relieve them of difficult tasks, to broaden their horizons and enrich their lives.

That our sciences of electronics and radio, still relatively in their early manhood, will prove able to meet all these challenges, and others far beyond our wildest imagination, I have not the least doubt. The Institution of Electronic and Radio Engineers closes its first 50 years with justifiable satisfaction; in my estimation it can look forward to the next fifty with excitement and confidence.

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UDC 621.382

Amorphous semiconductor devices and components

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Based on a paper first presented at a meeting of the South Western Section of the Institution in Bath on 23rd January 1974.

SUMMARY

The first part of this review describes, in terms intended for the general reader, the physical basis of amorphous semiconductors and their use in switching devices. The second part is devoted to a more critical appraisal of current thinking on conduction and switching mechanisms and recent advances in the technology and applications of amorphous semiconductor devices.

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1 Introduction

Most active electronic components today, e.g. transistors, integrated circuits, Gunn diodes, employ for their active medium single-crystal materials such as silicon, germanium or gallium arsenide. Now, the regular crystalline state is not a frequently occurring state (note, for instance, the scarcity of diamonds!) and it is much more usual for naturally occurring materials to have a more disordered atomic geometry, e.g. water, glass.

During the last few years there has been an upsurge of interest in the use of disordered or amorphous materials in electronic devices, which has resulted in a new class of semiconductor switches and numerous applications of these materials in the imaging, computing, display, photographic and other fields. It should be stressed, however, that amorphous solids are already used extensively in the electronics industry; the world turn-over for xerox-type copying machines, which use for their active medium a drum coated with amorphous selenium, for example, is over £500M per annum. (That is not to say that the physics of amorphous selenium is fully understood, which is a further demonstration of the technological innovation being in advance of knowledge of fundamental processes.) The disordered anodic oxides of aluminium and tantalum are used as the active material in electrolytic capacitors, the production of which is another multi-million pound industry, again without a complete knowledge of their operation. Glasses, which also have a characteristic disordered atomic structure, are also already firmly entrenched in the electronics industry, with far-ranging applications from delay lines and channel plate amplifiers to optical fibres for high frequency communications.

The purpose of this paper is to review the properties, manufacture and applications of the latest generation of amorphous semiconductor devices. We will also present our understanding of the current thinking on the various theories advanced to explain the physical properties of such materials.

2 Amorphous Semiconductor Electronic Switches

In amorphous semiconducting solids, the constituent atoms are in almost complete disarray, as they are for example in a liquid, but the chemical bonds which hold the solid together are essentially the same as in its crystalline version, so some slight regularity exists at least between immediate neighbouring atoms, giving a so-called short range ordering. Such materials are found to have resistivities intermediate between metals and insulators, behaving in some ways like intrinsic crystalline semiconductors. For example their resistivity, ρ, varies exponentially with temperature, T, according to

$$\rho = \rho_0 \exp (E_a/kT)$$

where E_a is an activation energy, usually of the order of 1 eV. This property is surprising in view of the material's disordered form. However, unlike their crystalline counterpart, amorphous semiconductors are not susceptible to the addition of small quantities of impurity material; they cannot easily be doped n- or p-type. In fact they can absorb relatively large amounts of doping impurities without significant changes in their electrical properties.

Obviously, materials with such exotic properties have interested physicists for some time, but there has been a marked escalation in activity, particularly from electronics engineers, since the introduction a few years ago of new practical electronic devices employing amorphous semiconductors. We will be returning to discuss the properties of amorphous semiconductors later, but first, as an introduction, let us consider the characteristics of the new switching devices.

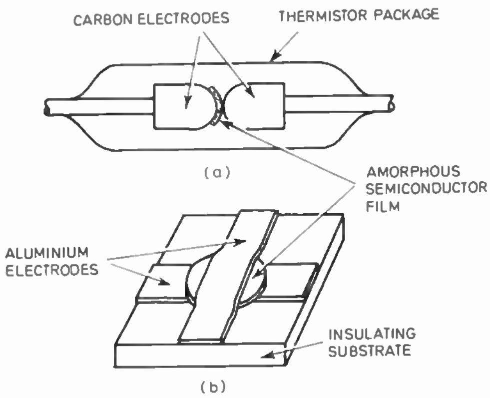


Fig. 1. Early discrete switches.

Switching phenomenon have been noted for a decade but Ovshinsky[1] first attracted international attention by producing a discrete component commercially in 1968. Figure 1(a) shows an early switch made by his company in which a thin film of undisclosed glassy amorphous material is sandwiched between massive carbon electrodes in a thermistor type package. Another possible discrete geometry used in earlier studies is the cross-over sandwich using thin film electrodes (Fig. 1(b)).

These devices and their more modern counterparts are so-called *threshold-switches* and their circuit configuration and resulting I–V characteristics are shown in Fig. 2. These devices have the remarkable property of having an initial OFF resistance, corresponding to region (a), of order tens of megohms, which drops to a much lower ON resistance, region (c) of around 100 Ω when the voltage across it exceeds a certain *threshold* value, V_{th}, typically around 10 V. The switching, which

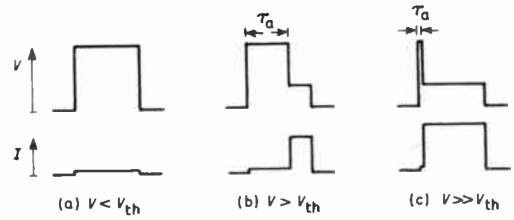


Fig. 3. Operation of a threshold switch in the pulsed mode.

occurs along a load line corresponding to the load resistor, region (b), happens in a time typically of order nanoseconds, but there is a delay time which can be as long as 10 μs, between the application of a switching voltage and the onset of switching. If the current in the ON-state is allowed to fall below a minimum holding value, I_h, the device reverts to its high resistance state, along region (d). In this sense, the device behaves as a monostable element. Notice that the switch is insensitive to the polarity of the supply; the I–V curve for negative voltages is a mirror image of that for positive values.

Unless threshold switches have particularly good heat sinking, which is not practicable with modern thin film arrays, the application of d.c. voltages can result in damagingly high dissipation in the relatively small active bulk, so it is usual for switches to be operated in a pulsed mode. Figure 3 shows some typical waveforms. For an applied voltage just in excess of V_{th} there is a relatively long delay time prior to switching, τ_d, but the delay time is found to decrease exponentially with overvoltage $(V-V_{th})$, given by

$$\tau_d \propto \exp -(V-V_{th})$$

One limitation of the threshold switch is that it is a two-terminal device. This is a disadvantage as far as circuit design is concerned, since there is no automatic separation of control signal source from the circuit being switched, as in a three-terminal device.† However numerous potential applications have been devised which overcome this difficulty; some of these will be discussed later.

The switches described so far can be distinguished from another class of device, called a *memory switch*, which can have a similar geometry but a different type of active medium. The choice of amorphous semiconductor to perform the various functions will be discussed later. Typical I–V curves are shown in Fig. 4.

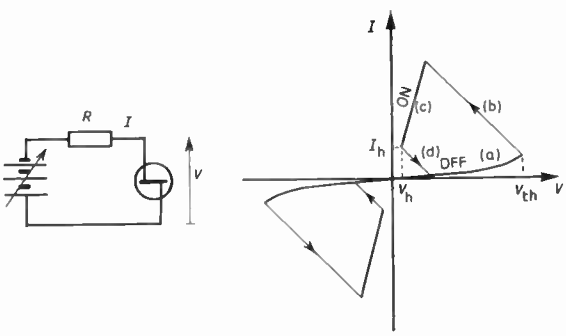


Fig. 2. Measuring circuit and voltage-current characteristic for a threshold device.

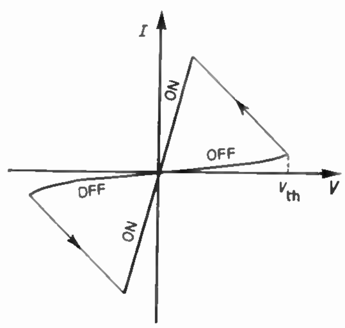


Fig. 4. Current-voltage characteristic for a memory switch.

† In fact, switching has recently been demonstrated by the authors in which triggering by a third electrode is non-thermal,[2] the device performance being similar to a thyristor.

Rapid switching again occurs from a high to low resistance state after a delay time, once a threshold voltage V_{th} is exceeded; but this time the device remains in the low resistance state no matter what excursions of voltages or current, even allowing the voltage to go negative. The device is bistable and retains a semi-permanent memory of the switching operation.

A typical operating cycle for a memory switch is shown in Fig. 5. The device is first switched into a low resistance ON-state by the application of a voltage exceeding V_{th} for a time longer than a characteristic *lock-on time.* (For shorter times the device behaves as a threshold switch.) While in the ON-state, its condition can be ascertained by an interrogatory voltage pulse, read ON; the voltage across the device will be small and the current high, corresponding to the low ON resistance. The ON-state persists indefinitely, even if the supply voltage fails. Such *non-volatile* performance is valuable and is exploited in computer memory applications, as we shall see.

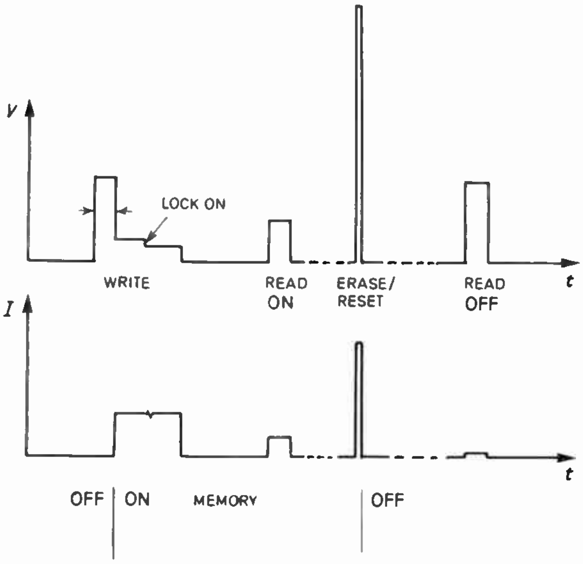
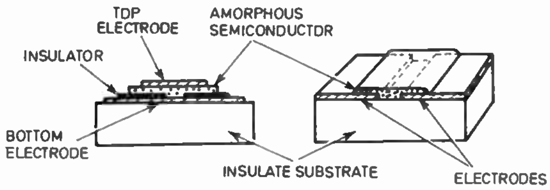


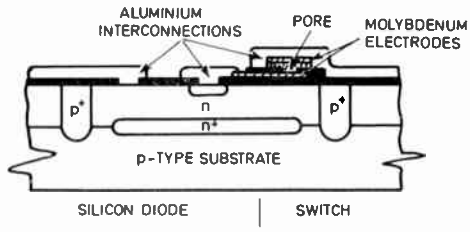
Fig. 5. Operating cycle for a memory device.

The ON-state can only be electronically erased by the application of a short (8 μs) high current (150 mA) pulse which, for reasons discussed later, restores the switch to its high resistance OFF state. A read voltage pulse in this state will produce little current and be mostly dropped across the device, as shown in Fig. 5.

An indication of the geometries of modern commercially produced threshold and memory devices is given in Fig. 6. Such thin film devices are either discrete or, more usually, form part of an integrated array (Fig. 6(c)). In order to reduce device capacitance which in conjunction with the inherent fast switching can produce irreparable damage, the active cross-sectional area is reduced to a minimum. In the *pore-structure*, shown in Fig. 6(a) the area of active material is defined by a pore cut in the oxide layer by conventional integrated circuit photolithographic techniques. The bottom and upper thin film electrodes consist of molybdenum, backed with aluminium to reduce access resistance; these



(a) Pore structure. (b) Gap-cell.



(c) One cell of a diode-isolated memory switch integrated array.

Fig. 6. Geometries of modern switches.

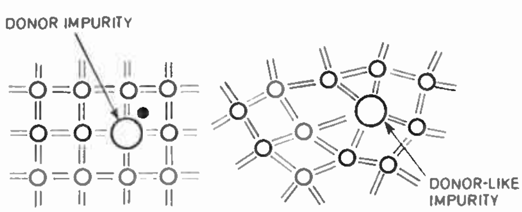
are separated by an appropriate switching glass. In the alternative *gap-cell* geometry shown in Fig. 6(b) the electrodes are coplanar and separated by a gap, typically a few micrometres wide, which is filled with active semiconductor.

3 Structure of Amorphous Semiconductors

We next discuss briefly the structure of amorphous switching materials to provide some insight into their properties and a basis for a subsequent discussion of possible switching mechanisms.

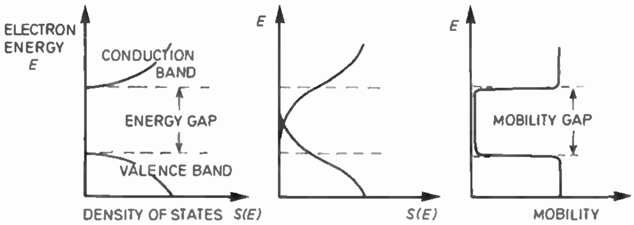
A crystalline semiconductor is characterized by its regular array of atoms, shown schematically in Fig. 7(a). Each covalent bond is accommodated in the intrinsic material. Conduction electrons or holes can be introduced into this material by substituting donor or acceptor impurities to produce extrinsic n- or p-type semiconductor.

In the amorphous material shown in Fig. 7(b) the atomic orientation is random; if a donor-like impurity is introduced as shown, which requires an additional covalent bond, this can be accommodated in the disordered material without producing an additional electron; the amorphous semiconductor cannot be doped and, because of its short-range order, behaves like an intrinsic semiconductor.



(a) Crystalline. (b) Amorphous.

Fig. 7. Schematic of the structure of crystalline and amorphous solids.



(a) Intrinsic. (b) Amorphous.

Fig. 8. Band structure of intrinsic crystalline and amorphous semiconductors.

A less simplistic description of the conduction mechanism in amorphous semiconductors assumes a band-structure as shown in Fig. 8(b). The usual conduction and valence bands, in which conduction can take place in extended states, are not separated by a forbidden energy gap as in a crystalline material but small tails to the density of states function, which sometimes overlap, exist in the gap, as shown. However, the corresponding energy states in the gap, which are due to the presence of traps in the material, are localized and the difficulty of conduction of carriers between such states leads to a very low mobility and a mobility gap, as shown in Fig. 8(b). It is this mobility gap which is thought to account for the pseudo-intrinsic behaviour of an amorphous semiconductor.

Other band structure models have been proposed. The experimental results of Anderson[3] on quartz and Corning 7059 glasses support the Mott and Davis model which assumes a large density of states at the Fermi level. However, for some chalcogenide glasses associated with switching, Marshall and Owen[4] have recently found evidence to support a band structure model which involves more discrete narrow band energy levels which are not at the Fermi level.

Switching has been observed in many materials, including amorphous oxides of vanadium, tungsten, silicon and germanium, but the most successful commercial devices use *chalcogenide glasses* to ensure long-life, reliability and repeatability. 'Chalcogenide' means 'oxygen-like' and applies to those elements in the same column of the periodic table, namely tellurium, selenium, sulphur. While 'amorphous', 'disordered', 'non-crystalline' and 'glassy' are roughly synonymous, the term 'glass' is reserved for those amorphous materials prepared by supercooling a liquid, e.g. window glass.

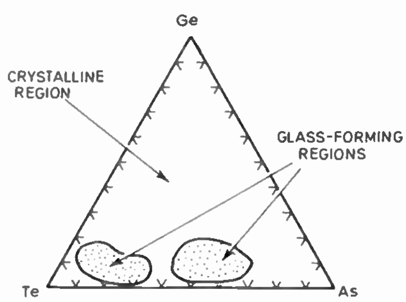


Fig. 9. Composition diagram for a three-element semiconductor. (From Hilton *et al.*)

In the more complex multielement chalcogenide glass systems used for practical switching devices, glasses can only be formed over a prescribed range of compositions. Consider, for example, amorphous Ge-As-Te, which is used for some memory devices. Possible compositions are defined as shown in Fig. 9; those proportions of the constituent elements which easily form glasses are shown inside the dotted area, the so-called glass-forming region; compositions outside this region more readily form crystalline solids. The composition of commercial memory devices is based on the Ge-Te eutectic with small additions of Sb and S.

One of the most promising threshold switching materials is a four-component amorphous chalcogenide glass made from the elements Si, Te, As, Ge, known as STAG glass (sometimes a small percentage of phosphorous is added in order to stabilize the structure). The glass-forming region in such complex materials is some volume within a tetrahedron defining possible compositions. For compositions well within the glass-forming region, fairly slow cooling from the melt can produce an amorphous material, but for compositions near to the boundary rapid quench cooling is necessary to ensure amorphous rather than polycrystalline material. We will see that such considerations determine whether a glass of particular composition is suitable for use in a memory or threshold mode.

As the boundary is approached from within the glass forming region, phase separation becomes more probable; the material is no longer homogeneous but can separate into different phases, some of which may be crystalline. Inhibition of such phase separation in threshold devices is thought to be necessary to increase their life.

4 Preparation of Glasses and Thin Films

Turning to the production of the basic amorphous semiconducter, powdered, pure constituent elements are first sealed into an evacuated quartz tube, heated in a rocking furnace at around 1000°C for many hours and then quench-cooled, often in air, to produce a glassy boule. A target for r.f. sputtering can then be formed by remelting and pressing, to form a solid disk.

Thin film devices are usually fabricated by r.f. sputtering or possibly electron-beam methods. Substrates which support the thin film arrays vary; low alkali content glasses to prevent ionic-induced crystallization have been popular, but silicon and alumina are now more common. Silicon has the double advantage of good thermal properties and the possibility of including in it all ancillary circuits and devices, using conventional planar technology.

Thin-film devices are produced on the various substrates using standard integrated circuit photolithographic techniques.

5 Applications of Amorphous Materials and Devices

A considerable number of applications for memory switches have been demonstrated. A few applications for threshold switches have been developed but most of the work on these devices has concentrated on the study of the switching phenomena.

5.1 Radiation Hardness

A considerable advantage of amorphous devices over crystalline semiconductor components is their radiation hardness. Thus these devices offer potential for applications in electrical circuits which will be situated in a hostile environment. Astable multivibrators, AND/OR gates and J–K flip flops containing threshold switches have been operated in a transient ionizing radiation of at least 10^{11} rad s^{-1} (referred to silicon) and a neutron radiation of at least 10^{20}n m^{-2} without circuit malfunction.[5,6]

Memory materials have been successfully operated[7] in an environment of neutron radiation of 10^{21}n m^{-2}. It is possible to construct a radiation-hard microprogrammer with amorphous memory devices and radiation-hard silicon circuitry. This latter application has enormous potential for military applications. Although radiation hard, the structure of amorphous material is highly sensitive to temperature, but recently glasses have been developed with high glass transition temperatures so that the full military temperature specification of −55°C to 125°C may be achieved.[8]

5.2 Memory Applications

Memory arrays have been constructed with up to 1024 bits on one silicon slice (Fig. 6(c)). These are electrically-alterable read-mostly memories, since the relatively long set-times (> 500 μs) limits their use to applications where the devices are only occasionally reset. The main advantages of the amorphous memories apart from their radiation hardness is their non-volatility, electrical alterability, low degradation of stored information and compatibility with d.t.l. and t.t.l. logic levels.

Examples of systems in which these memories have been demonstrated are antenna tuning systems, television tuning control, repertory dialler and security applications. Both the tuning applications require a memory to store tuning information but the memory must be capable of being reprogrammed when the system is used in a different geographical locality. The repertory dialler enables a limited range of telephone numbers to be stored and selected for automatic transmission. The subscriber is able to change a stored number when required. Elaborate coding, recording and recoding systems have been devised using a programmable coding electronic key and lock system.

5.3 Recent Developments in Device Performance

A detailed study of failure mechanisms in memory devices has resulted in a considerable improvement in the life expectancy of memory arrays by inhibiting electromigration effects. Lifetimes of 10^7 cycles should be possible in the near future. A considerable amount of electromigration of the elemental species occurs during the relatively high current reset. ECD specified a reset current of 150mA for their r.m.m. 256-bit arrays. Recently, by using short bursts of pulses to produce complete rehomogenization of the switching filament material, reset currents as low as 10 mA have been successfully used.[8] Thus increased device lifetime is produced as well as a considerable reduction in the power requirements of the supply. The latter advantage permits larger scale integration to be achieved, increasing the packing density to 10^5 bits/in^2 for a vertically stacking array, where the amorphous elements are deposited on top of the isolation diodes.

Recently a 1024-bit integrated memory array with full X and Y decoder contained in the same package has been developed.[8] The ultimate aim is to construct a 1024-bit array with X and Y line decoder plus driver circuits on one chip. The recent improvement in device lifetime and the reduction in power requirements makes this latter aim realizable.

The amorphous memories will have to compete with m.n.o.s[9] and f.a.m.o.s[10] which use conventional silicon technology and thus there is considerable reluctance to use new materials and technologies. However, with the considerable improvement in device lifetime and the major advance achieved in reducing the reset currents, the totally integrated array, with fast read-times, could provide a major breakthrough, giving amorphous memories a permanent niche in microprogramming.

5.4 Imaging Applications

If a phase transition from the amorphous to crystalline state is created, the resultant changes in physical properties can be utilized for information storage and display. This transition can be initiated by light, heat, electric field, chemical catalyst and stress, and can result in a change in the material's resistance, capacitance, relative permittivity, charge retention, index of refraction, surface reflexion, light absorption, transmission, scattering and differential wettability. This process of change in the physical properties of a material have been applied to produce optical mass memories, computer-controlled multiple copy printing (Ovography), dry process add-on microfilm, dry process continuous tone film and revisible recording film. A considerable advantage of amorphous films in these applications is that they can be deposited over large areas.

5.4.1 Optical mass memory

Short light pulses (10^{-8} J) from an argon-krypton laser incident on an amorphous Ge-Te or Se-Te alloy can cause a reversible structure change.[12] In the amorphous-crystalline transformation the optical transmission is changed by several orders of magnitude for wavelengths close to the absorption edge and the reflectivity changes in Te-rich alloys by a factor of 2. In some alloys, scattering due to changes in film morphology appears to be the dominant effect. It has been shown that the laser does not necessarily just act as a thermal pencil but light-accelerated crystallization promotes the transition, as the light creates a large number of electron-hole pairs which affects the localized bonding strength of the structure.[13] Due to the small size of the laser dot (~2 μm) a large bit density is possible.

5.4.2 Electron beam memory

Dakss and Sadagopan[14] indicated that writing with an electron beam is equally possible. A theory of read-out modulation efficiency of recording by surface deformation of amorphous semiconductor targets in an electron beam has been developed by Chen and Wang[15] which is based on the enhancement of secondary yield due to oblique incident electrons. The number of write/erase cycles which can be achieved with these techniques is not clear.

5.4.3 Ovography

This process is similar to xerography with the conducting drum covered in a layer of polycrystalline Se-Te rather than Se. A change in resistance in the film is produced by an incident modulated laser beam. A major advantage is that, unlike the xerographic process, multiple copies can be made from one exposure, because the amorphous image does not disappear after printing.

5.4.4 Dry process film

A latent image can be produced in an amorphous film by photonucleation and the subsequent image can be developed by heat or uniform radiation.[16] In the latter case the exposure occurs at elevated temperatures in order to accelerate the crystal growth in the exposed areas by photocrystallizations. A grey scale can be provided by the variation of crystal size with exposure. Resolutions of 500 lines per mm has been achieved; this is controlled by the number and size of the crystallites in the exposed area. The optical contrast after exposure of 2 : 1 can be increased to 1000 : 1 by etching, toning or dry stripping.

Ovonic graphic art films include contact and projection types, both of which can be produced in either positive or negative mode. Another high contrast, high resolution film which has unique properties has just been produced by ECD. It is a microfilm which provides means of maintaining updatable records of printed and typed documents in microfilm file card form. This ovonic microfilm system permits step-and-repeat recording of up to 98 sequential hard copy documents at a reduction ratio of 24× on a single 4 in × 6 in fiche card. As the film is not affected by environmentally encountered light additional documents can be recorded on the unexposed frames.

6 Threshold Applications

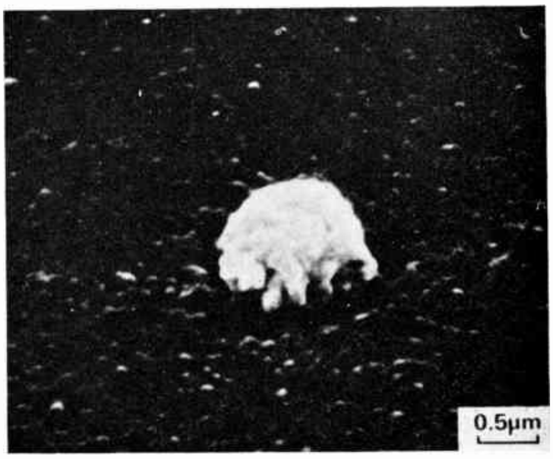
Apart from the logic circuits mentioned earlier most of the applications for threshold switches have been for latching elements in ZnS electroluminescent displays and liquid crystal displays. A stable d.c. operated threshold switch with high OFF resistance (1 MΩ), a 100 V threshold voltage and a holding current of approximately 30 μA is required for the latching element of a d.c. ZnS display. By altering the external circuitry Adler and Flora[17] and Hughes *et al.*[18] have found that the holding current can be reduced and the threshold voltage increased by using gap devices of increasing gap width. However, there is still some difficulty in finding a suitable switching material which has long d.c. lifetime and high OFF resistance. Another possibility is to hold the array ON with a memory switch and then erase through a threshold device.

Liquid crystals operate from an a.c. supply; continuous switching of display elements has been demonstrated by Hughes *et al.*[19] using threshold gap devices switching with alternate polarity pulses.

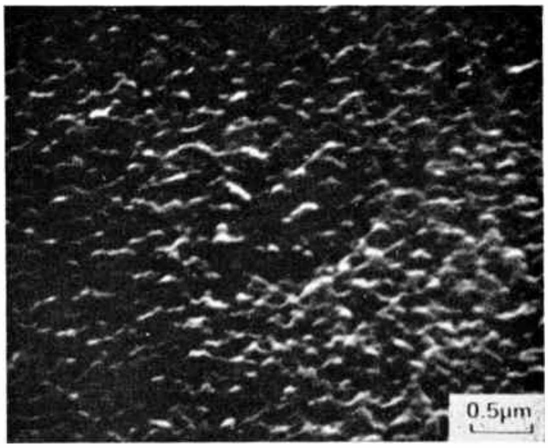
7 Theories of Switching

7.1 Memory Switching

Many theories of threshold switching have been proposed but the subject still remains somewhat controversial. In contrast, the establishment of the permanent low resistance ON-state in memory glasses is much better understood. The memory action is based on the reversible crystallization and revitrification of the material in a current filament. Sie *et al.*[20] observed a 2 μm diameter filament of polycrystalline Te and GeTe in a switched memory device by etching away the top contact and examining the material with a scanning electron microscope (see Fig. 10). The reset pulse revitrifies the crystalline filament and with a short trailing edge on the reset pulse the material is quenched, producing a return to an amorphous structure.



(a)



(b)

Fig. 10. Photomicrograph of etched memory material after (a) SET and (b) RESET (after Sie *et al.*[18]).

The lock-on time is the time taken for the Te and GeTe crystallites to grow to form an uninterrupted path between the electrodes. It is found to have a log-normal distribution and decreases with higher current due to the enhanced crystallization kinetics.[21] A major failure mechanism in memory switches occurs in the reset operation when the resulting OFF-state has a threshold voltage below a minimum specified value. The gradual degradation of threshold voltage with cycles of operation is due to electromigration of constituent elements of the amorphous material.

7.2 Threshold Switching

Threshold switching theories can be divided conveniently into three classes.

7.2.1 Heterogeneous model

Coward,[22] Bosnell and Thomas[23] reported marked changes in threshold voltage and off state conductivity in threshold devices after the first few switching events (see Fig. 11). This process of *forming* has caused considerable debate in the field and has often confused the

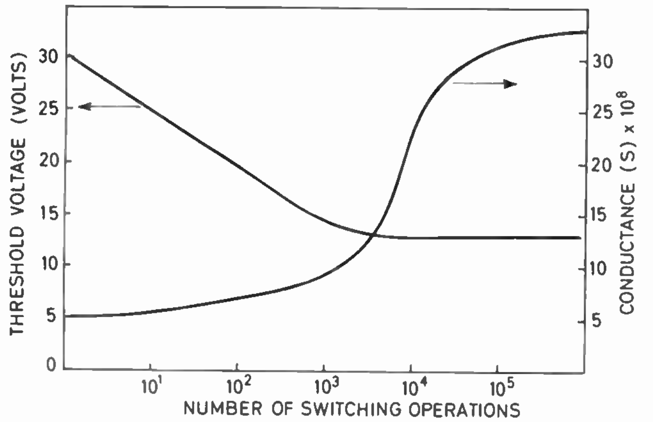


Fig. 11. Reduction of the threshold voltage and increase in the conductance of a device as it is progressively formed.

interpretation of experimental data. The Bosnell–Thomas model of switching is based on the phase separation and crystallization of the material inside a current filament that exists in the off state. They have observed crystalline needles inside a filament in a SiTeAsGe threshold switch.[24]

Ormondroyd *et al.*[25] have studied in detail the forming process in SiTeAsGe switches by examining the change in electrical characteristics of the device. They have varied the Si content of SiTeAsGe switches, to produce an activation energy in the virgin state which varies from 0·44–0·71 eV; however, the activation energy of the material that dominates room temperature conduction in the fully formed device is ~0·44 eV for all SiTeAsGe glasses. In addition, there is a volume of material around the OFF-state filament which can also contain phase separated glass and at certain temperatures will provide the primary conduction path; the extent of this effect depends on the geometry of the device. Therefore, it is clear that any measurements of the OFF-state taken on a previously switched device has to be interpreted with extreme care. Also Ormondroyd *et al.*[26] have shown that the ON-state characteristics can be markedly affected by, and have a marked effect on, the electrical properties of the formed OFF-state. The OFF-state conductance is affected by the length of time the device has been previously held in the ON-state and repetition frequency of previous switching pulses (see Fig. 12).

It is believed that these results are brought about by crystalline growth in the filament which eventually leads to the failure of the threshold device when a permanent crystalline filament is formed as in a memory switch. However, it should be said that some researchers are now claiming that non-forming glasses can be made. The details of how these glasses are prepared and the testing of the characteristics of such devices has unfortunately not been made available.

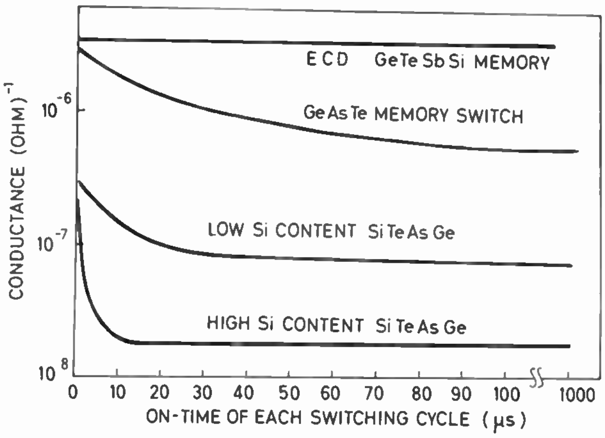


Fig. 12. Variation of the conductance of devices having several glass compositions after forming with different ON-times.

It is widely felt that the forming process is not in itself a prerequisite for switching but the authors feel that a detailed study of this process will lead to its possible elimination in new glasses. A rigorous testing of new non-forming materials which are currently being developed is necessary before some of the more subtle experiments on switching mechanisms are attempted.

For a formed pore device, a filament of diameter ~5 μm is produced which has a much higher conductivity than the surrounding virgin material. Thus the filament dominates the electrical properties of the switch and due to its relatively high electrical conductivity and the poor thermal conductivity of the surrounding virgin material, thermal effects are thought to dominate the switching process.

7.2.2 Electrothermal model

The simple thermal model of switching is based on thermistor type action. When a current flows in a semiconductor, Joule heating occurs, thus increasing the temperature in the device which in turn causes an increase in current. A steady state equilibrium situation is reached when the heat conducted away from the device equals the heat generated within. The hottest region of the device will be at its centre and thus the current will tend to concentrate in a filament. The heat transport equation can be written:

$$C\frac{\partial T}{\partial t} = \nabla . K\nabla T + j . E$$

where C is the heat capacity, K is the thermal conductivity and $j = \sigma E$ where σ is the electrical conductivity.

Kroll[27] has recently published a very comprehensive thermal analysis and obtained solutions to the heat equation to predict the form of the time dependent I–V characteristics.†

Kaplan and Adler[28] showed that negative resistance cannot be obtained when the electrodes act as perfect heat sinks because the cold material adjacent to the electrodes has a high resistance. Warren[29] considered heat flow perpendicular to the current flow which resulted in a hot current filament and negative resistance. However, both these cases are extreme. In practice the electrodes do not act as perfect heat sinks and due to the very low thermal conductivity of chalcogenide glasses, the heat flow will not be completely in the direction perpendicular to the current direction.

Electrothermal theories, in contrast to thermistor theories, take into account the field dependence of the conductivity in the OFF-state. Walsh *et al.*[30], Fagen and Fritzsche[31] and more recently, Marshall and Miller[32] have found the conductivity can be expressed in the form:

$$\sigma = \sigma_0 \exp\left(-\frac{\Delta E_a}{2kT} + \frac{E}{2E_0}\right)$$

where ΔE_a is the activation energy, E is the electric field and $E_0 = kT/ea(T)$ where $a(T) = a_0 - \alpha T$, is of the order of 100 nm. Marshall and Miller attribute this field dependence to the mobility rather than the carrier density. They have analysed the field dependent conductivity in many materials and show that electrons and holes in nearly all cases have a field dependent conduction of this form and that holes are the majority carriers. However, despite many attempts, the mechanism for conduction in the OFF-state has not yet been successfully explained. Space charge currents, Poole-Frenkel emission, hopping conduction and field stripping have all been suggested as possible mechanisms for the high field conduction.

Two exponential field regions are obtained at low temperatures in some glasses, in particular the memory glass $Ge_{15}Te_{81}Sb_2S_2$. The inclusion of the field dependent conductivity in the thermal calculations results in a reduction in the resistance of the cold regions near the electrodes because the large field that will be developed across them due to the low resistance of the hot regions. Thus a negative resistance can be obtained even with perfectly heat sinking electrodes.

Kroll[27] considers the uniqueness and stability of the solutions to the thermal equations. He explained many of the observed effects in terms of his thermal analysis. The proximity of an unstable region to the OFF-state suggests that the system moves from the OFF-state to the unstable regime as a result of statistical fluctuations in either temperature, thermal conductivity or electrical conductivity or current. The delay time is explained as the time taken by current or temperature fluctuations to reach a critical size. At large over-voltages switching ceases to be statistically controlled and agrees with the observed relationship between over-voltage and delay time. The ON-state is limited to the cold regions adjacent to the electrodes and where the hot filament is constricted. The recovery of the threshold voltage and the transient ON-state can be explained by the nucleation and growth of a cold region.

Popescu[33] has refined the electrothermal theory by taking into account local defects (pre-existing or built in during the forming process). The model developed can be used to explain some experimental results which might appear non-thermal in nature.

The extent to which thermal effects may dominate switching will depend on the geometry of the device and the shape and length of the switching pulse. If the thermal time-constant of the device is less than the switching pulse width, then a non-uniform temperature distribution can be established resulting in a non-uniform field distribution. Thus switching can be initiated in the regions of high field. Buckley and Holmberg[34] and Maine[35] have demonstrated how the geometry of the virgin device can influence the device current-voltage characteristics and the threshold voltage (see Fig. 13). Increasing device area or thickness of the chalcogenide layer, lowers the voltage at which deviations occur from the OFF-state conduction characteristics of $\log G \propto V$ (or $\log \sigma \propto E$). Buckley and Holmberg[36] have shown that thermal effects can be minimized by using short switching pulses. Adiabatic heating occurs when the applied pulse width is less than the thermal time-constant of the device. Switching then occurs at a critical field, the value of which depends on the amorphous material and the temperature produced when the

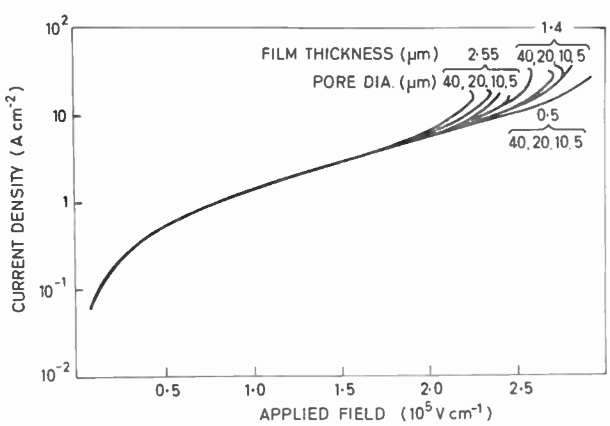


Fig. 13. Current density versus field for GeTeSbS devices of different thickness and pore diameter (after Buckley and Holmberg[54]).

device is adiabatically heated. However, they have shown that isothermal conditions can be approximated by switching devices with very short 1–10 ns pulses. A unique critical switching field ($3{\cdot}8 \times 10^7$ V m^{-1} for

† Note that all calculations so far have been made for sandwich devices.

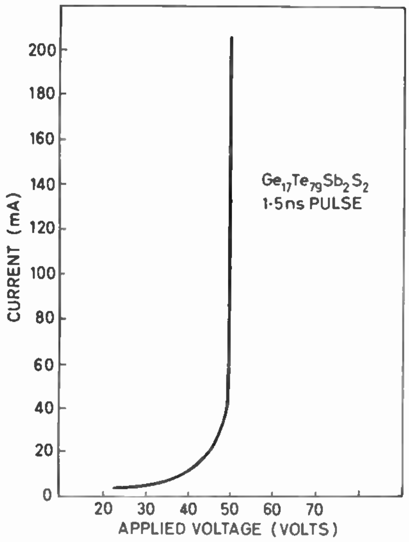


Fig. 14. Current-voltage characteristic for $Ge_{17}Te_{79}Sb_2S_2$ device for an applied pulse width of 1·5 ns (after Buckley and Holmberg[32]).

$Ge_{17}Te_7$-SbS_2) can be measured and the resulting current voltage characteristics shown in Fig. 14 are obtained.

This experimental evidence for switching with short pulses is not consistent with thermal or some existing electronic theories of switching.

7.2.3 Electronic theories

Under normal switching operations thermal effects cannot be eliminated. A current channel will form, inside which the temperature rise can be very high. However, many observed experimental results can be successfully explained by electronic theories which under certain circumstances can dominate thermal effects. Most of the evidence supporting electronic theories comes from a study of the ON-state.

It has been found that the holding current is practically independent of temperature, electrode separation and electrode area. Thus it has been deduced that the electric field across the sample appears across the regions adjacent to the electrodes. Adler and Flora[17] found that the ON-state could not be frozen in even at 1·6 K which implies a non-thermal state and that deep traps are not involved in the maintenance of the ON-state. In addition they found that the recovery curve for the ON-state (see Fig. 15) is temperature independent, implying that the recovery process is purely electronic in nature. In addition Henisch and Pryor[37] previously reported that the recovery curve remains essentially unchanged when the ON-current of a previous pulse is increased by ten times. These results imply that carriers injected into the sample tunnel through the potential barriers established at the contacts, as suggested earlier by Böer and Ovshinsky.[38]

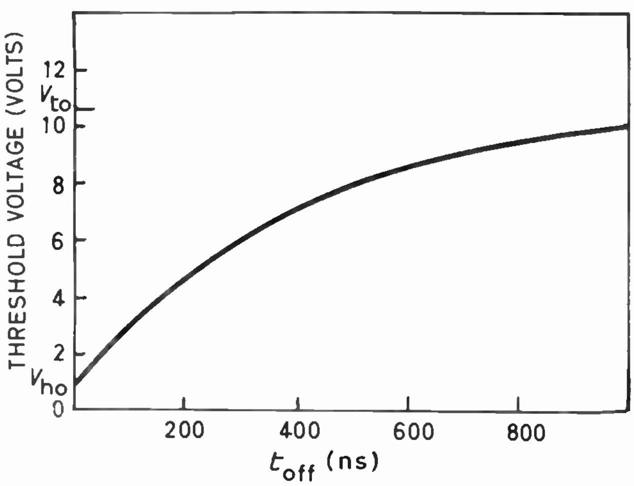


Fig. 15. Recovery of threshold voltage with time after turn-OFF, t_{off} for a 1 μm thick chalcogenide-glass film sandwiched between Mo electrodes (after Adler and Flora[17]).

Fritzsche and Ovshinsky[39] suggested that the ON-state is initiated by field-enhanced conduction which creates a situation where the excess current cannot be replenished completely by the electrodes. Thus the exclusion of carriers creates a positive space-charge at the cathode and a negative space charge at the anode. The subsequent increase in field at the electrodes causes an increase in injection as the carriers eventually tunnel into the device. Henisch, Fagen and Ovshinsky[40] suggested the now well-publicized double injection model (see Fig. 16). In this model electrons are injected into the sample and then trapped in the region near the cathode, creating

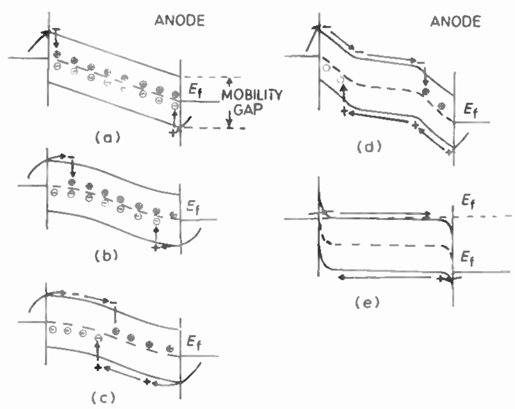


Fig. 16. Energy band diagrams for the switching sequence for a double injection model of switching (after Henisch *et al.*[38]).

a negative space-charge. Similarly, a positive space-charge is created at the anode due to hole injection. The presence of the space-charge causes the electric field in the sample to be redistributed, creating an increased field in the centre. When the applied field is increased sufficient for the two space charge regions to overlap a region in the centre is created in which all hole and electron traps are full and thus the high field in the central region will collapse. This produces an increase in the field near the electrodes, causing the overlap region to extend until the field appears only at the contact regions and the ON-state is established.

Henisch and Pryor[37] have observed polarity effects at reduced temperatures. Using a double pulse-arrangement, they found that if the first switching pulse was reversed in polarity then the delay time for the second pulse was extended. Such effects cannot be explained by a thermal model.

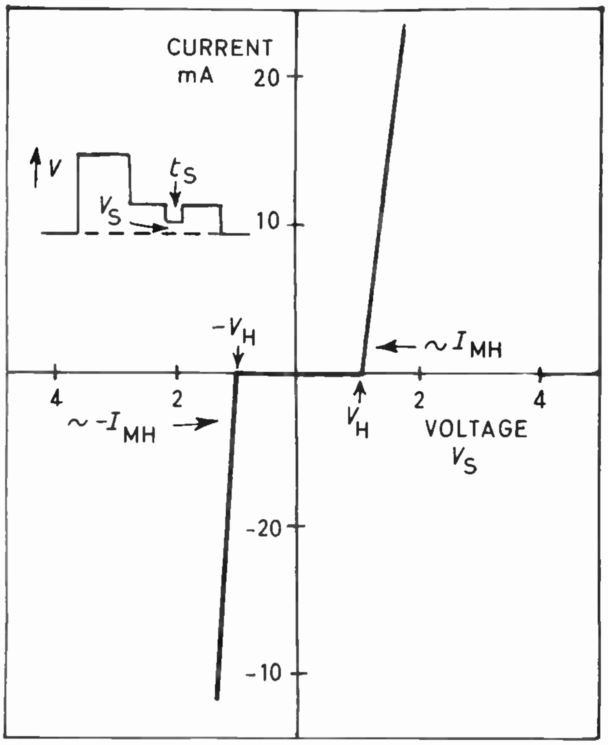


Fig. 17. Transient current versus voltage for the ON-state (after Henisch *et al.*[35]).

Pryor and Henisch[41] and Vezzoli[42] have studied the transient ON-state characteristics (see Fig. 17). They found that it is possible to reverse voltages and currents within nanoseconds. That such results are independent of temperature has led Lee[43] to conclude that, as equilibration via deep traps would be slow, free carriers or only very shallow traps produce the space charge. This view is supported by the recent fast switching experiments of Buckley and Holmberg[36] where the ON-state appears to be established in a few nanoseconds. It should also be noted that, excluding heating effects, no thickness dependence has yet been found in the conductance characteristics of the OFF-state near the threshold voltage as would be expected for a charge injection model. However, Allison and Dawe[44] obtained good agreement between a single injection model and with experiment data for delay time measurements and the constant current switching in the statistical delay time region when $V_{th} < V_{applied} < 1{\cdot}2V_{th}$. They suggested that field redistribution occurs when the injected charge traverses the sample and switching occurs when a critical field is reached somewhere in the sample.

The idea of switching occurring at a critical field has been considered earlier by other authors. This idea, along with Buckley and Holmberg[36] fast switching experiments, tends to support Hindley[45] and Mott's[46] early proposals that beyond a critical field, avalanche and impact ionization occurs. The statistical nature of the delay time at small over-voltages supports their proposal. Henisch[47] suggests that it is difficult to resolve the impact ionization theory with his own results of the independence delay time for switching on illumination. However, a more significant result which supports the impact ionization theory but cannot be resolved with thermal or electronic injection theories, is that Henisch *et al.*[48] found that the critical field was independent of illumination level. These experiments were performed on $Si_{18}Te_{40}As_3Ge_7$ devices which, it was claimed, did not form.

Recent observations have been made of radiative emission from switching devices. Kolomiets *et al.*[49] observed that the wavelength of the light corresponded to half the mobility gap whereas Vezzoli *et al.*[50] observed band gap radiation. In the latter case the light output from the threshold switch is only observed when the devices are overdriven. It appears to be highly spatially confined, suggesting stimulated emission. The radiation intensity appears not to be uniform but greater towards one electrode; however, it is not clear whether emission occurs for every switching event. Recombinative radiation is an important observation, as this lends support to the injection models for the ON-state. However, it has not yet been established whether the radiative emission is intrinsically linked with switching or if it is a contact phenomenon not directly involved in switching.

The injection of large amounts of charge in the ON-state is thought to be highly probable. Reinhard *et al.*[51] have deduced the band structure of junctions between $Si_{17}Te_{39}As_{36}Si_{17}P_1$ and n or p-type silicon. Peterson and Adler's[52] results on switching of such structures indicate that the ON-state is sustained by *electrons* injected from the glass into the Si. They have

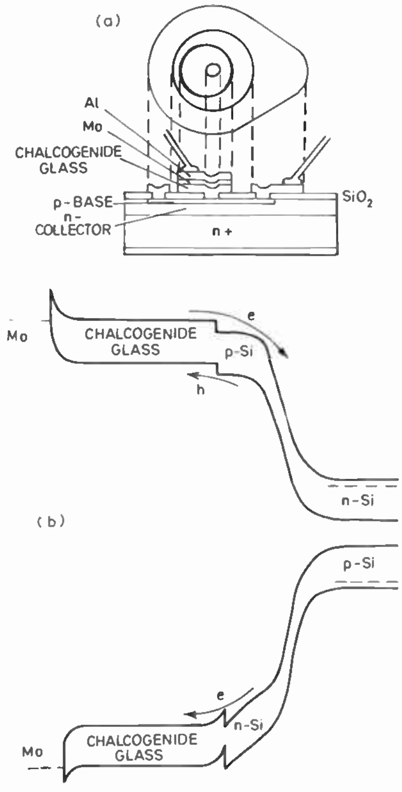


Fig. 18. (a) Structure of transistor with an amorphous emitter region. (b) Energy band diagrams for transistor configurations Mo-chalcogenide-(p-Si)-(n-Si) in which gain is obtained, and for Mo-chalcogenide-(n-Si)-(p-Si) in which no transistor action is observed (after Peterson and Adler[50]).

fabricated a unique device employing a threshold chalcogenide glass as the emitter of a heterojunction transistor (see Fig. 18(a)). The most important conclusion from the transistor experiments concern the band structure and charge injection (see Fig. 18(b)). The band structure suggests that electrons are injected from emitter amorphous regions into the Si. Peterson and Adler suggest that the reason why gain (~ 3) is observed in the device is that the electron injection from the chalcogenide is greater than hole injection from the base due to the fact that electrons are the predominant carriers in the ON-state. This is a somewhat surprising result as it is known that holes are the majority carriers in the OFF-state.

Finally, mention should be made of van Roosbroeck's theory of switching.[53] He introduced the concept of relaxation semiconductors in which the dielectric relaxation time τ_d exceeds the carrier lifetime τ_e. From this he predicts that majority carrier depletion can be established due to minority carrier injection and that all the electric field appears across a recombination front when the device is in the ON-state. There remains much argument as to whether amorphous semiconductors behave as relaxation semiconductors as there is some debate as to how τ_d and τ_e should be measured. However, apart from this, some recent computer calculations of Popescu and Henisch[54] have revealed that, if diffusion effects are taken into account, some of van Roosbroeck's original deductions are no longer valid.

In conclusion there appears to be considerable evidence to suggest that, in the absence of excessive heating, when a critical field is reached, a process of impact ionization initiates the switching. In the ON-state, injection of carriers occurs, probably by tunnelling through barriers at the contacts, and electron conduction appears to predominate. However, it should be said that thermal effects will still be present and that these effects can easily predominate the switching under many conditions. The electrothermal theories provide some impressive quantitative data that agrees with many experimental observations.

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Design of digital filters with severely quantized coefficients

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SUMMARY

Two simple techniques are described for the design of recursive digital filters in the cascade configuration, which minimize the coefficient word-length. These are intended for cases where a statistical treatment is not valid because of the coarseness of quantization.

The derivation of the discrete set of pole positions for the basic second-order section in the form of a z-plane pole grid is reviewed. This concept is fundamental to both techniques. They have been implemented by means of interactive operation on a small computer, but the more sophisticated technique, which is a form of one-at-a-time optimization, could be organized as a batch-processed algorithm.

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1 Introduction

The low cost and availability of integrated circuit technology have made possible the hardware implementation of sophisticated digital signal processors. The cost, complexity and speed of such processors depend on both the data and coefficient word lengths.

The principal effect of data quantization in most cases is the addition of a noise component to the output signal. The data word-length therefore is determined by the signal/noise ratio and dynamic range requirements. Coefficient quantization on the other hand causes deviations from the desired frequency response and thus the resolution must depend on the shape of the response and on the permitted tolerances. Since multipliers account for the major part of the total hardware, any reduction of coefficient resolution leads to significant savings in complexity and cost.

In a set of high resolution coefficients the round-off error can be assumed to be a random variable, independent from coefficient to coefficient, and uniformly distributed. This is the basis of the 'stray transfer function' method described by Knowles and Olcayto[1] which enables the mean square error in the frequency response to be evaluated as a function of coefficient word-length. There is no way of defining a lower limit to what may be considered to be 'high resolution' in this context, but, in the experience of the authors, eight bits seems a reasonable value for low to medium-order filters.

For short coefficient word-length however the round-off error tends to become deterministic, so that the above statistical treatment is no longer valid. In addition, the procedure of simply rounding off each coefficient does not necessarily give the best response for a given word-length. An alternative is to use an optimization procedure which searches the discrete set of coefficients or corresponding pole/zero positions in the vicinity of the infinite resolution coefficient. Such methods[2] tend however to be expensive in computer time, which may be a significant factor in certain applications.

This paper introduces two simple and computationally economical design methods for digital filters with quantized coefficients, suitable for filters specified in terms of amplitude characteristics (such as Butterworth, Chebyshev, etc.). Both methods use the cascade configuration because of the simplicity in the realization of zeros and the ease with which the cascade elements can be used in the design. Since the second-order digital network is the basic building block of a cascade realization, its main characteristics are discussed before the design methods are presented.

2 The Second-order Digital Network

A second-order digital network with the transfer function

$$H(z) = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1 + b_1 z^{-1} + b_2 z^{-2}} \quad (1)$$

has a pair of complex conjugate poles and is asymptotically stable[4] if the coefficients b_1, b_2 satisfy

$$\left.\begin{array}{r} -2 < b_1 < 2 \\ -1 < b_2 < 1 \\ -(b_1+1) < b_2 < (b_1-1) \end{array}\right\} \quad (2)$$

and

$$b_1^2 < 4b_2. \quad (3)$$

Conditions (2) define a triangle in the b_1, b_2 plane which contains the set of all stable pairs (b_1, b_2), while (3) defines the set of (b_1, b_2) which give complex conjugate poles.

For quantized coefficients (2) define a finite set of pairs with a distribution depending on their word-length and the type of numerical representation employed, i.e. fixed or floating point.

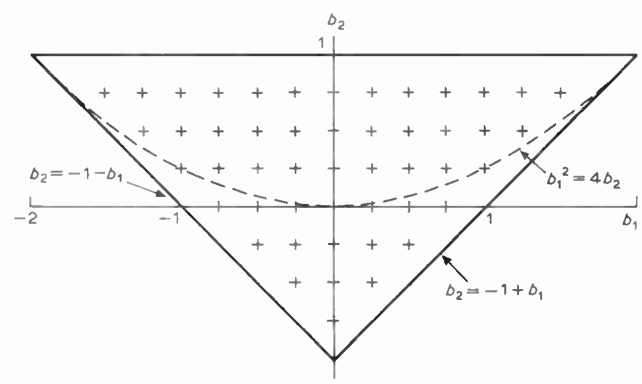


Fig. 1. (b_1, b_2) plane for four-bit coefficients.

For hardware realization fixed-point arithmetic is commonly used and the discussion is limited to this form of representation. As a typical illustration, the realizable (b_1, b_2) pairs for four-bit coefficients, and the stability region from (2) and (3) are shown in Fig. 1. Both coefficients are in sign + magnitude format with one integer bit and two fractional bits. The distribution of (b_1, b_2) is uniform which is a property of the normal binary representation.

The subset of (b_1, b_2) giving complex pairs of poles is of most interest since real poles occur singly and would be implemented as first-order sections.

To each realizable set (b_1, b_2) there is a corresponding discrete set of poles inside the unit circle in the z-plane, with a distribution which depends on the distribution of (b_1, b_2). Expressing the pole position in polar form

$$z = r \exp(\pm j\phi) \quad (4)$$

then it can be easily shown that

$$b_1 = -2r \cos \phi \quad (5)$$

$$b_2 = r^2 \quad (6)$$

Thus the poles are located at the intersection of a grid[3] consisting of circles, centred at the origin with radii $\sqrt{b_2}$, and lines parallel to the imaginary axis at distance of $-b_1/2$. For four-bit coefficients the corresponding pole grid is as shown in Fig. 2(a).

A feature of the pole grid for fixed point representation is the non-uniform distribution of the poles and their concentration around the imaginary axis. The low density of poles near the real axis is the reason for the use of high precision coefficients in narrow band low-pass filters.

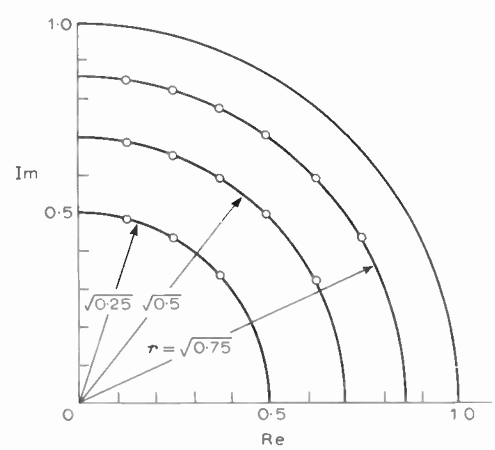
The pole distribution can become uniform as shown in Fig. 2(b), if use is made of the coupled resonator, introduced by Gold and Rader.[4] However, its realization entails an increase in computation and/or hardware, so that this kind of network is only likely to be useful for extremely low cut-off frequencies.

3 Preliminary to the Design

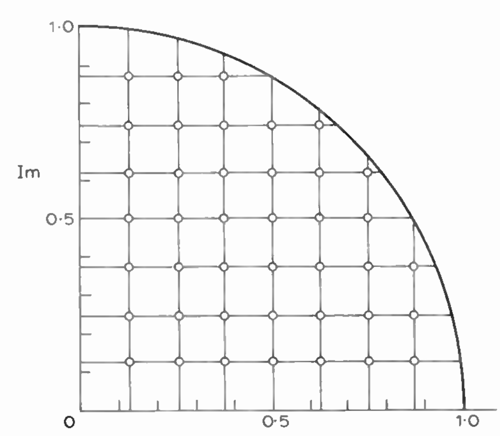
It can be inferred from Section 2 that any attempt to reduce the resolution of the coefficients will result in a variation of the response, and the question now arises of how to select a pole set with reduced resolution which will satisfy the required response within acceptable tolerance limits. In order to arrive at a rational design method, two constraints are imposed on the finite coefficient resolution filter:

(i) the order of the finite resolution filter must be equal to that of the infinite resolution filter, and

(ii) over an appropriate set of frequencies $\omega_1, \omega_2, \ldots, \omega_n$, the corresponding set of response errors $\Delta v_1, \Delta v_2, \ldots, \Delta v_n$ must be within the set of specified tolerances $\Delta e_1, \Delta e_2, \ldots, \Delta e_n$ (henceforth for convenience these will be referred to as the frequency set Ω, the error set ΔV and



(a) Four-bit pole grid for single resonator.



(b) Four-bit pole grid for coupled resonator.

Fig. 2. Pole grids.

the tolerance set ΔE) i.e. the design must satisfy

$$\Delta v_i = |H_\infty(j\omega_i) - H_F(j\omega_i)| \leqslant \Delta e_i, \quad i = 1, 2, \ldots, n \quad (7)$$

where $H_\infty(z)$ and $H_F(z)$ are the filter transfer functions with infinite and finite resolution coefficients respectively.

Constraint (i) ensures that the complexity of $H_F(z)$ will equal that of $H_\infty(z)$, and (ii) that the tolerance limits will always be satisfied.

The criterion in (7) is not the only one available, but it has the advantage of weighting all the errors equally. It is of course possible for different criteria to be used for various subsets of Ω, but the selection of any particular criterion depends on the application.

Filter designs are based on approximations,[5] and the nature of the approximation is revealed by the pole distribution in the s-domain. In the design of digital filters where a continuous prototype is used, the design is accomplished by mapping the pole locus from the s-domain to the z-domain. Among the available mapping functions[6] the bilinear transform is perhaps the most successful in carrying the properties of the s-plane into the z-plane, where the magnitude response in the pass and stop bands is of prime importance.

As a typical example of mapping the s-plane into the z-plane through the bilinear transform, consider the Butterworth family of filters. In the s-plane the pole locus is a circle centred at the origin. Under the bilinear transform the pole locus in the z-plane is again a circle, with co-ordinates

$$u = \frac{1 - R^2}{1 - 2x + R^2} \qquad v = \frac{2y}{1 - 2x + R^2} \qquad (8)$$

centered at

$$u_0 = \frac{1 + R^2}{1 - R^2} \qquad v_0 = 0 \qquad (9)$$

and radius

$$\rho = \frac{2R}{1 - R^2} \qquad (10)$$

where (x, y) are the co-ordinates in s, R the radius in s, and (u, v) the co-ordinates in z. The equations (8), (9) and (10) apply to a low-pass filter but similar relationships hold for the other filters as well. The poles of the infinite resolution filters lie on the arc of the pole locus inside the unit circle and their position depends, for the Butterworth family, on the order of the filter. For other filter families the pole locus changes with the order and the allowed passband ripple (as in the Chebyshev family). In spite of the difference with regard to the pole locus all filters possess some general properties which correspond to the general properties of the continuous filters.[5] They are summarized here because they are used in the design techniques to be described.

(i) Complex poles appear in conjugate pairs and they are symmetrically (or very nearly) distributed about the filter reference frequency. By reference frequency we mean the frequency with respect to which all the specifications are derived.

(ii) Digital filters derived from the continuous filters with zero at infinity, have a number of zeros equal to the filter order. The zeros for low-pass are at $z = 1$ and at $z = -1$ for high-pass filters. Band-pass filters have a number of zeros equally divided between $+1$ and -1. If the continuous filter belongs to the elliptic (Cauer) family, the digital filter has zeros on the unit circle, equal to the number of zeros of the continuous filter, plus a number of zeros at either $+1$ or -1 (or both), so that the numerator and denominator are of equal order.

4 Direct Design Technique

The direct design technique uses the geometric properties of the pole grid and pole locus to produce designs based directly on the quantized coefficients. The technique is presented on a stepwise procedure and it is based on the cascade realization.

(i) On the basis of the response specifications select the suitable continuous filter family and order. Select suitable frequency and tolerance sets.

(ii) Compute and plot within the unit circle in the z-plane the pole locus of the filter (using the bilinear transform) and superimpose the pole grid for the selected coefficient word-length in the vicinity of the passband.

(iii) Select a set of poles (and zeros) according to the general characteristics presented in Section 3. The poles and zeros must be as close as possible to the pole locus.

(iv) Compute the error set ΔV from

$$\Delta v_i = |H_\infty(j\omega_i) - H_F(j\omega_i)| \qquad i = 1, 2, \ldots, n$$

and if all $\Delta v_i \leqslant \Delta e_i$ the design is accepted, otherwise—

(v) Select a new set of poles on the basis of the performance achieved with the last set and repeat.

(vi) If the available poles are exhausted and the error bound is not satisfied, increase the coefficient word-length by one bit and return to (ii).

Two examples will be presented which serve to illustrate the outlined procedure.

Example 1. A low-pass digital filter is required with a cut-off frequency of $0{\cdot}125 f_s$ and at least 20 dB attenuation at $0{\cdot}25 f_s$. The response must be monotonic and may only deviate from the theoretical one by $\pm 0{\cdot}5$ dB in the passband and $+1$ dB elsewhere.

The specifications (after frequency warping[4,6]) call for a third-order Butterworth filter. The piecewise linear frequency response and the specified tolerances are shown in Fig. 3.

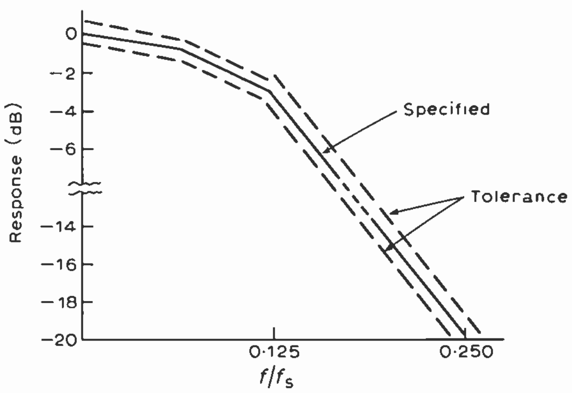


Fig. 3. Specification for Example 1.

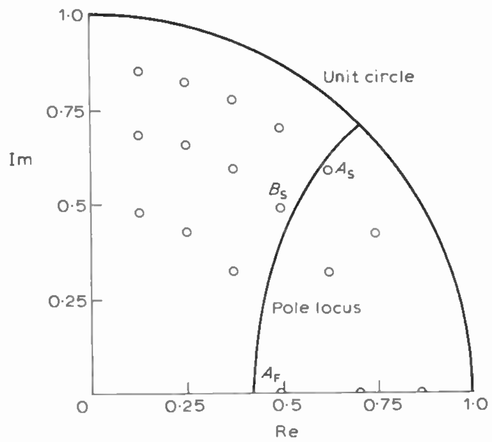


Fig. 4. Pole grid and pole locus for four-bit of Example 1.

The design starts with four-bit coefficients (sign and magnitude). The pole locus and the pole grid are as in Fig. 4. The first pole set is (A_S, A_F) with three zeros at $z = 1$. The corresponding frequency response is as in Fig. 5(a). The tolerance set is not satisfied and a new pole set is needed. The peaking of the response at $0{\cdot}125 f_s$ indicates that the new pole set should contain a more relaxed complex pole. Such a set is (B_S, A_F), with a frequency response as in Fig. 5(b). This pole set satisfies the specifications and the transfer function is given by

$$H(z) = \frac{(1-z^{-1})^3}{(1-z^{-1}+0{\cdot}5z^{-2})(1-0{\cdot}5z^{-1})}.$$

Specifications for the stopband would be superfluous with filters whose response is monotonic outside the

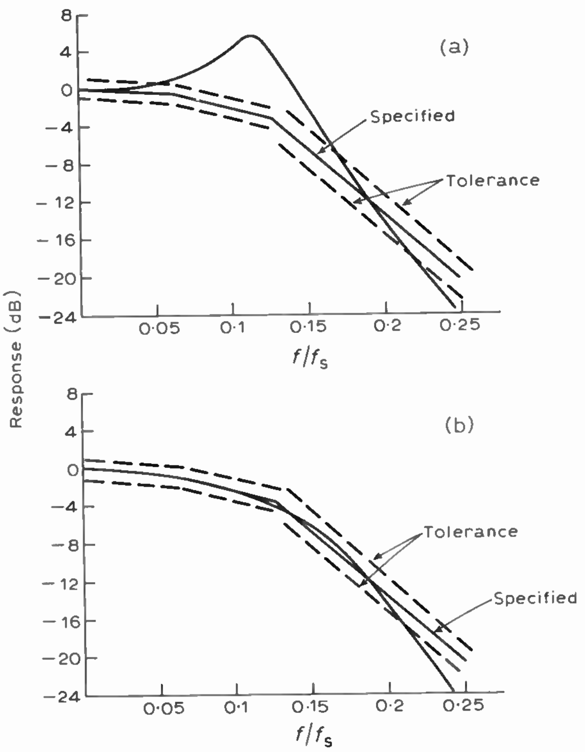


Fig. 5. Frequency response of Example 1.
(a) Response for poles A_S and A_F.
(b) Response for poles B_S and A_F.

passband, because the zeros at $z = 1$ make sure that the attenuation would exceed the minimum required in the transition band.

Example 2. Consider the design of a bandpass filter with cut-off frequencies at $0{\cdot}125 f_s$ and $0{\cdot}2 f_s$, and at least 20 dB attenuation at $0{\cdot}02 f_s$ and $0{\cdot}3 f_s$. The acceptable tolerance is $\pm 0{\cdot}5$ dB in the passband and 2 dB in the transition band, with a monotonic response.

A second-order low-pass Butterworth prototype satisfies the requirements and the design of the fourth-order band-pass filter begins with four-bit coefficients. Pole grid and pole locus are shown in Fig. 6(a). Attempts to produce an acceptable design with this word-length proved futile and the word-length was increased to five bits, Fig. 6(b). Those filter poles which might give a satisfactory design are enclosed in rectangles. Still the tolerance scheme is not satisfied, the best that could be

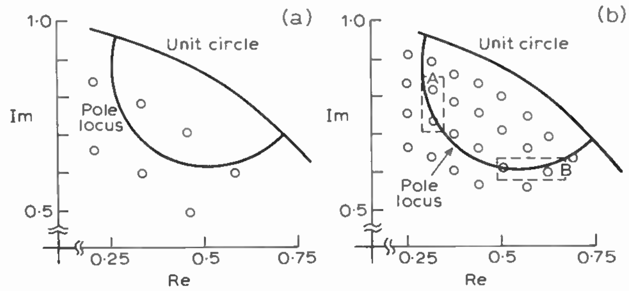


Fig. 6. Pole grids for Example 2. (a) four-bit, (b) five-bit.

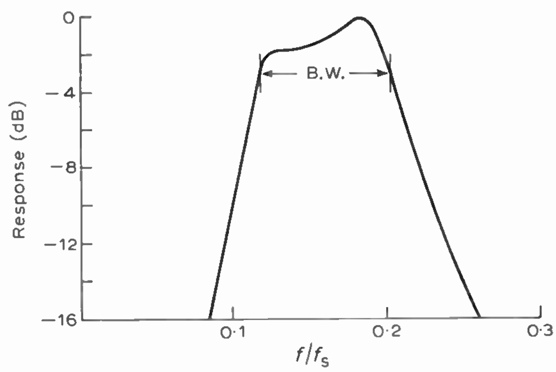


Fig. 7. Response for five-bit of Example 2.

done being shown in Fig. 7. The increase of the word-length to six bits leads to the pole grid of Fig. 8(a). Potential poles are enclosed in rectangles and finally the pole pair (A, B) yields a satisfactory design, Fig. 8(b). The design over-satisfies the specifications below $0{\cdot}125 f_s$ which is unavoidable since the double zero at $z = 1$ is very close to the filter bandpass. The transfer function is

$$H(z) = \frac{(1-z^{-2})^2}{(1-0{\cdot}625z^{-1}+0{\cdot}6875z^{-2})(1-1{\cdot}1875z^{-1}+0{\cdot}75z^{-2})}.$$

5 Indirect Design Technique

Two critical steps in the direct design technique are the construction of the pole locus and the selection of the initial pole set. The pole locus is not always easy to construct and the selection of the initial pole set depend on a good understanding of the underlying theory.

These two steps can be avoided if, instead of using the pole grid and pole locus, use is made of the pole grid and the infinite resolution poles computed with the available transformation from the suitable continuous filter.

The essence of this technique is the systematic selection and testing for each pole of the nearest discrete positions. From Fig. 1, it is clear that each infinite resolution pair of coefficients is enclosed by a square, the corners of which are the four nearest finite resolution pairs. Since there is a one-to-one mapping between points in the (b_1, b_2) plane and pole positions in the z-plane, an infinite pole position can most easily be considered to lie within a cell defined by the four discrete poles corresponding to the corners of the square in the (b_1, b_2) plane. In most cases these four will be the nearest positions in the z-plane also. In some cases two of the discrete positions will be on the unit circle and are therefore discounted. The technique is presented again as a stepwise procedure.

(i) From the given specification compute the infinite resolution poles and define the frequency and tolerance sets.

(ii) Select the coefficient word-length, compute the corresponding realizable poles and select, for each infinite resolution pole, four realizable poles which form the smallest cell enclosing the former.

(iii) Select the initial pole set, so that each finite resolution pole gives the minimum positional error

$$\Delta p_i = |{}_{\infty}p_i - {}_{F}p_i|_{min}$$

where ${}_{\infty}p_i, {}_{F}p_i$ are the ith infinite and finite resolution pole positions respectively.

(iv) Compute the error set Δv from

$$\Delta v_i = |H_{\infty}(j\omega_i) - H_F(j\omega_i)| \qquad i = 1, 2, \ldots, n.$$

If for all i $\Delta v_i \leqslant \Delta e_i$ the design is accepted, otherwise—

(v) Exchange the pole with the maximum Δp_i sequentially, with the remaining three of the cell and repeat (iv). If none of them produces an acceptable design, then keep the one yielding the minimum Δv, and repeat the procedure with the other poles in order of descending Δp_i. If all the available pole cells are exhausted without yielding an acceptable design, then increase the word-length by one bit and start with step (ii).

An example will serve to illustrate the procedure.

Example 3. Consider again the specifications of Example 2. The realizable pole grid for five-bit coefficients and the infinite resolution poles are as in Fig. 9(a). The Δp are large and application of the technique fails

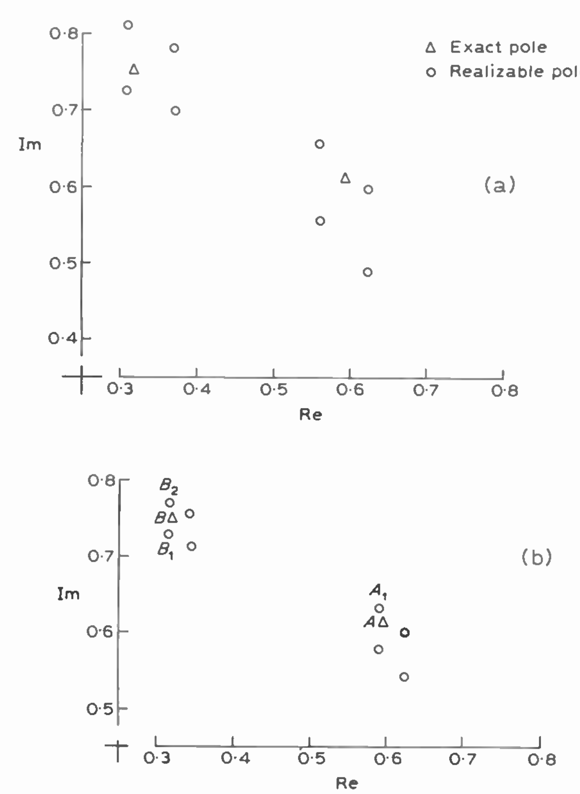


Fig. 9. Pole grids for Example 3. (a) five-bit, (b) six-bit.

to yield an acceptable design. For six-bit coefficients the pole grid is as in Fig. 9(b), and the first trial set is (A_1, B_1). The frequency response over the passband is shown in Fig. 10. The pole at A_1 yields the required -3 dB $\pm$ 0·5 dB at $0{\cdot}125 f_s$ but the pole B_1 yields an error of nearly 1 dB at $0{\cdot}2 f_s$. The pole B_1 is interchanged with B_2 on the basis of the next shortest Δp and the frequency response, for the pair (A_1, B_2), satisfies the specifications

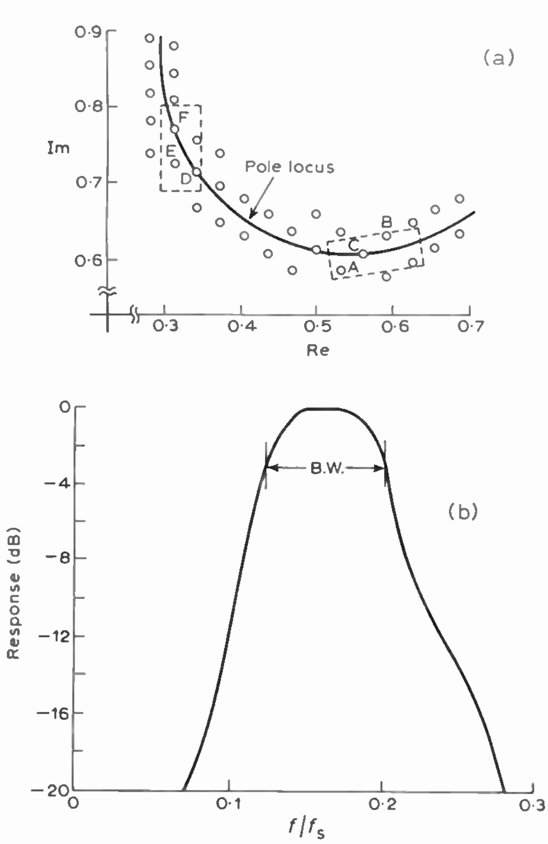


Fig. 8. Example 2 for six-bit coefficients. (a) Pole grid, (b) Frequency response.

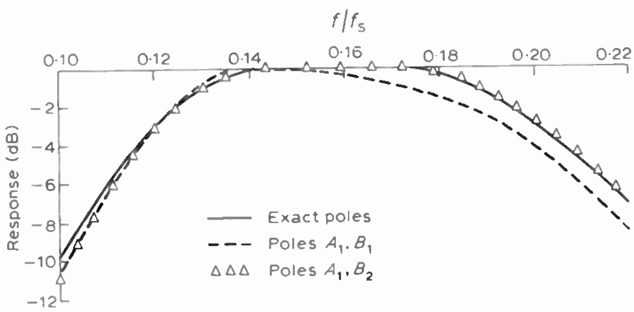


Fig. 10. Frequency response of Example 3.

(Fig. 10). The denominator coefficients are as below:

'Infinite' resolution:

Section I $1-0{\cdot}63754177z^{-1}+0{\cdot}67136014z^{-2}$

Section II $1-1{\cdot}1920755z^{-1}+0{\cdot}73256135z^{-2}$

Finite resolution:

Section I $1-0{\cdot}625z^{-1}+0{\cdot}6875z^{-2}$

Section II $1-1{\cdot}1875z^{-1}+0{\cdot}750z^{-2}$.

The zeros for each section are at $z = \pm 1$. The coefficients are similar to those of Example 2.

6 Special-purpose Coefficients

The two techniques were presented on the basis of a straight binary representation for the coefficients. However, in hardware realizations it is possible to decrease the number of bits without impairing the response. The most obvious saving comes from the coefficients b_2, since for stable complex poles $0 < b_2 < 1$ and consequently the b_2 coefficients can have finer resolution by one bit as compared to b_1 (see Fig. 11 for four-bit coefficient). With such a representation the required word-length for the last example becomes five bits. With a dedicated multiplier even the sign bit can be suppressed and the b_2 coefficient has a two-bit advantage over the b_1. The higher resolution of b_2 is represented in the pole grid by the increased number of available radii. Other special purpose coefficients may include the shift-only (right or left) and the shift-and-add, but once the appropriate pole grid is constructed the technique can be applied as described above.

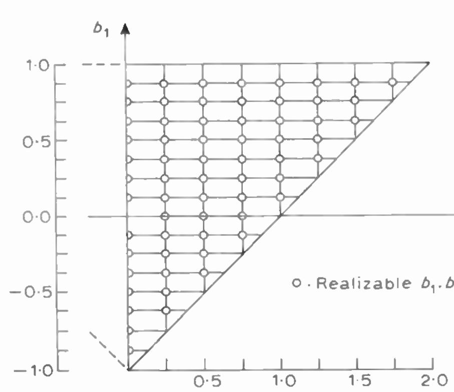


Fig. 11. (b_1, b_2) plane for four-bit special purpose coefficients.

7 Conclusions

The two design techniques presented in this paper have been successfully used in the design of recursive filters for m.t.i. and pulse Doppler radars. Both techniques have been implemented in an interactive mode with a Honeywell DDP–516 digital computer and on-line visual display.

The direct technique proved suitable for the design of relatively low order filters of the Butterworth and Chebyshev families. It would be wasteful to program the technique as an algorithm without interactive action.

The indirect technique was found useful for medium-order filter design. It was developed for interactive operation, but it could easily be programmed as an automatic algorithm because it is essentially a one-at-a-time optimization procedure. In such cases the search would be carried out in the (b_1, b_2) plane instead in the pole grid. The pole grid was used in the interactive mode mainly because it provided more physical insight into the procedure.

Both techniques are very useful in situations where the coefficients are not implemented by conventional binary multipliers but by special purpose ones. Such multipliers include the shift-only (right or left) and the shift-and-add. Of course flexibility is lost to some extent with these multipliers, but in some special applications they may prove very useful.

8 Acknowledgments

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Tropospheric transhorizon propagation characteristics at 2 GHz in Northern India

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SUMMARY

Based on radiometeorological observations at 2 GHz and 120 MHz over two co-located trans-horizon tropospheric propagation paths in Northern India during 1971, this paper describes the propagation characteristics and analyses the mechanisms of propagation at 2 GHz. Correlation of hourly median signal with refractivity gradient was found to be good while correlation with surface refractivity was much poorer. Evidence is presented to show that scattering was responsible for weaker values of observed signal, reflexion for intermediate signal levels which include the long-term median, while the guided mode was responsible for the higher levels of observed signal.

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1 Introduction

The predominance of any particular mechanism or mechanisms of propagation of ultra-short waves beyond radio horizon depends upon path-geometry, radio frequency and the structure of radio refractive index in the propagation medium. The characteristics of propagation are determined by the dominant mechanism. Thus, according to homogeneous turbulence theory, field strength relative to free space is characterized by a $\lambda^{-1/3}$ law and a $\theta^{-11/3}$ law, λ being the wavelength and θ the scattering angle.[1] On the other hand, according to reflexion theory, wavelength dependence varies from λ^0 to λ^2 and angle dependence varies from θ^{-4} to θ^{-6} depending upon the layer dimensions, wavelength and geometry.[2,3] Further, the sensitivity of signal to refractivity parameters such as initial gradient of refractivity or lapse of refractivity across thin atmospheric layers depends upon the dominant mechanism and it has been suggested[4] that over the same range of parameter variations, change in signal level due to reflexion will be higher than that due to homogeneous turbulent scattering.

In this paper, an attempt has been made to analyse the mechanisms of transhorizon tropospheric propagation at a frequency of 2 GHz based on radiometeorological observations at two radio frequencies (2 GHz and 120 MHz) over two co-located transhorizon paths in Northern India during 1971. One terminal for each path was located at the same station. The field strength data have been analysed in terms of hourly median values to determine the diurnal cycle and cumulative distribution of hourly medians as well as correlation with surface refractivity N_s and also refractivity gradients across different vertical sections of the medium. On the basis of models describing scattering due to homogeneous turbulence of refractive index field and reflexions of electromagnetic wave due to thin curved reflecting sheets,[4] calculated field strengths are compared with observed hourly medians over a range of parameter values in these models. In addition, by scaling the v.h.f. data to the same geometry as for the microwave by adjusting for unequal angular distance, common volume and antenna heights, wavelength dependence of received signals is determined. It is inferred from these studies that at 2 GHz super-refraction and duct-scatter are responsible for the very high signal levels, reflexion for intermediate levels including the observed long-term median and scattering due to homogeneous turbulence for only the weaker values of field strengths.

2 System Description and Path Geometries

The microwave transmission tests were conducted on a 24-hour basis during the month of June 1971. A description of the equipment and path geometry is given in Table 1.

The v.h.f. propagation tests were made during the period of January through December 1971 on a regular basis and data were available for all the days on which microwave experiment was conducted. A combined analysis of v.h.f. and microwave propagation data has been made for the overlapping period. A description of

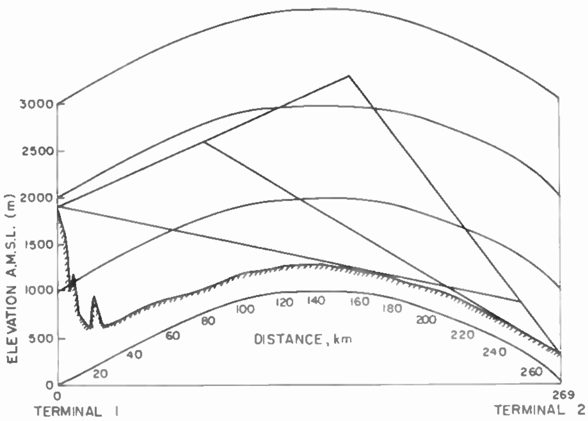

Fig. 1. Terrain profile—microwave path.

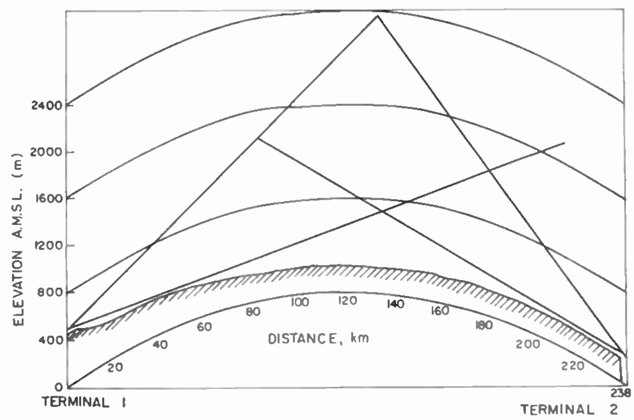

Fig. 2. Terrain profile—v.h.f. path.

Table 1

Equipment	Path geometry (Fig. 1)
Frequency 2 GHz	Effective Earth's radius 9000 km
Transmitter power 800 W	Terminal 1 elevation 1·92 km a.m.s.l.
Transmitting antenna gain 34·5 dB	Horizon distance 170 km Terminal 2 elevation 290 metres a.m.s.l.
Receiving antenna gain 34·5 dB	Horizon distance 34 km
Receiver sensitivity −100 dBm	Path length 269 km Angular distance 7 mrad

Table 2

Equipment	Path geometry (Fig. 2)
Frequency 120 MHz	Effective Earth's radius 9000 km
Transmitter power 1000 W	Terminal 1 elevation 448 m
Transmitting antenna gain 20 dB	Horizon distance 42 km
Receiving antenna gain 3 dB	Path length 238 km
Receiver sensitivity −113 dBm	Angular distance 20 mrad

the equipment and path geometry for v.h.f. propagation experiment is given in Table 2. Figures 1 and 2 show the path profiles on 9000 km effective Earth's radius diagrams.

3 Meteorological Conditions

Information on refractivity profile characteristics over the paths was available through hourly surface observations of pressure, temperature and humidity at two stations over each path and radiosonde observations twice daily (00.00 and 12.00 hours G.M.T.) at the common terminal of these paths. These data have been received from the India Meteorological Department.

Analysis of the surface refractivity gradient for the month of June in this area has shown that the value of the gradient was variable over a wide range in course of a day and also from day to day (range of variation being from −26 to −100 N-units). Super-refraction was fairly frequent during early morning hours and ducting gradients were observed on several occasions.

4 Microwave Propagation Characteristics

The microwave propagation tests gave the following results: (a) the average hourly median signal was consistently higher than the scattered signal level calculated by homogeneous turbulence theory except for six hours around noon time, although signal enhancement due to refraction has been allowed for in the path profile itself; (b) mean hourly median values during night time and morning were about 30 dB more than given by homogeneous turbulence theory; (c) on certain occasions, observed field strength was near the free space value for several hours at night and early morning; (d) the transition from high to low signal period was marked by abrupt changes of nearly 20 dB in hourly median signal over two successive hours; and (e) at times such abrupt changes were also observed for a short while when the field strength was otherwise steady for a long duration. The observations are considered significant because these illustrate the changes in the characteristics of signal as a result of change in the dominant mechanism of propagation.

4.1 Diurnal Pattern and Cumulative Distribution of Hourly Medians

Figure 3 shows the diurnal pattern of microwave signal based on averages of hourly median values during the period. The night time and early morning field strength from 20.00 hours (I.S.T.) through 08.00 hours (I.S.T.) is much higher (about 30 dB) than daytime values. A rapid fall in level starts around 06.00 hours, going to a minimum at 12.00 hours while from 16.00 hours, the hourly median rises steadily. The hourly average surface refractivity is also presented in this figure to examine possible correlation of this parameter with field strength. The diurnal trends as seen in the figure agree with each other fairly well. The regression coefficient of diurnal cycle of field strength has been found to be 2 dB per unit change in N_s. It is to be mentioned, however, that the coefficient of correlation between individual hourly median signal and corresponding surface refractivity value has been found to be only 0·15, which is considered insignificant.

The cumulative distribution of hourly median signal is presented in the same figure and shows the field strength relative to free space exceeded for specified percentages of time. Thus, for 1% of time, signal is at the free space level while for 99% of time, this is −65·5 dB relative to free space level. The median of all hourly medians is −45·5 dB. The fading range between 1% and 99% probability levels is 65·5 dB which is extremely high. This range and high signal levels cannot be explained in terms of scattering theory as discussed later. There is a suggestion that the slope of the cumulative distribution curve changes near 80% probability level, and it is probable that the propagation mechanism changes at the corresponding value of signal.

4.2 Correlation with Meteorological Parameters

As stated earlier, correlation of individual hourly medians with N_s (surface refractivity) has been found to be poor. Correlation with vertical gradients of refractivity was examined next. The initial gradient (ΔN_g) was obtained from difference between surface refractivity and refractivity at 950 mb whose average altitude was 200 metres above surface. Figure 4 shows hourly median values of signal for morning and evening hours against initial gradient of refractivity at terminal 2. Fairly good correlation is observed at all signal levels with a significant change of slope at −50 dB level. The higher sensitivity to change of ΔN_g above this field strength probably suggests a change of dominant propagation mechanism. The regression coefficient has been found to be 0·2 dB/N-unit up to −50 dB signal level, 0·36 dB/N-unit up to −30 dB level and 0·30 dB/N-unit above this level.

To examine further the possible contribution of different propagation mechanisms, correlation of observed field strength with refractivity gradients at higher altitudes was investigated. These gradients were obtained from radiosonde data at terminal 2 at 950 mb, 900 mb, 850 mb levels and also at significant levels in between.

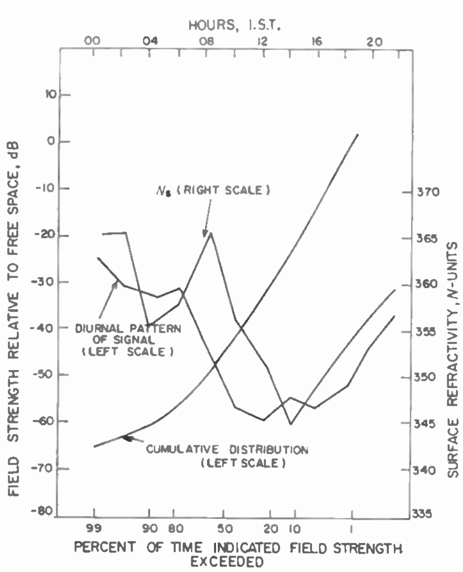

Fig. 3. Diurnal cycle and cumulative distribution of hourly median at 2 GHz.

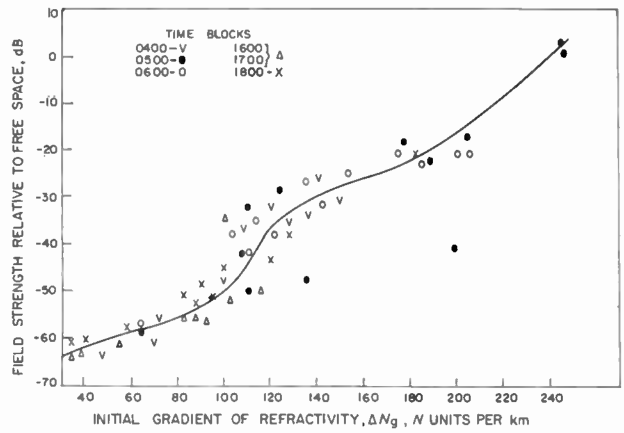

Fig. 4. Correlation of hourly median at 2 GHz with initial gradient of refractivity.

The vertical sections ranged in thickness from 50 metres to 500 metres and were in the height range from 0·2 to 1·5 km approximately. Good correlation was observed over the range of gradient values from −40 to −90 N-unit/km. Above and below this range, there was a wider scatter of data. In the region of good correlation, the regression coefficient was 0·4 dB per N-unit which compares with 0·36 dB per N-unit in Fig. 4 for the higher field strength region.

4.3 Observed Signal Characteristics vs. Theoretically Calculated Values

In order to interpret the observed signal characteristics from the theoretical point of view, we compared our observations with calculated signal strength according to the homogeneous turbulence theory[1] and also with values expected due to reflexion based on Eklund–Wickerts model[4]. These calculations were made for a fairly wide range of possible values of spectral intensity C_n^2 ($0{\cdot}8\times10^{-16}$ to 80×10^{-16} (metre)$^{-2/3}$) of refractive index fluctuations and of Δn (0·024 to 2·4 N-units), which is the change of refractive index through sharp reflecting facets. These calculations showed that the expected signal according to homogeneous turbulence theory would lie in the range of −67 dB to −46 dB (relative to free space) while according to Eklund–Wickerts model of reflexion, this range would be from −70 dB to −30 dB. The observed signal corresponding to 99%, 50% and 1% probability levels were respectively −65 dB, −45·5 dB and 0 dB relative to free space. It would thus appear that reflexion theory can account for the higher values of observed signal and a higher range of variation.

5 Signal Strength Variations at Microwave vs. V.H.F. and Wavelength Dependence

In the absence of any specifically designed scaled experiment at two different frequencies, the propagation data at 2 GHz and 120 MHz over co-located paths during the same period (June 1971) have been compared to get further insight into the roles of various propagation mechanisms. In view of difference in the path geometries as seen from the path profiles, the v.h.f. data have been scaled in the following manner:

(a) On the basis of observed angular distance dependence of field strength beyond radio horizon obeying, on an average, a $\theta^{-5\cdot 2}$ law, signal level was scaled from an angular distance of 20 mrad (v.h.f. path) to 7 mrad (microwave path). This angular distance law has been determined from extensive propagation observations at 120 MHz covering a distance range of 200 to 700 km and angular distance range from 0 to 45 milliradians.[5]

(b) The frequency gain function has been determined for both the cases[6] and additional loss of 5 dB over the v.h.f. path was taken into account.

(c) Unequal common volumes have been taken into account by determining the ratio of calculated power in the wide beam case[7] to that for the narrow beam case.[1]

(d) Unequal refraction effect over two paths has been taken into consideration by lowering the v.h.f. signal by 5 dB on an average.

The following assumptions are involved in the analysis:

(a) Unequal base height of common volume for the two geometries does not materially affect the relative received powers. This is based on published results[8] that variation of scattering efficiency with height up to about 0·5 km is negligible.

(b) Approximately the same regions of the medium contribute effectively to received signals at the two frequencies.

(c) No special consideration is involved even though the spatial wave numbers are different by nearly one order.

Figure 5 shows the hourly median signal level scaled in the above manner at v.h.f. against the corresponding hourly median at 2 GHz. If the propagation mechanisms at the two frequencies are the same, the mean curve in this figure would have a slope of 45°.[4] The curve, however, shows three different slopes having the following features:

(a) in the region where 2 GHz signal is below -55 dB, the microwave signal varies much less rapidly than the v.h.f. signal;

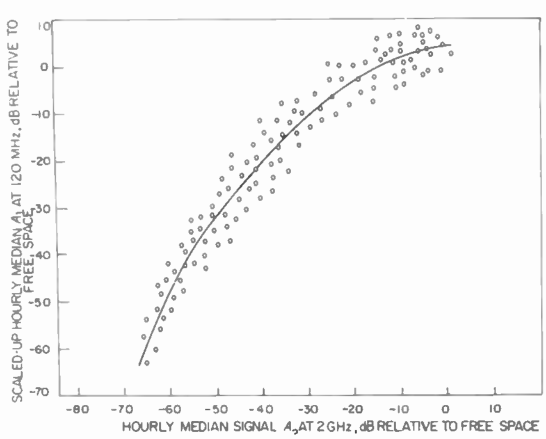

Fig. 5. Hourly median (scaled) at 120 MHz vs. hourly median at 2 GHz.

(b) from -55 dB to -25 dB level (2 GHz), a 45° slope is observed; and

(c) above -25 dB, the microwave signal varies much more rapidly than the v.h.f. and the slope is again very much different indicating a change in propagation mechanism.

Figure 6 shows the wavelength exponent against field strength at 2 GHz. The wavelength exponent q is given by:

$$\frac{A_1}{A_2} = \left(\frac{\lambda_1}{\lambda_2}\right)^q \qquad (1)$$

where

q is the wavelength exponent
A_1 is the field strength relative to free space at 120 MHz
A_2 is the field strength relative to free space at 2 GHz
λ_1 is the wavelength at 120 MHz and
λ_2 is the wavelength at 2 GHz.

The wavelength exponent in Fig. 6 has been evaluated from the ratio of hourly median field strength at v.h.f. to hourly median at 2 GHz. In this figure, the average values of initial refractivity gradients associated with hourly median field strength are shown at the top to identify the meteorological conditions associated with

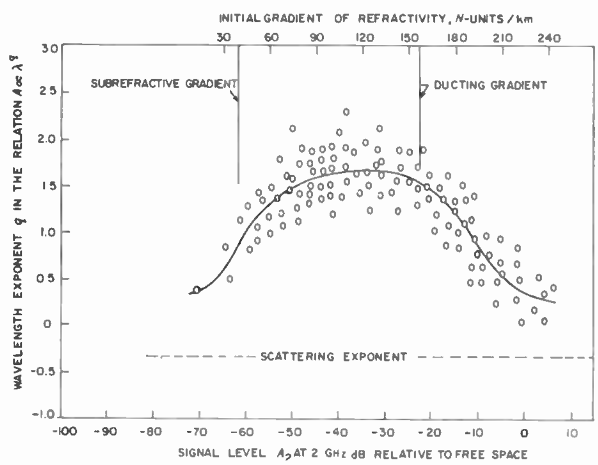

Fig. 6. Wavelength exponent vs. signal at 2 GHz and initial refractivity gradient.

different values of wavelength exponent. Also for comparison is shown the expected wavelength exponent on the basis of homogeneous turbulence theory, which is $-\frac{1}{3}$. It is observed that in the range of signal level of -50 to -20 dB at 2 GHz, the wavelength exponent is almost constant around a value of 1·5. Above and below this region, the mean exponent decreases. The region of nearly constant value of q is associated with initial gradient values from slightly above standard (-40 N-unit/km) up to almost ducting conditions (-157 N-unit/km).

Based on the values of wavelength exponent in different regions, the following conclusions can be drawn. The region of nearly constant exponent is that where propagation mechanism at two frequencies is the same.

The value of q, change of slope to 45° in Fig. 5, higher regression coefficients with refractivity gradients (Sect. 4.2) as well as calculated values of field strength (Sect. 4.3) lead us to the conclusion that reflexion is the dominant mechanism for signal levels lying approximately between −55 dB to −25 dB (2 GHz). Below the −55 dB level, the slope of curve in Fig. 5 (much higher than 45°), lower regression coefficients with refractivity gradient, and comparison with the theoretical models indicate that scattering is responsible for the observed signal at 2 GHz. However, the wavelength exponent never attains a value of $-\frac{1}{3}$ as expected by homogeneous turbulence theory. This result can be explained by assuming reflexion to be the dominant mechanism at v.h.f.

6 Explanation for High Field Strengths at 2 GHz

As stated earlier, it is difficult to explain the occurrence for about 10% of time of field strengths in excess of −25 dB relative to free space at 2 GHz on the basis of reflexion or scattering. In addition, decrease of wavelength exponent above this level indicates a mechanism which favours microwave propagation more than v.h.f. This is possible only in the case of guided wave propagation and the high refractivity gradients associated with these signal levels point towards this possibility. However, for an asymmetrical path like the one in our case, simple duct propagation due to a duct at one level, either surface-based or elevated, is not practicable. One possible mechanism is propagation via surface duct which is fed by energy from terminal 1 by reflexion at some terrain feature at a distance of 20 km or more from this terminal. The conditions to be satisfied are (a) the horizontal extent of this surface should be greater than the Fresnel zone dimension which is about 1 km and (b) a slight downward slope (about 1° to 2°) to ensure reflected energy reaching the duct at a low angle with its axis. Both these conditions can be easily satisfied. Energy loss associated with this process is estimated to be about 20–25 dB[9] but signal enhancement due to propagation of several modes inside a duct can cause an enhancement of the order of 10 dB with respect to free space[10,11] and consequently a resulting signal of −10 to −15 dB is possible at the receiving end. However, a quantitative explanation for field strength comparable to or higher than free space level is not possible without detailed knowledge about layer dimensions and their orientation. Qualitatively, such enhanced signal would be possible due to (a) presence of super-refractive layers of limited length at both the terminal heights simultaneously or (b) presence of a tilted super-refractive layer covering both the terminals.

7 Conclusions

The following conclusions can be drawn from our analysis:

(a) Propagation at 2 GHz is characterized by well-defined diurnal trends in which night-time hourly median signal is higher than midday value by 25 dB on an average. The diurnal variations of hourly median and that of N_s are nearly similar.

(b) There is a wide range of variation of hourly median (about 65 dB between 1% and 99% probability levels) which cannot be explained by homogeneous turbulence theory.

(c) The lower values of field strength at 2 GHz associated with probability level of 80% and more can be explained in terms of homogeneous turbulence theory, signal strength between 80% and 10% probability levels can be explained by reflexion while higher field strength can be accounted for by guided wave propagation.

(d) The sensitivity of signal to refractivity gradients over the surface or in the higher layers depends upon the propagation mechanism, higher regression coefficient being associated with reflexion.

(e) Correlation of hourly median signal with refractivity gradients which are available for morning and evening hours has been found to be much better than with N_s.

8 Acknowledgments

The authors wish to express their gratitude to Dr. A. P. Mitra, Head of the Centre of Research on Troposphere, National Physical Laboratory, New Delhi, for many helpful discussions and also for suggesting a number of amendments to the paper prior to publication. Thanks are due to the India Meteorological Department for providing the relevant meteorological data.

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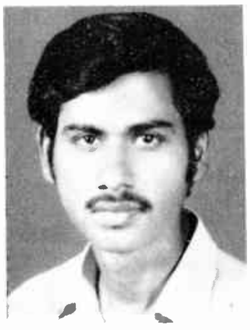

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*See also page 41

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Some investigations into optical probe testing of integrated circuits

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SUMMARY

An introduction to the effects of light on semi-conductor devices and their use in testing integrated circuits is given. The possibilities are discussed of utilizing a focused laser beam as a minute, movable, non-destructive probe. This may be used to feed information into integrated circuits, to locate and simulate faults, and to shorten the time required to test these circuits. Experiments performed have shown that a few microwatts of laser beam power can switch internal nodes in m.o.s. digital circuits in less than a microsecond. By using an appropriately modulated beam binary sequences have been injected in a similar manner. The beam was also used to determine the minority carrier diffusion length in m.o.s. digital circuits.

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1 Introduction

As devices in integrated circuits have become smaller and smaller, the problems of individual device measurement, fault diagnosis, location and repair become more and more difficult. In fact, the repair problem with integrated circuits is purely academic. However, fault diagnosis and location are essential, particularly for design correction and for reliability investigations. To 'get into' an integrated circuit as one may do with a discrete component circuit is essentially not possible with a mechanical probe. This inability to gain access to internal points of sophisticated logic and memory integrated circuits leads to uneconomically long test programs. What is needed is a tiny, lightweight probe which does not damage the device; an electron or light beam appears suitable. The electron beam requires a vacuum and charges up oxide layers; this alters device characteristics and may even damage the specimen. A light beam in the form of a finely focused laser would seem ideal, and the use of such a probe is discussed in this paper.

Visible light is essentially absorbed in the top one or two microns in silicon. This is the region of most interest for many bipolar and m.o.s. structures, Schottky barrier devices, etc. Scanning of the surface of the silicon has been discussed by a number of authors. A laser spot can be scanned across the surface in a raster pattern and the electrical output signal used to modulate either the beam intensity or deflection of a c.r.o. which is being scanned in synchronism. The laser scanner can provide valuable, and in some cases unique, information on resistivity gradients,[1] surface conditions such as inversion layers,[2,3,4] oxide contamination[5,6] and on circuits, transistor gain variation and circuit malfunction.[7]

Samples may also be illuminated by an infra-red beam and the variation in sample transmission measured by location of a detector behind the sample. Variations of doping density in amount and position, and structural defects have been recorded in this way.[8]

Most of the above applications used the laser as a 'passive' observation tool, whereas in this paper we are more concerned with the actual interaction of the laser with the circuit, which is thought to have considerable potential. The laser can change the mode of operation of a circuit and this approach to fault diagnosis, simplification of test routines and direct feed-in of information to integrated circuits is considered here.

Information on the variation of carrier lifetime across an integrated circuit slice is of interest[9] and an indirect method of measuring lifetime in a digital circuit will also be described.

2 Photo-effects in Silicon Integrated Circuits

In a semiconductor such as silicon, light creates hole-electron pairs. The electrical effect of this depends on the material properties at the point illuminated. The carriers recombine locally or, if an electric field is present, the electrons and holes are separated causing a current to flow. This field may be due to an externally applied voltage or may arise from the presence of doping gradients within the semiconductor. A p-n junction is an extreme case of such a gradient. Where a p-n junction is not present the effect of the sample illumination may be seen as a variation of the sample conductivity. However, because the fractional variation in conductivity is small, it is difficult to detect small inhomogeneities by this method. A more sensitive method is to measure the e.m.f. induced in the specimen due to the separation of the injected carriers by the local fields.

When examining semiconductor slices for inhomogeneities, the photo-e.m.f. is therefore measured by probes placed on the periphery. By scanning the source of illumination across the slice—a laser beam spot, for example—a picture of the electrical inhomogeneities in the sample can be built up.[1]

On the other hand, when a semiconductor circuit is to be examined the effects of the separation of the injected hole-electron pairs by the p-n junctions can be observed.

The equivalent circuit of an illuminated p-n junction is shown in Fig. 1. The magnitude of the current source (I_{sc}) is proportional to the light intensity since holes and electrons are generated in or near the depletion layer at a rate proportional to the light intensity.

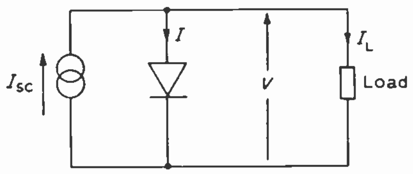

Fig. 1. Equivalent circuit of an illuminated p-n junction.

The diode current is given by the usual diode equation

$$I = I_o \exp\left(\frac{qv}{kT} - 1\right) \tag{1}$$

Consequently, the current through the load in Fig. 1 is given by

$$I_L = I_{sc} - I_o\left(\exp\frac{qv}{kT} - 1\right) \tag{2}$$

So that I_L may be calculated for any value of I_{sc} and load resistance. For the short-circuit case the current I_L is equal to I_{sc}, and for the open-circuit case the photo-voltage developed is

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{I_{sc}}{I_o} + 1\right) \tag{3}$$

The value of I_{sc} is determined by the power of the incident laser beam, P, the wavelength of the light, λ, and the quantum efficiency (which is the number of hole-electron pairs producing current for each incident photon of light). The energy of each photon is hc/λ, where h is Planck's constant and c is the velocity of light. The short-circuit current is therefore given by

$$I_{sc} = \frac{qP\lambda}{hc} \tag{4}$$

For a beam power of 2 mW at a wavelength of 632·8 nm, assuming unit quantum efficiency, a current of approximately 1 mA is generated.

There are two factors which result in the quantum efficiency being less than unity. First, although little absorption takes place in the oxide, not all the radiation incident on the circuit enters the silicon, due to reflection of light at the outer surface of the oxide and at the oxide–silicon interface. The refractive indices of both silicon dioxide and silicon are well known, so the fractional amount of the incident radiation entering the silicon can be calculated for any particular system. Unfortunately, the calculation is complicated because rays in the beam are incident at various angles depending on the optical arrangement and the objective lens used. Also, the oxide thickness is of the order of the wavelength of light and so forms an interference layer on the silicon. The transmission of this layer will depend on the thickness of the oxide on the particular device being used.

Secondly, since the light intensity inside the silicon decreases exponentially with distance from the surface, the number of carriers created varies with depth. For the laser used in the above example the absorption length is 2 μm, which is similar to typical junction depths. The proportion of these which cross a junction depends mainly on the ratio of the distance between the generation point and the edge of the junction depletion layer to the diffusion length of the carriers. It also depends on the doping profile near the junction which can create an in-built field and cause the carriers to drift as well as to diffuse. These effects have been studied in connexion with photodetectors and solar cells.[10] The quantum efficiency will therefore depend on the following factors:

(a) The optical arrangement, particularly the numerical aperture of the microscope objective used to focus the laser spot.

(b) The oxide thickness (and nitride layer, if present).

(c) The carrier diffusion length in both the p and n regions.

(d) The junction depth.

(e) The doping profile in the silicon.

In view of this complexity, the usual method of determining the quantum efficiency is to measure it, using a beam of known power and a junction accessible directly from a contact. Illumination of an accessible node on one device studied, the SS1032, gave a value of η of 0·64.

When a reverse biased junction is illuminated, an increase in the reverse leakage current of I_{sc} is observed. Under short-circuit (equation (4)) or reverse biased conditions the photo-current is directly proportional to the light intensity, enabling linear effects to be investigated. For example, in a bipolar transistor circuit, illumination of the collector-base or emitter-base junction of a transistor which is being supplied with a constant base current causes a photo-current which appears as a base current drive. If the change in collector current can be measured, for example by monitoring the power supply current, the common emitter gain of the transistor can be found if the quantum efficiency is known.[7]

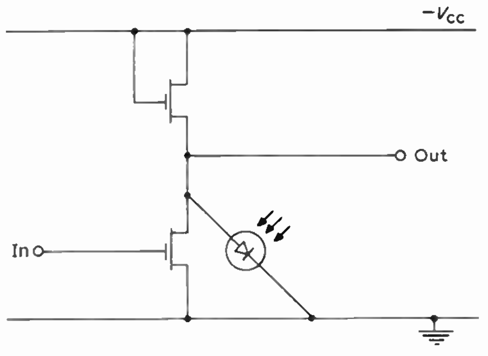

Fig. 2. Schematic of an illuminated m.o.s. inverter circuit.

Digital circuits can be investigated by using the probe to inject digital information. The increase in leakage current of a junction caused by illumination can be used to discharge a nodal capacitance or upset a voltage ratio in a circuit so that the circuit switches and the digital information stored is changed. The subsequent circuit behaviour is monitored at the output terminals.

Although bipolar circuits can be investigated, m.o.s. digital circuits are particularly convenient to study by the laser method since the currents flowing in the internal transistors are relatively small and there are optically-accessible diffused regions connected to most of the useful circuit nodes. In the inverter shown in Fig. 2 the channel areas and also load drains are normally not accessible to illumination as they are covered with aluminium; the driver sources are visible but not useful as they are shorted to the substrate. However, illumination of the driver-drain/load-source diffusion causes a photo-current to flow between the diffusion and the substrate; the effect on the circuit will depend on the state of the inverter. If the driver is 'on' and hence of low impedance, the node potential will be close to that of the substrate, so that the photo-current will merely cause a change in the current flowing through the driver and not significantly affect the load current or the circuit behaviour.

If the driver is 'off', the photo-current will be drawn through the load from the power supply. By monitoring the power supply current it is therefore possible, in principle, to decide whether the illuminated node is 'high' or 'low'. In addition, if the photo-current is sufficiently large the node will be driven from the high to the low state. In other words, the probe can be used to inject data at a node just as a mechanical probe might be used. Although it is not possible to drive the node 'high' by this method (since the light effectively shorts the driver), it is not a serious limitation in practice, since often a '0' at a particular node is equivalent to a '1' at another.

There are two principal ways in which these effects on a circuit may be used. The first is in routine testing, where the time taken to test an l.s.i. circuit comprehensively with electrical input signals can be prohibitively long. By using the laser beam to reach internal nodes it is possible to greatly reduce this time.

A second use is a diagnostic one, aimed at obtaining information about the fault in a circuit which is known to malfunction. Such a fault can be catastrophic (e.g. a stuck-at-one fault) or marginal (e.g. appearing at high speeds only) and can originate from faulty design, processing or life-behaviour of the circuit.

A further use of the technique is the measurement of the minority carrier diffusion length (to obtain a fair assessment of the lifetime) by noting the increase in laser spot energy needed to switch a digital circuit storage node as the spot is moved away from the relevant junction. Normally, the light spot is focused onto the diffusion so that the generated carriers are close to the junction and the intensity of light required to switch the node from high to low is minimal. If a small light-spot is at a distance x from the junction, then from simple theory only a fraction of the injected carriers $\exp(-x/L)$, will reach the junction (L is the diffusion length). The required intensity will therefore be higher and measurement of the variation with distance enables the diffusion length to be calculated.

The life-time, τ, is often more important than the diffusion length but, as they are related by $L = (D\tau)^{\frac{1}{2}}$ and the diffusion constant, D, is known approximately for a particular material, the value of τ may be obtained. This use is interesting in that analogue information on device parameters is obtained, even though the circuit is a digital one and the device is not directly accessible from the contacts.

3 Experimental Arrangement

3.1 Optical System

Figure 3 is a schematic drawing of a simple test apparatus we have used to demonstrate the principles of the laser probe technique. Light from a 2 mW He–Ne

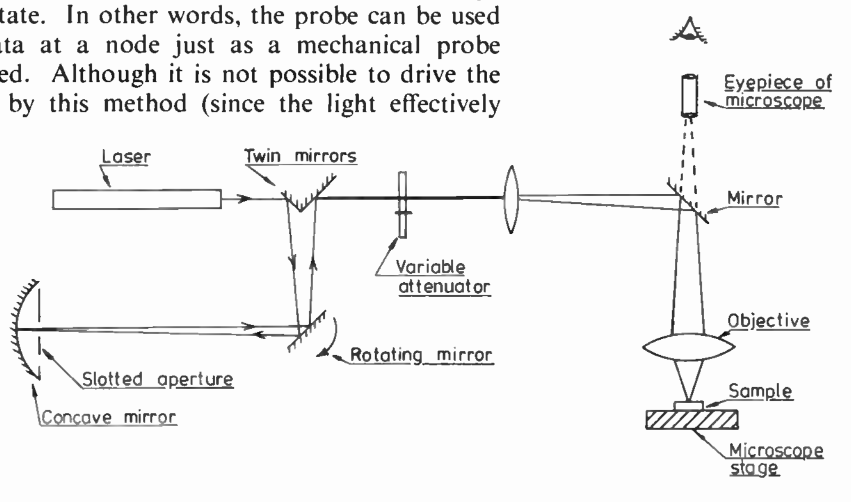

Fig 3.
Diagram to show the optical arrangement used.

laser (628 nm wavelength) was passed through a variable attenuator, chopped, and focused through a microscope onto the circuit. In the present arrangement the laser spot is fixed and the circuit can be moved by the X–Y stage of the microscope.

The laser beam enters the microscope through the port normally used for metallurgical illumination. The usual semi-silvered mirror is replaced by a small front-silvered mirror to avoid multiple reflections. The laser beam is brought to a focus before it enters the microscope to enable the spot and the circuit to be in focus at the same time. This also allows expansion of the beam to almost fill the microscope objective which is necessary if the smallest spot is to be obtained. With a 20× objective a spot diameter of ~ 4 μm was obtained. Measurements of relative laser beam intensities were made by interposing a calibrated photocell in the beam.

To obtain light pulses the beam was chopped mechanically by a rotating mirror as shown in Fig. 3. The shortest pulse obtainable was set by the motor speed and by the width of the laser beam at the aperture in front of the concave mirror. With the equipment as described the shortest pulse obtainable was less than 1 μs. The rate of rise and decay of the light pulse also depends on the beam divergence and the motor speed; if pulses with relatively steep edges are required, the mirror aperture must be large compared with the beam diameter at the mirror. A train of pulses can be obtained by using a suitable mask in place of the single aperture. The system using mechanical chopping has two major disadvantages. First, jitter is present in the repetition rate, making synchronization with the digital circuit clock pulse difficult. Secondly, the repetition rate is limited by the maximum speed of the motor. These limitations can be avoided by using a more sophisticated electro-optical system.

3.2 Electronic System

Shift registers were chosen for the study as representative of sequential circuits which could be readily obtained in different degrees of complexity from various manufacturers using different fabrication processes. Electronic instruments needed were regulated power supplies, a clock generator allowing manual and repetitive clocking, and a data input circuit which could also be used to circulate data in the register. The output was observed with an oscilloscope.

4 Results

4.1 Laser Probing of Shift Registers

A General Instrument's multiple (16, 8, 4, 2, 1, 1-bit) static shift register, type SS 1032, was studied first. It is basically a large geometry thick oxide device with nitride protection and aluminium gates. Clocking and bias signals were applied and the shift register output was observed with and without laser illumination of the circuit. It was found that any 'bit' of the shift registers could be switched by the attenuated laser beam. Most experiments were carried out on the 8-bit shift register. The circuit has two series of inverters, cross-coupled to form storage loops, and is symmetrical about ground

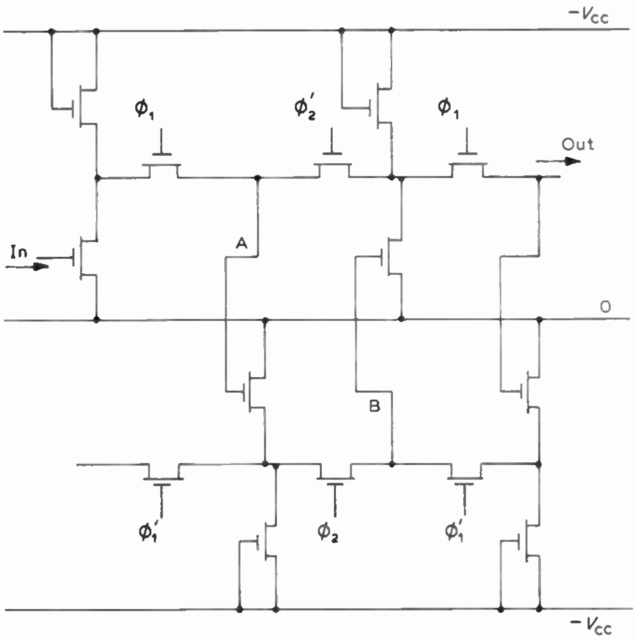

Fig. 4. Circuit of the shift elements of the SS 1032 shift register

(Fig. 4). By illuminating the appropriate node of a storage loop, either a 1 or a 0 was fed into the shift register, e.g. the illumination of node A when the 'bit' contains a 1 will change it to a 0. A shift register node could be switched by pulses of duration down to the shortest attainable, which was less than 1 μs, with a repetition rate of 176 Hz. Also with a continuous series of 1's being electrically clocked into the shift register at 100 kHz, a laser pulse of 1 μs could be used to insert a single 0, which was subsequently observed at the output. This is shown in Fig. 5.

Similarly a sequence of laser pulses produced a corresponding sequence at the shift register output. Figure 6 shows the output obtained when using a 1000101 sequence of light pulses obtained by placing an aperture

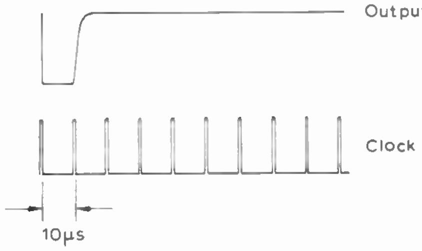

Fig. 5. Single 0 insertion into the register full of 1's.
Upper trace—Voltage observed at output of shift register.
Lower trace—Clocking pulse.

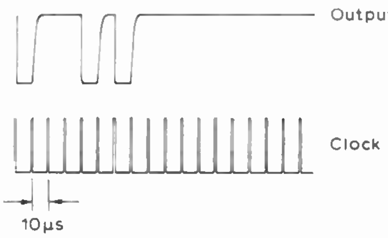

Fig. 6. Sequence of 0's introduced into register full of 1's.

with 3 slits in front of the concave mirror. A transition occurring midway through a clock interval was not observed because the trace was taken from the shift register output.

Figure 7 shows the output of the shift register resulting from a double laser pulse applied to point B when the shift register was fed with 0's.

The clocking rate was varied for a constant laser pulse length of 8 μs (Fig. 8). If the input to the shift register was a train of 1's, the light pulse introduced 0's into the register when illuminating a node such as A of Fig. 4. The number of 0's introduced depended on the clocking rate, as expected. With the clocking-pulse rate set at twice the light pulse repetition rate and the laser beam focused onto an appropriate node, the shift register output was a series 101010, etc.

The sensitivity of the circuit to the laser beam was measured. The most sensitive points were at nodes such as A (Fig. 4) where switching action took place with 6 μW beam power onto the sample for pulses of 1 μs duration. With a dynamic shift register or other circuit which relies upon capacitive storage it is calculated that similar laser power levels would be needed to effect an information content change in < 1 μs. It should be noted that as long as a sensitive node such as A (Fig. 4) is illuminated, its potential will remain close to that of the substrate and even though the circuit is clocked, no information will pass the node; that is, the node will appear to be faulty or 'stuck at' zero.

The effective spread of the injected carriers was examined by using the maximum intensity of the focused laser beam and observing how many adjacent nodes were affected. The exposures were made in the absence of a clocking pulse and the effects observed by clocking out the information later. Only two nodes could be switched at one time even when using the maximum beam power of 2 mW focused onto the most sensitive areas. This was as expected for a device of this size since no point on the chip was within a few carrier diffusion lengths of more than two source-drain diffused areas.

A Mullard GYN 111 shift register was also studied. This is a dual, 100-bit static shift register. It uses enhancement mode p-channel silicon gate m.o.s. devices and was chosen because the clock, input and output voltage levels were essentially the same as those used for the SS 1032. However, the method of fabrication is different (silicon gate instead of aluminium), the circuit is more complicated and the geometry is significantly smaller.

As with the SS 1032 it was possible to inject 0's into the register initially containing 1's. The injection of 0's was obtained both with continuous illumination and with 1 μs laser pulses For the more complicated circuits the '0' (or '1') introduced by the laser can actually be used to locate the position of the high-spot within the circuit. With the shift register initially containing all 1's, for example, exposure of a node to the laser introduces a '0', and it is a simple matter to count the clocking pulses (shifts) before the '0' appears at the output.

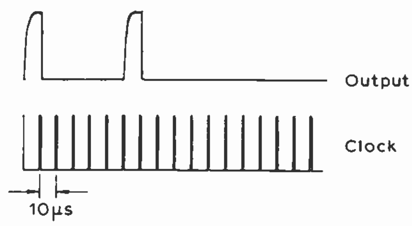

Fig. 7. Two 1's introduced into register full of 0's.

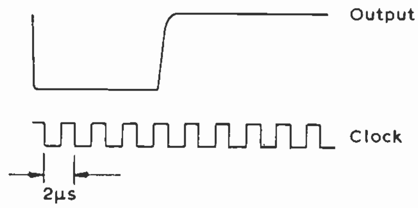

Fig. 8. Multiple 0's introduced into register full of 1's.

The GYN 111's smaller geometry enabled the focused laser beam at maximum power to switch four nodes simultaneously. This was because, for some locations of the spot, four sensitive areas were within a few diffusion lengths of the perimeter of the spot. At the normal beam power of about 0·02 mW, reliable switching of only one node at a time was obtained.

4.2 Lifetime Measurement

An estimate of the lifetime was obtained by measuring the diffusion length. The laser power necessary to just excite the circuit was determined for a series of positions of the light spot as the distance from a sensitive p-type diffusion was varied. The results were plotted on semilog graph paper and the diffusion length obtained from the slope of the linear portion of the graph on the assumption that the expression $N = N_0 \exp(-x/L)$ was applicable. N is the number of carriers which travel a distance, x, from the point of injection and $L = \sqrt{(D\tau)}$, where D is the diffusion constant and τ the minority carrier lifetime. For the SS 1032, L was measured as 8 μm which corresponds to a lifetime of 0·06 μs assuming that $D = 10\ \text{cm}^2/\text{s}$. This value was unbelievably low, and thought to be due to the presence of adjacent diffusions which had a screening effect. Measurement on a diffusion remote from others gave a more realistic value of 32 μm for the diffusion length, corresponding to a lifetime of 1 μs.

The more direct method of measuring τ by using the exponential decay of excess carrier concentration with time, $I = I_0 \exp(-t/\tau)$ could not be used in this instance, because the individual junction was not readily accessible electrically. Also the laser could not be turned off in a time which was short compared with τ; a 'Q-switched' laser could remove this second limitation.

5 Discussion—Testing of Integrated Circuits

It has been demonstrated that information can be fed into digital integrated circuits in a time which corresponds to megahertz rates. There are a number of possible applications for this, the most useful probably being that of fault location. It is usually possible to feed in information of either sense into a circuit by finding the correct node to force to 0.

5.1 Fault Isolation

Often, in more simple combinational circuits, one can trace or locate a fault by commencing the feed-in of information by the laser beam at the circuit output and gradually stepping back through the circuit until there is no longer a correct response detectable at the output. The suspect node can be identified either by observing the spot position or, in case of shift register circuits, by counting the number of clock pulses between the optical data insertion and the change in output as mentioned earlier. The node could then be examined further by optical and other techniques. The circuit connection and the proximity of other devices would dictate whether the laser probe could be used to explore the fault further, e.g. for lifetime anomalies, microplasmas, etc.

5.2 Testing of Sequential Circuits

With sequential circuits which have internal storage points, feedback loops, etc., it is difficult not only to isolate a fault, but even to determine whether one is present. If only the normal electrical inputs are available, the time taken to test a circuit comprehensively can be extremely long, even when an optimized, computer-derived testing routine has been established.

The laser offers the possibility of switching or of blocking an electrical pathway, i.e. controlling the effective circuit topology. In this way a circuit might be partitioned by the laser into several blocks, each of which could be tested in a very much shorter time. For example, a circuit with 20 inputs has 2^{20} or about 1,000,000 possible input combinations. If this could be partitioned into two sub-circuits, each with ten inputs, there are only 1,000 input combinations for each part.

Where possible, the complete sequential circuit would be partitioned into combinational units, each of which could be tested and the faults located as before. The laser has the advantages over built-in testing blocks in an m.o.s. circuit, of saving silicon chip area, and providing circuit isolation. Further, a particularly attractive feature is its ability to vary the partitioning of a circuit. This could make it economic to test, and therefore to manufacture, larger logic arrays. For such applications it would obviously be useful to have more than one node illuminated simultaneously.

5.3 L.S.I. Test Routines

As mentioned above, the comprehensive testing of l.s.i. circuits may be very time consuming and the use of the most economic testing routines is desirable. Of the various methods used for deriving test routines,[11] one is based on the 'stuck-at' model. For simplification, this assumes that faults can be represented by an appropriate node being permanently at either a 1 or a 0. By examining the behaviour of circuits with such faults, routines can be built up to diagnose and locate the existence of such faults in the most effective manner.[12]

An alternative approach is to simulate the circuit and its assumed fault on a computer. Test routines are again built up to diagnose and locate the faults. The first approach is closest to reality and, if fault insertion were accomplished by laser at arbitrary points and in a reversible manner on actual circuits, no simulation stage is necessary, which could reduce design time and costs.

The laser system can therefore be used both in the generation of the test routines and in their verification.

5.4 Future Possibilities

Although in this investigation m.o.s. circuits were used, the technique is also applicable to bipolar circuits. Our measurements indicate that, due to the higher operating currents in these circuits, a laser power of 10 mW will be required.

The work so far carried out in our laboratory has used only one laser beam. Where it is desirable to use several spots, these might be generated from a laser by using a hologram, or by using several lasers. Semiconductor lasers are becoming available which appear suitable and would facilitate the independent illumination of several nodes.

Alternatively, if access to a particular node is of continuing interest, the permanent attachment of a tiny l.e.d. could be considered. The direct coupling of information carried on optical fibres to an integrated circuit appears feasible. With the advent of variable frequency lasers, the variation of the depth of penetration of the light with wavelength might be used to explore changes in device structure with depth.

6 Conclusions

The application of lasers to the study of semiconductor devices and circuits has been briefly reviewed and experiments have been described which show that:

1. In some circumstances the carrier lifetime at remote points of a digital integrated circuit may be calculated by observation of effects of the laser on the circuit operation.
2. Data can be fed into m.o.s. integrated circuits with a low power laser beam ($< 0{\cdot}02$ mW) in a time of < 1 μs. As a result, it is anticipated that lasers will not only be used to locate, simulate and diagnose faults but also feed information directly into an integrated circuit in order to modify its function or simplify its fault-finding test routine. The direct interaction of integrated circuits with both analogue and digital signals carried by optical fibres appears feasible.

7 Acknowledgments

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The authors

Dr. W. D. Edwards graduated with first class honours in physics from Birmingham in 1946 and obtained his doctorate from the same University in 1949 for his research on electrical breakdown mechanisms in liquids. He was awarded a Post-doctoral Fellowship at the National Research Council of Canada and later joined the staff of the Ottawa Laboratories. In 1956 he went to the Radio Physics Laboratory of CSIRO in Sydney where he constructed the first vacuum silicon crystal furnace in Australia. In 1958 he returned to Canada and has since studied a number of semiconductor material and device problems. He has contributed numerous articles to the technical press and is the holder of patents in the field. He recently spent a year of educational leave at Southampton University.

After graduating in physics from King's College, London, **Mr. J. G. Smith** worked at Mullard on the development of silicon transistors and integrated circuits and of infra-red and visible photo-detectors. He has continued in these fields of interest since becoming a Lecturer in the Microelectronics Group of the Department of Electronics, University of Southampton in 1968, and has served as a consultant on camera systems and other optical techniques involved in microelectronics for several semiconductor manufacturers and for overseas universities. At present he is engaged on several microelectronics research projects concerning optical and infra-red techniques, with a view to their future commercial exploitation.

Mr. H. A. Kemhadjian obtained a first degree in electrical engineering at Southampton University in 1956 before working for Mullard Ltd. at the Southampton Semiconductor Development Laboratories. During a period of eight years, he held a number of posts concerned with applications of semiconductor devices, their characterization and electrical development. He joined the Electronics Department of the University of Southampton as a Lecturer in 1964 and is now a Senior Lecturer. His main research interests are microelectronics and the modelling of semiconductor components for computer aided circuit design.

IERE News and Commentary

New Year Honours

The Council has congratulated the following members of the Institution whose names appear in Her Majesty's New Year Honours List:

LIFE PEERAGE (BARON)

Sir John Edward Wall, Kt., O.B.E., B.Com (Companion 1969). Director, Exchange Telegraph (Holdings) Ltd. (formerly Chairman of International Computers Ltd.)

MOST EXCELLENT ORDER OF THE BRITISH EMPIRE

To be an Ordinary Officer of the Civil Division (O.B.E.)

Michael David Kendall Kendall-Carpenter (Member 1972, Associate 1969). Manager, Cable & Wireless (W.I.) Ltd., Cayman Islands (now with Cable & Wireless Business Review Unit in London).

To be Ordinary Members of the Civil Division (M.B.E.)

Roy Austin Ottman (Associate 1974) Acting Director of Posts and Telegraphs, The Gambia.

CEI Offers Support to Prime Minister

Professor John Coales, Chairman of the Council of Engineering Institutions, has written to the Prime Minister offering the help of professional engineers in reviving British industry—and calling for Government help in protecting the professional independence of professional engineers who are under pressure to join powerful unions in which they would be a tiny minority.

In his letter Professor Coales suggests that the Prime Minister should set up a high-level working group with the CEI and both sides of industry to consider what action could be taken to increase manufacturing productivity and enhance the quality of engineering and engineering management in Britain.

Professor Coales suggests that there are five specific areas in which the CEI could help;

In the recruitment of more engineering students and trainees of the right calibre;

In encouraging well-qualified engineers to play their full part in management, particularly in those areas directly concerned with the shop floor;

In fostering better relations between employers and employees in manufacturing industry;

In setting up an organization for teaching and training in manufacturing technology such as has been proposed by the Department of Industry;

In bringing about the symbiosis between the universities and polytechnics and industry which the Department of Education and science believes essential if engineering courses are to be improved.

Pointing out that the CEI represents some 300 000 engineers covering the whole field of engineering through 15 chartered institutions, Professor Coales says that they welcome the initiative taken by the Prime Minister and the Government in publishing the 'Strategy for Survival'. But this strategy could only be successful if the engineering profession was enabled to play its full part in it.

Traditionally, engineers have not only been innovators and designers, but have also been a valuable link between the skilled men on the shop floor and the management and owners. It was now essential for the engineers to be seen as a strong and united profession and it was to bring this about that the member institutions were determined to reorganize the CEI in a sensible manner.

'In this respect' Professor Coales says in his letter, 'one of the most serious obstacles is the uncertainty over 'closed shop' legislation and the actions of certain unions in trying to force chartered engineers to join them. It is vital that the quite unjustifiable action of certain powerful unions in blacking the legitimate work of chartered engineers in order to force the hand of the management to dismiss them, or make them join a particular union against their will, be stopped'.

Professor Coales concluded: 'Even if the profession is not yet as united as we would wish, we all want to help in the revival of British industry and will co-operate with you and your Ministers, provided it is made possible for us to do so.'

Standard Frequency Transmissions—November 1975

(Communication from the National Physical Laboratory)

November 1975	Deviation from nominal frequency in parts in 10^{10} (24-hour mean centred on 0300 UT)	Relative phase readings in microseconds NPL—Station (Readings at 1500 UT)	
	Droitwich 200 kHz	*GBR 16 kHz	†MSF 60 kHz
1	−0·2	695·7	612·4
2	−0·1	694·9	612·4
3	−0·1	695·7	612·2
4	−0·1	695·7	612·2
5	−0·1	696·2	612·2
6	−0·1	696·2	612·1
7	−0·1	697·2	612·2
8	−0·1	696·5	612·2
9	−0·1	695·3	612·2
10	−0·1	697·0	612·3
11	−0·1	694·3	612·2
12	−0·1	696·7	612·2
13	−0·1	696·2	612·1
14	−0·1	696·3	611·9
15	−0·1	695·7	611·9
16	−0·2	694·2	611·9
17	−0·2	696·3	611·9
18	−0·2	697·2	611·9
19	−0·2	695·7	612·0
20	−0·2	695·7	612·0
21	−0·2	697·1	612·0
22	−0·1	695·9	612·0
23	−0·2	696·3	612·1
24	−0·2	697·3	611·9
25	—	696·6	611·9
26	−0·2	695·9	611·9
27	−0·2	694·9	612·0
28	−0·2	696·6	612·2
29	−0·2	695·8	612·3
30	−0·2	697·8	612·2

All measurements in terms of H-P Caesium Standard No. 334, agrees with the NPL Caesium Standard to 1 part in 10^{11}.

* Relative to UTC Scale; (UTC_{NPL}–Station) = +500 at 1500 UT 31 December 1968.

† Relative to AT Scale; (AT_{NPL}–Station) = +468·6 at 1500 UT 31 December 1968.

EUREL General Assembly 1975

Professional engineers from nearly every country in Western Europe met in Milan on 21st November at the Fourth Annual Assembly of EUREL—the Convention of National Societies of Electrical Engineers of Western Europe. There are currently seventeen participating societies drawn from thirteen countries, namely Austria, Belgium (two societies), Denmark, Germany, Finland (two societies), France, Italy, Netherlands (two societies), Norway, Spain, Sweden, Switzerland and the United Kingdom. The United Kingdom is represented by the Institution of Electrical Engineers and the Institution of Electronic and Radio Engineers. At the Milan Assembly the IERE delegates were Professor William Gosling of the University of Bath, a past Vice-President and a member of the Institution's Executive Committee, and Mr. Frank Sharp, the Institution's Editor.

The main item on the agenda of the Assembly was the discussion and adoption of the report by the Chairman of the Executive Committee, Mr. F. Bianchi di Castelbianco. Matters dealt with included the adoption of a Sharing Formula for the Finances of EUREL and measures for sponsoring and supporting conferences. The principal conference is Eurocon 77, to be held in Venice in May 1977 and sponsored by EUREL and Region 8 of the IEEE. Delegates also signed on behalf of their societies an agreement laying down the conditions whereby individual members can enjoy reciprocal rights and privileges in attendance at conferences and meetings and in obtaining publications at reduced subscriptions. The introduction of a EUREL membership card was also approved. (Details of these arrangements will be announced shortly.)

The greater part of the main session, however, was concerned with the discussion and adoption of a statement by the member societies on the importance of exploiting nuclear power. (The text of the agreed statement is given below.)

EUREL is essentially an informal organization which has not attempted to build an expensive structure round itself: the President of one of the societies takes the chair for a year, and the organization is serviced by the Secretariat of his society. The Presidency and Secretariat have just been transferred from Italy to West Germany and are now respectively held by Dr. R. Dingeldey (Fernmelde technisches Zentralamt) and Dr.-Ing. H. Fleischer of the VDE. The executive committee of EUREL comprises three permanent members—France, Germany and the United Kingdom and four other members.

One of the principal advantages of EUREL is that it provides opportunities of establishing personal relationships between the honorary officers and officials of its member societies which make for easy communication and cooperation in a multitude of ways. In the second, informal, session of the Assembly, delegates put forward their views on the problems of professional societies using as a background a paper prepared by Mr. Bianchi on "The Engineer in Society". This gave all present a very much clearer view of the similarities and differences between organizations of engineers in the countries represented.

Warning by Engineers on Energy Generation

EUREL (Convention of National Societies of Electrical Engineers of Western Europe—see above) forecasts a shortage of energy if we do not press on with nuclear power development. Failure to proceed could dramatically affect the future pattern of life: unemployment, reduction in living standards and reduced rate of improvement in less developed countries. The statement, which is being circulated widely, is as follows:

> EUREL considers it to be its duty to call attention to the consequences that must be faced if the development of energy generation suffers undue delay.
>
> The availability of energy from its traditional sources—water, coal, oil and gas—is endangered by natural limits or by economic or political circumstances. No increase in the efficiency of the use of energy can be sufficient to provide for future requirements. Other potential sources of energy such as the sun, the wind, tides or terrestrial heat cannot be expected to make a substantial contribution to the world's needs for many years to come. The only source at present available for extensive exploitation is nuclear power.
>
> EUREL considers that failure to proceed with the installation of nuclear power plants will lead to a shortage of available energy that will have a drastic effect upon the future pattern of life. It will result in the unemployment of large numbers of workers and a reduction in the availability of food, water, heating, transportation and other features of life to which more highly developed countries have been accustomed, and it will drastically reduce the rate of improvement of the standard of living in the less developed countries.
>
> Reports from many countries show that one of the greatest obstacles to the installation of nuclear power plants is the inadequate information of public opinion, which is rightly concerned with the potential danger of these plants.
>
> Engineers responsible for the development and construction of nuclear plants must continue to be acutely conscious of the need to protect the safety of the operators of these installations and the world population as a whole from the hazard of the release of radioactive materials, and of the need to reduce further the risks, which are already extremely low.
>
> EUREL considers it is high time that questions in regard to the danger of nuclear plants should be recognized to have been authoritatively answered, and that the risk should be assessed in relation to the consequences which must be faced if nuclear energy is not used.
>
> EUREL sees the need for the world community to face now the choice between accepting the residual risk in the development of nuclear energy and accepting the economic and social consequences of a serious shortage of available energy in the foreseeable future.

The EUREL communique is effectively supported by the recent report from the Energy Technology Support Unit (ETSU) of the UK Department of Energy, on the energy potential for the UK from waves, tidal, wind, geothermal or solar energy and whether these could be serious alternatives to the development of nuclear power. ETSU found that the five systems studied could at best contribute no more than 6–8% of Britain's energy requirement by the end of the century.

Who wants Modular Courses?

B. F. GRAY, B.Sc.(Eng.), A.C.G.I., C.Eng., F.I.E.E., F.I.E.R.E.

Chairman's views following the Education and Training Group Colloquium on Modular Courses held in London on 6th March, 1975.

Modularization of courses at Universities and Polytechnics involves dividing up the curriculum into learning packages. These present the student with flexibility in matching his studies to ability and inclination and facilitate hybrid degrees. The author argues that these factors lead to real disadvantages and may devalue a degree award, particularly in engineering.

Introduction

Education is very much a creature of change, never more so than over the past decade. The changes have been widespread affecting every level of education from the nursery school to the university. We have seen the School Certificate replaced by the General Certificate of Education which in turn appears to be threatened by the Certificate of Secondary Education. We have seen the establishment of the Colleges of Advanced Technology followed by the new Universities and finally (?) the Polytechnics. We are currently seeing the Colleges of Education going through a rationalization phase. Some of these changes are due to economic constraints, some are the outcome of political dogma, a few are the result of educational pressure.

Our educational system is a vast, complicated and expensive organization which responds to pressures relatively slowly and it is of paramount importance that any changes which it undergoes are seen as improvements. It is very wasteful of time, energy and money to make alterations for the sake of change, especially when there is doubt whether the final output will be any improvement over what we have already. At the risk of our simplifying the situation we might argue that the present economic climate forces us to reconsider education at all levels and make alterations such that either we offer the same education as at present—but more cheaply, or we offer a better education for the same investment.

Bernard Gray (Fellow 1959) is now Dean of Engineering at the Hatfield Polytechnic. He joined the staff in 1956, and became Head of the Department of Electrical Engineering and Physics, following seven years at Luton College of Technology and previous industrial experience with Marconi Instruments Ltd., and George Kent Ltd. He graduated in telecommunication engineering from Imperial College of Science in 1944.

Mr. Gray has served on the Education and Training Committee since 1960 and was its chairman from 1968 to 1972; from 1968 to 1971 he was a member of Council.

He has represented the IERE on the Joint Committee for Higher National Certificates in Electrical and Electronic Engineering, on the Electrical/Electronic Engineering Board of C.N.A.A., and on the City & Guilds Telecommunications Advisory Committee.

Mr. Gray has travelled overseas on several occasions to advise on educational matters, most recently to the University of Mauritius in 1972 and Malawi in 1974.

At the higher levels of education it is especially necessary to examine the expenditure of money and consider whether we are spending our resources in the right way.

The Universities and Polytechnics are under pressure to supply courses which meet the demands of the professions, industry and the students. It is paradoxical that the greatest pressure from the students appears to be mainly in Arts whereas the demand from industry appears to be mainly in Science and Technology.

So perhaps the first difficult decision is whether or not to respond to these pressures: which leads us to consider ways and means of offering curricula which can perhaps meet both industrial demand and student choice.

The Concept of Modular Courses

One approach to this problem is the adoption of Modular Courses so that hopefully the present resources can be used more effectively while at the same time a wide range of subjects is open to the student. Modular courses at the higher levels of education in this country have up to now been rare. In the secondary schools they are quite common, being epitomized by the General Certificate of Education. Perhaps at this point it would be worthwhile to define what is generally accepted as a modular course. One could suggest that modules are present in many existing courses where distinct options occur within a scheme of study. This is typically the situation in many degree courses. Yet by no stretch of the imagination could one define such a structure as modular.

Modularization involves dividing up the curriculum into learning packages. Each module of such a course would be regarded as a discrete entity occupying a given number of hours of study. These study hours might be spent in lectures, laboratories, tutorials in contact with a teacher or they might be spent in private study in one's home. A course or programme would prescribe a certain number of modules and the final award of a diploma, certificate or degree would depend upon their successful completion. Inevitably there would need to be some structuring of such a programme and it would be necessary to apply certain restrictions recognizing the fact that some modules would be at a higher conceptual level than others and some sort of sequence would have to be followed. For example Mathematics II could not be studied until Mathematics I had been completed.

It would also be necessary to ensure that the award at the end of the course depended not only upon the number of modules successfully completed but also upon the level of the modules. If we consider for example a three-year course one might suggest that ten modules should be studied per year and in general modules in year two would be at a higher intellectual level than those in year one. The award might be given for success in, say, 25 modules, at least 8 being at the third-year level. The flexibility of the scheme should be self-evident in that a wide range of modules could be offered at each level and students would then be in a position to make up their study programme from these modules. Additional flexibility is also available from the fact that students would not necessarily be required to be successful in each module studied. This, the 'credit system', has been employed in the USA for many years. In this country the credit system is essentially the one adopted by the 'O' and 'A' level examinations. It is rare to find its use extended to tertiary education; the one major area where it is used is the Open University.

The Case for Modular Courses

The strongest educational reason for adopting modular courses is based on the flexibility they offer. Student motivation is a key factor in any course of study so that studying what one wants to study is liable to lead to greater success than studying what one is directed to study. Modular courses undoubtedly provide a basis for more attractive study programmes.

An additional feature is the fact that students need not necessarily pass all subjects in a series of examinations at one sitting—they will be credited for any success achieved. A student might therefore collect the necessary number of credits for the final award over four to five years instead of the more usual three. In other words the pace of study can be adjusted to suit the rate of assimilation of the individual concerned. Also, the possibility of hybrid degrees becomes very real and general engineering degrees with major options in, for example, economics or modern languages or law can then be made available within other courses already in existence.

Another attractive feature is the prospect of rationalization. Students wishing to study the same subject could be accommodated within one module irrespective of the faculty in which the students were based, and it would therefore be unnecessary to repeat the same work with different groups of students, as sometimes happens in existing courses.

At the expense of some compromise more and more modules could become standardized and make the production of associated learning packages a viable proposition.

The Case against Modularization

While many of the features outlined seem attractive both from the students' and the educational establishments' point of view, they need to be studied very carefully. Flexibility is a double-edged weapon. Students may choose subjects for the wrong reason. For example the 'able lecturer' or the 'soft option' may prove irresistible whether or not the subjects are of real benefit to an individual. This is particularly relevant if he (or she) is intending to become an engineer. Students presented with a wide range of topics may find great difficulty in choosing and may be persuaded as much by their friends' choice as their own. 'Difficult' subjects will tend to be shunned. The flexibility may also be more apparent than real since inevitably some subject clashes will occur and a student's choice may be more limited for this reason. Moreover since some structuring will undoubtedly be necessary students will find that they have to meet certain prerequisites before they can go on to study modules at higher levels, and failure in a prerequisite will deny students entry into these higher modules. The attractiveness from the educationalist's point of view begins to fade when a wide range of student ability and interest appears in each group studying a particular module. The relevance of the subject to a student's main interest may be difficult to put over when the student group contains very wide interests. The motivation could be adversely affected. Subject teaching would tend towards isolationism and in an area such as engineering where interdependence on subjects is so important the total learning might suffer. The rationalization brought about by bringing students together becomes less attractive as additional tutorials are found necessary to make good the compromise situation that modularization has brought about. Also, since common modules will occur mainly at the lower levels where student numbers are relatively large, accommodation difficulties might well occur.

The pace of the course is one which, purely from an educationalist's point of view, should be variable. There are unfortunately very real practical limitations, namely the cost of student grants and the fact that the student body will increase, imposing further stress on student accommodation—both domestic and tutorial. It is frankly doubtful if we can afford this luxury especially in vocational courses where the demands from industry for trained manpower is acute.

The need for hybrid degrees is one which is debatable. Inevitably, within the span of a three-year degree course one can only learn so much. If half the time is devoted to non-engineering topics then the level attained in the engineering topics must be about half that attained in a so-called 'specialist' engineering course. Whether or not such a graduate would be as useful to industry is debatable. Whether or not such hybrid courses would be attractive to students is equally debatable. Although such courses might prove attractive to the 'Arts' student, unless such a person had an adequate Science and Mathematical background he would find the pace of the course too much.

The production of learning packages only becomes viable if the number of students coming forward is large enough or if the number of years over which a course runs is long enough. The latter inhibits change.

Some Personal Thoughts

Modularization and its associated credit system may lead to a devaluation in the degree award. Whatever its attraction to the non-vocational student its appeal to the engineering student must be less if the award does not receive national (and possibly international) recognition. The Council of Engineering Institutions may deserve a great deal of the criticism it receives in educational matters because of its rather rigid attitude to recognition of courses. Nevertheless one must acknowledge its right to safeguard standards and lay down clear guidelines on what it considers the level and, in broad terms, the content of an engineering degree course.

The very nature of the disciplines (whether it applies to mechanical, electrical or civil engineers) requires a structuring of the course of study. There must inevitably be a certain amount of mathematics, physics and technology. There must be provision too for updatingcourses, since the pace of technology (especially in electronics) has been so fast in the past two decades. While acknowledging the fact that engineers need 'Communication Studies' within their curricula (incidentally most students do), I do not see that necessarily some aspects of 'Social Studies' have the same right in the undergraduate course. While such studies should be available to engineering students should they wish to study them, they should not be compulsory and should never occupy more than about 15% of the time unless a student is on a hybrid course. While the general education of an engineering student is important he can obtain this within his technical subject, or during his training or in extra curricula activities. (I have yet to see General Engineering Studies featuring in an Arts degree course.) So much nonsense has been written about the narrowness of the engineer and his need for 'broadening'. It is just unfortunate that he is so busy that his political awareness is often dulled. This last point is one which is being brought up time and time again. It is certainly true that most engineering students have a full curriculum. Most technology students spend between 20 and 25 hours per week in class contact activities (in some cases more than 25). This is in sharp contrast to the Arts student who will spend often only half of these hours in lecture and tutorial activities (and in some cases much less). The engineering sandwich student will not have the long vacations that his arts counterpart receives.

There is an argument that we 'over teach' the engineering student and he ought to be capable of 'reading' for his qualification. Yet reading a highly analytical text may prove virtually impossible without some help via the lecture or tutorial. Reading a Shaw play undoubtedly needs concentration but the ability to move from page 1 to 2 is much easier than the situation in a mathematical text where the student is unsure of the full meaning of a partial derivative at the bottom of page 1 and page 2 begins to develop a partial differential equation. Perhaps the curriculum is too full and perhaps a two-stage degree in engineering spanning four years is to be the next stage—2 years to an 'Associate Degree' and two further years to the Master level.

But all this is moving from the Modular Concept. When one adopts a Common Modular Structure within a University or Polytechnic one comes up against the significant differences in the requirements of the 'Arts' degree and the 'Engineering' degree. It would be quite foolish to say that one is more difficult than the other. It is however fair to say that the Arts man can 'get away' with more. A capable Arts student can still produce brilliant essays whether or not he has attended lectures. An engineering student cannot write up his report on an experiment unless he performed the experiment (short of downright copying of a colleague's report).

Directly a modular structure is imposed on a Polytechnic or a University such differences become more apparent and the engineering student will find that inevitably he will be forced either to study more modules or do more work within each module. While such disparities exist already, the direct curriculum comparison is seldom made. Within a common modular course such comparisons will lead to some engineering students choosing alternative schemes of study.

Being a little cynical this might produce a better overall image of the engineer as the student less enamoured by technical studies chooses alternatives. But I do really wonder whether this country can afford to invest its future in what appears to be a contraction in Technology and an expansion in Non-Technology. Modular courses, I fear, may accelerate this trend. I only hope that I am proved wrong.

Manuscript received by the Institution on 1st October 1975.
(Paper No. 1700/ET 17).

Technical News

MacRobert Award for 1975

For only the second time in its seven years' history, the MacRobert Award—the major engineering award in Great Britain—has been won by two separate teams of five individuals, from the British Railways Board for developments in new railway vehicle suspensions, and from Westland Helicopters for their contribution to the development of the semi-rigid rotor system and to conformal gearing for the *Lynx* helicopter.

The winning team from British Railways Board is Dr. S. Jones, Dr. K. H. Spring, Dr. A. O. Gilchrist, Mr. M. Newman and Mr. A. H. Wickens. The basis of the developments in railway vehicle suspensions is a careful analysis of the instabilities of steel wheels running on steel rails. Careful experimentation and mathematical analysis by the staff of British Rail Research at Derby led to an understanding of the oscillations that arise from the coning of the wheels and certain features of traditional suspension designs. This understanding led them to develop an entirely new approach to suspension design which eliminates the hunting oscillation even at high speeds and with worn, hollow treads rather than purely conical treads as provided on new wheels.

The new approach to suspension design is of outstanding merit because it breaks from tradition which is 150 years old and introduces a new philosophy into rolling stock design. Its advantages are—

(1) a higher quality ride on existing track;

(2) reduced dynamic stresses in vehicle and track components;

(3) reduced flange and rail wear, so considerably reducing the cost of maintenance;

(4) reduced risk of derailment with freight vehicles;

(5) safe operation at higher speeds on existing track with no increase in maintenance costs.

The new design approach is of general application—it can be used on two-axle as well as on bogie freight vehicles, on passenger coaches and on traction units. It enables vehicles to traverse curves at high speed with virtually no flange contact. Some of the new principles are already in use on the High Speed Passenger Train, but the most spectacular application of the complete system is on the Advanced Passenger Train.

The winning team from Westland is Mr. J. Speechley, Mr. V. A. B. Rogers, Mr. K. T. McKenzie, Mr. D. E. H. Balmford and Mr. G. J. Smith-Pert. The submission by Westland Helicopters is based on two major innovations embodied in the design of the *Lynx* which have been responsible for its emergence as a world-leading, record-breaking helicopter. The innovations are the *semi-rigid rotor system* and *conformal gearing*.

The rotor system of the conventional helicopter involves flap, lag and feathering articulations with a consequent large number of mechanical components. In the *Lynx* design only the feathering hinge has been retained, as it has been possible to reduce the flap and lag hinges by flexible titanium elements resulting in a reduction of 80% in the number of components required. Mathematical techniques derived by Westland have enabled the structural properties of the flexible elements to be determined accurately, thus enabling the required precise dynamic properties of the total rotor system to be achieved.

The use of conformal gearing is unique in helicopter engineering and follows Westland's research activity which started in 1959. This research established tooth profiles which give enhanced strength compared with conventional gearing. This results in high power transfer by small light gears and again leads to great simplification through a reduction of more than 40% in the number of components.

Each of the parent organizations received a Gold Medal from H.R.H. The Duke of Edinburgh, President of CEI, and each team of individuals a half-share of the total prize money of £25,000. The MacRobert Award is made annually by CEI on behalf of the MacRobert Trusts.

Marine S.S.R. for Rescue Service

An unusual radar system has recently been developed for the St. John's Ambulance Brigade in Guernsey, Channel Islands, who operate a number of sea-going vessels (a marine ambulance and inshore rescue boats) and have often problems in locating their own vessels and guiding them to ships needing assistance, particularly in bad weather. The system is based on a modified harbour radar (Decca HR 1216) mounted in a trailer which can be towed to the most convenient of a dozen prepared sites around the island. This solves part of the problem, i.e. to cover a difficult coastline and surrounding waters efficiently and economically. The remainder of the problem is to identify the rescue vessel under conditions of extreme difficulty, caused by the numerous small islets and rocks, apart from sea-clutter. Particularly in rough seas very poor echoes are received from the inshore rescue boats which are basically rubber catamarans and have almost no radar reflective properties. The linking of a beacon system with the radar has provided a very satisfactory solution to this problem. The SJAB vessels carry small active transponder beacons which send back a signal that is fed on to the plan position indicator of the radar. This 'secondary radar' picture can be displayed alone or with the primary radar picture, which can also be observed by itself.

Technically and operationally this system of marine secondary surveillance radar, believed to be unique and developed for the SJAB by Mr. T. W. Welch of T. W. Welch & Partners who are radar consultants, in cooperation with the Marine Division of Decca Radar Ltd., fulfills the specified requirements very effectively. The inshore boats can be followed out to about 7 miles and the marine ambulance—which is similar in size and configuration to a lifeboat—can be tracked to about 17 miles. Both primary radar and the beacon system work in X-band, the latter having been modified to operate on only one frequency, about 0·135 GHz below the radar frequency, instead of sweeping through the band. Modifications to the radar thus have included arranging for it to receive its own echoes and the transponder returns on alternate scans. The scan rate of 28 per minute and the tube afterglow provide suitable viewing continuity for moving marine targets.

The overall system, known as a radar and rescue coordination unit, is completed by incorporating full communication facilities in the trailer: v.h.f. marine bands (4 channels); v.h.f. air/sea rescue channel; m.f. s.s.b. marine band (4 transmitter channels); private-band v.h.f. (2 channels) to communicate with SJAB vessels, vehicles and headquarters; and temporary connexions to Island telephone system.

The novelty and at the same time the practical value of this project may be judged by the granting of a five-year experimental licence by the Home Office. Considerable interest has been shown by numerous marine organizations throughout the U.K.

Cardiac Stimulator with Nuclear Battery

A nuclear-powered implantable pacemaker is to be made at the Harwell Atomic Energy Research Establishment. Conventional pacemakers with chemical batteries have to be replaced surgically about every three years, but prolonged trials indicate that the implanted lifetime of the Harwell units could reach 10 or even 20 years.

The Department of Health and Social Security has placed the first production order with British Nuclear Fuels Limited for 100 of the new nuclear batteries and an order for another 200 batteries is following. The work has been sub-contracted to Harwell, where a team has been developing the technology for six years.

Under the present contract Harwell will prepare the heat-producing nuclear sources, each containing less than a fifth of a gram of plutonium oxide, and assemble them, with their miniature thermocouples, in strong metal housings to form the nuclear batteries that power the pacemakers. At the request of DHSS, Harwell has also undertaken for an interim period to assemble 100 pacemakers in which solid-state d.c./d.c. converters and electronic pulse generators (the former also made at Harwell) will be connected to the batteries. The assembly is encapsulated in an epoxy resin known to have lasting compatibility with living tissue.

About 100 pre-production models of the nuclear battery have already been made at Harwell and fitted into pacemakers of similar design by the Implant Division of Devices Limited of Welwyn Garden City. The pacemakers have been subjected to long-term controlled trials at recognized cardiological centres under DHSS supervision. First, they were tested in animals and then, during the last five years, in human patients—the earliest of whom is still using hers.

Internationally-agreed safety standards require stringent tests on the batteries. These ensure that there is no radiation hazard and that they will withstand the most severe accident—fire, impact or even cremation—that they are ever likely to encounter. The isotope plutonium 238 has been chosen for the heat source because its power output falls by only 1% per year, and its radiation, mainly alpha particles, requires the minimum of shielding for implantation. This isotope is specially prepared for the pacemaker batteries and is markedly different from the very long-lived plutonium isotopes associated with nuclear weapons and nuclear fuel.

These pacemakers will only be available for selected clinical trials. Confirmations from the trials of the safety and efficiency of the battery is confidently expected to lead to exploitation of the Harwell battery by BNFL through pacemaker manufacturers throughout the world.

Satellite for Measuring Natural Microwave Radiation

The ways in which measurements of the natural microwave radiation from the Earth's surface can be used in surveys of the Earth from space will be investigated under a £67,000 Study Contract awarded to the Electronic and Space Systems Group of the British Aircraft Corporation by the European Space Research Organisation.

PAMIRASAT (Passive Microwave Radiometer Satellite) is the name given to a possible future European satellite for this task. In addition to collecting data on the world's oceans, polar ice caps and land regions, it would collect meteorological information and monitor pollution of the upper atmosphere. BAC's study will identify the applications of this unique type of measurement in detail, and will define several possible versions of the operational PAMIRASAT system. It will also propose a development programme based on use of the European *Spacelab*, which will be orbiting the Earth in the USA's Shuttle in the early 1980s.

Estimates of the cost of developing and operating PAMIRASAT will be made towards the end of the study and these will include the costs of the supporting research and technology programme. BAC will be working in collaboration with microwave radiometer specialists from the Technical University of Denmark, with scientists at Bristol University and the Appleton Laboratory of the Science Research Council, and with oceanographers in Denmark and Sweden.

Conference Programme *(cont. from facing page)*

'Epidural spinal cord radio-frequency stimulation in multiple sclerosis'
By Prof. A. W. Cook, Dr. A. Abbatte and Dr. M. Atallah (*Long Island College Hospital, U.S.A.*)

'The application of auditory evoked responses to the location of brain-stem lesions'
By Dr. A. R. D. Thornton (*Southampton University*)

'Neuromuscular assist for equinovarus deformity in hemiplegia'
By B. A. Roper (*London Hospital*)

'Radio-telemetry and e.e.g. analysis in the study of patients with seizures'
By R. G. Willison (*National Hospital, London*)

'Localization of dipoles in cerebral hemispheres'
By Dr. S. R. Butler, Dr. A. Glass, and D. J. Henderson (*University of Birmingham*)

SESSION 9. REHABILITATION

'A method of measuring the temporal distance factors of gait'
By J. C. Wall and M. Dhanendran (*Polytechnic of Central London*)

' "Polgon": an aid to gait analysis'
By P. R. Styles (*Medelec Ltd., Woking*)

'A television computer system for the analysis of human locomotion'
By M. O. Jarrett, B. J. Andrews and J. P. Paul (*University of Strathclyde*)

SESSION 10. SCANNING AND IMAGING

'The Compton effect gamma camera detector system'
By J. S. Flemming and B. A. Goddard (*Southampton General Hospital*) R. J. M. Nightingale, D. B. Everett and R. W. Todd (*University of Southampton*)

'A clinical whole body counter'
By G. M. Owen (*University Hospital of Wales, Cardiff*)

'Swept focusing system for ultrasonic pulse-echo diagnosis'
By E. J. Guibarra, Prof. K. T. Evans and Dr. P. N. T. Wells. (*University Hospital of Wales, Cardiff*)

'Techniques and results of C. T. scanning of the brain and body'
By R. H. Davies (*EMI Medical Ltd., Hayes, Middlesex*)

Closing remarks by W. J. Perkins, Chairman of the Conference Organizing Committee.

The Conference will be supported by an Exhibition.

Further information from Conference Department, IERE, 9 Bedford Square, London WC1B 3RG. (Telephone 01-637 2771, Ext 3).

Conference on 'The Applications of Electronics in Medicine'

Organized by THE INSTITUTION OF ELECTRONIC AND RADIO ENGINEERS with the association of The Biological Engineering Society, The Hospital Association, The Institute of Electrical and Electronics Engineers, The Institute of Physics, The Institution of Electrical Engineers and The Royal Society of Medicine.

University of Southampton, 6th to 8th April 1976

Provisional Programme

Tuesday, 6th April

Opening Address by Dr. J. Hewer (*Middlesex Hospital*)

SESSION 1. ULTRASONICS

'A ultrasonic study of uterine artery blood flow'
By Prof. K. J. Dennis, D. M. Moore and M. E. House (*Southampton General Hospital*)

'Non-invasive haemodynamic flow measurement techniques for routine clinical use'
By L. H. Light, G. Cross and P. L. Hansen (*Clinical Research Centre, Harrow*)

'Clinical experience with transcutaneous aortovelography'
By G. C. Hanson and A. Buchtal, (*Whipps Cross Hospital*)

'The use of ultrasound to monitor the quality of cardio-pulmonary bypass'
By D. W. Bethun (*Papworth Hospital, Cambridgeshire*)

SESSION 2. CARDIOLOGY

'Studies on the origin of heart sounds by simultaneous high resolution echo- and phono-cardiography"
By G. Leech and A. Leatham (*St. George's Hospital, London*)

"Matched filter location of e.c.g. complexes"
By Dr. F. C. Monds and R. W. Telford. (*Queen's University of Belfast*)

'Obtaining useful information from the heart without the use of a computer'
By Prof. T. Shelley (*Royal South Hants Hospital*)

'The continuous precise measurement of foetal heart interval during pregnancy'
By A. J. Murrills and Prof. T. Shelley (*Southampton General Hospital*) and T. Wheeler (*Department of Obstetrics, Oxford*)

SESSION 3. THORACIC IMPEDANCE PLETHYSMOGRAPHY

'Long-term respiration monitoring using an electrical impedance analogue computer'
By Dr. E. G. A. C. Boyd (*Guy's Hospital, London*)

'A field approach to thoracic electrical impedance plethysomography'
By C. Bryant and Dr. D. W. Thomas (*University of Southampton*)

'A new method for the calculation of cardiac output from electrical impedance variations'
By J. R. Hawke (*University of Manchester*) C. R. Birch and D. J. Rowlands (*Manchester Royal Infirmary*)

'The physiological events associated with changes in the thoracic electrical impedance during systole.'
By G. B. Claridge, M. Girling, F. D. Thompson and A. M. Joekes (*St. Philip's Hospital, London*)

Wednesday, 7th April

SESSION 4. RESPIRATORY MONITORING

'A breathing model of the respiratory system'
By H. M. Bali and K. B. Saunders (*Middlesex Hospital, London*)

'Computer simulation of gas exchange during anaesthesia'
By Dr. D. A. Scrimshire (*University of Aston, Birmingham*)

'Analysis of gaseous transport mechanisms in human lungs and diagnosis of dysfunction'
By T. J. Jones and Dr. D. A. Scrimshire (*University of Aston, Birmingham*)

SESSION 5. INFORMATION SYSTEMS

'An adaptive system for the interrogation of hospital patients'
By Dr. R. W. Lucas, Dr. R. P. Knill-Jones, Prof. W. I. Card and Dr. G. P. Crean (*Southern General Hospital, Glasgow*)

'The evaluation of computer interrogation of hospital patients'
By Dr. R. W. Lucas, Dr. R. P. Knill-Jones, Prof. W. I. Card and Dr. G. P. Crean (*Southern General Hospital, Glasgow*)

'Patient investigation simulation: computerized education system'
By R. D. Williams (*Southern General Hospital, Glasgow*)

'Computer based medical record information system in primary medical care'
By Dr. E. M. Clark (*Southampton General Hospital*)

'Information retrieval systems for patient records'
By K. G. Trickett (*Stabletron Ltd., Hitchin*)

'Computer diagnosis of migraine from data collected by questionnaire'
By Dr. B. G. Batchelor (*University of Southampton*)

SESSION 6. COMPUTER ANALYSIS

'A recognition system for the detection of cardiac arrythmias'
By D. G. Kyle and W. M. Portnoy (*Texas Technological University, U.S.A.*)

'Transfer function analysis methods used for arterial disease'
By S. J. Morris, D. R. Owens, Dr. P. N. T. Wells and J. P. Woodcock (*University Hospital of Wales, Cardiff*)

'Improved delivery of radiotherapy treatment through computer automation'
By Prof. J. G. Kreifeldt and P. W. Neurath. (*Tufts University, U.S.A.*)

SESSION 7. AUTOMATION AND CONTROL

'Bulk processing of human blood plasma'
By D. A. Ross and B. White. (*Protein Fractionation Centre, Edinburgh*)

'Patient controlled administration of intravenous analgesics'
By J. P. McCarthy, M. Rosen, J. Evans and M. Hogg (*University Hospital of Wales, Cardiff*)

'Demand pacing of the heart; analysis of sensed bioelectric signals and their importance in pacemaker design'
By J. Norman and Dr. A. Rickards (*National Heart Hospital, London*)

'A new approach to control above-knee prosthesis'
By S. C. Saxena and Prof. P. Mukhopadhyay (*University of Roorkee, India*)

'An electronic method of controlling induced labour'
By P. J. Steer (*St. Mary's Hospital, London*)

Thursday, 8th April

SESSION 8. NEUROLOGICAL SYSTEMS

'Augmented sensory feedback in CNS lesions; neural control of locomotion'
By Dr R. Herman (*Moss Rehabilitation Hospital, Philadelphia, U.S.A.*)

'Delayed auditory evoked potentials in brain-stem lesions'
By K. N. Humphries, P. Ashcroft and E. Douck (*Guy's Hospital, London*)

(*Cont. on facing page*)

INSTITUTION OF ELECTRONIC AND RADIO ENGINEERS

Applicants for Election and Transfer

THE MEMBERSHIP COMMITTEE at its meeting on 9th December 1975 recommended to the Council the election and transfer of the following candidates. In accordance with Bye-law 23, the Council has directed that the names of the following candidates shall be published under the grade of membership to which election or transfer is proposed by the Council. Any communication from Corporate Members concerning the proposed elections must be addressed by letter to the Secretary within twenty-eight days after publication of these details.

Meeting: 9th December 1975 (Membership Approval List No. 216)

GREAT BRITAIN AND IRELAND

CORPORATE MEMBERS

Direct Election to Fellow

BENJAMIN, Ralph. *Cheltenham, Gloucestershire.*

Direct Election to Member

JONES, Ronald William, *Littleborough, Lancashire.*
WEBSTER, Brian Gordon. *Gourock, Renfrewshire, Scotland.*
WOOD, Roger Jeremy, *London.*

NON-CORPORATE MEMBERS

Direct Election to Graduate

HO, Pak-Kwong *Newport, Gwent.*
SHARPLES, David. *Blackburn, Lancashire.*

Transfer from Student to Graduate

CHUNG, Chun Man *Fallowfield, Manchester.*

Direct Election to Associate Member

AISIKHAUA, Zaccheus A. *Holloway, London.*
OREM, Albert Echua, *New Cross, London.*
HARRISON, Athol Ernest V. *Kew Gardens, Surrey.*

STUDENTS REGISTERED

BUCHAN, Dennis Edward, *Bristol.*
EKPENYONG, Ekpo, *Middlesbrough Cleveland.*

OVERSEAS

NON-CORPORATE MEMBERS

Direct Election to Graduate

LIANG, Chi Keung, *Hong Kong.*

Transfer from Student to Graduate

LEUNG, Fu Yee, *Hong Kong.*

Direct Election to Associate Member

LAI, Kwok Hong, *Hong Kong.*

Transfer from Student to Associate Member

CHONG, Yet Fye, *Malacca, Malaysia.*
KWOK, Chi-Wah. *Hong Kong.*

Transfer from Student to Associate

SCAFE, Roy Barrington, *Kingston, Jamaica.*

STUDENTS REGISTERED

FUNG, Yuen-Kwong P. *Hong Kong.*

Addendum

Meeting: 17th June 1975 (Membership Approval List No. 210)

OVERSEAS

NON-CORPORATE MEMBERS

Direct Election to Associate Member

NG, Thain Ser, *Singapore.*

Corrigendum

Meeting: 6th November 1975 (Membership Approval List No. 214)

GREAT BRITAIN AND IRELAND

CORPORATE MEMBERS

Transfer from Graduate to Member

BRADSHAW, Terry. *Wesham, Dorset* should read: *Wesham, Lancashire.*

Electronics Provides Oil Platform Deployment Control

An advanced remote control and monitoring system to link Burmah Oil Developments' giant £300 million Thistle 'A' platform with the towing and laying vessels during its deployment in the Thistle oil field is to be supplied by the Systems & Automation Group of EMI Electronics Limited under a contract worth almost £250,000. EMI is supplying a complete package system with full engineering support services to provide control and monitoring functions during the critical phases of platform tow-out, rotation and placement.

Deployment of the 'A' platform is scheduled for Spring of 1976. Recognizing the importance of the tow-out and placement phases of the operations, Burmah and its consultants specified a sophisticated and highly reliable remote control and monitoring system for the platform.

The 213 m (700 ft) steel-jacket platform has a base area 91 m (300 ft) square. The tow-out phase from the Laing yard at Graythorpe on Teeside to its location north of the Shetlands could take up to 15 days. For towing, the platform travels on its side: for positioning on the seabed, ballasting compartments in the structure are flooded in a carefully-controlled sequence, to turn it through 90 degrees and settle its four steel legs on the seabed.

The system being supplied by EMI utilizes a radio communications link between the platform and support vessel during tow-out, and both a cable and radio link during the deployment phase transmitting 150 control signals governing the operation of valves, etc., and monitoring over 40 analogue levels and more than 240 indications of platform status. The system uses digital cyclic encoding techniques for maximum integrity of control and monitoring signals. The system also includes a unit for attitude measurement during the turnover manoeuvre and an acoustic measuring system for checking leg-to-sea-bed distances during the final touch-down phase.

Considerable attention is focused on ensuring the highest operational integrity of every part of the system and complete duplication of the encoding/decoding and radio equipment is being provided with automatic changeover to achieve maximum reliability.

EMI is undertaking extensive radio-modelling tests for the project at its Feltham laboratories, using a 4 m (13 ft) model of the platform to simulate the radiation patterns which will be encountered, thus ensuring full radio system fidelity during actual deployment. Similarly, the entire system will be subjected to full environmental testing with vibration and temperature cycling prior to delivery. The quality control and proving procedures employed will be identical to those used by EMI Electronics in developing missile telemetry systems, where immediate, first-time equipment is also imperative.

Forthcoming Institution Meetings

London Meetings

Wednesday, 3rd March

COMMUNICATIONS GROUP

Colloquium on TROPOSPHERIC SCATTER COMMUNICATIONS

IERE Lecture Room, 2 p.m.

Advance registration necessary. For further details and registration forms, apply to Meetings Secretary, IERE.

Thursday, 18th March

COMMUNICATIONS GROUP

Global Communications

By D. Weedon (*Cable and Wireless*)

IERE Lecture Room, 6 p.m.

Wednesday, 31st March

JOINT IEE/IERE COMPUTER GROUP

Colloquium on SYSTEMS SIMULATION

IERE Lecture Room, 2 p.m.

Advance registration necessary. Registration forms available from the Meetings Secretary.

Kent Section

Wednesday, 18th February

Ceefax: a New Form of Broadcasting

By J. D. Chambers (*BBC Research Department*)

Medway and Maidstone College of Technology, 7 p.m.

Wednesday, 17th March

Education and Training for the Electronic Engineer

By K. J. Dean (*S.E. London College*) and K. J. Coppin (*IERE*) Medway & Maidstone College of Technology, 7 p.m.

Southern Section

Wednesday, 11th February

Waveguides and Components in the Sub-millimetric Range

By Prof. D. Harris (*UWIST*)

Portsmouth Polytechnic, Anglesea Road, Room A2-6. 7.30 p.m.

Wednesday, 18th February

JOINT MEETING WITH IEE

Control and Stabilization of Satellites

By A. Bailey

Southampton University, 6.30 p.m.

Wednesday, 25th February

Project Management

By R. H. Bradnam (*Urwick-Orr Technology Ltd.*)

Lanchester Theatre, University of Southampton, 7 p.m.

Tuesday, 2nd March

Signal Processing without Tears

By D. Cox (*School of Signals, Blandford Camp*)

Bournemouth College of Technology, 7 p.m.

Wednesday, 3rd March

Systems Simulation

By J. Muller (*Brighton Technical College*) Brighton Technical College, Pelham Street, 7 p.m.

Wednesday, 10th March

ANNUAL GENERAL MEETING OF THE SECTION

Followed by a lecture on
Concorde Electronics
By N. Brenchley (*British Aircraft Corporation*)

Lecture Theatre F, University of Surrey, Guildford, 7 p.m.

Wednesday, 17th March

JOINT MEETING WITH IEE

Ambisonics

By Professor P. B. Fellgett (*University of Reading*)

RAE Farnborough Director's Mess, 7 p.m.

Thursday, 18th March

Electronics in Yachts

By P. I. Pelham (*Brookes & Gatehouse Ltd.*) South Dorset Technical College, Weymouth, 6.30 p.m.

Wednesday, 24th March

JOINT MEETING WITH IEE

Symposium on Current Trends in Digital Image Processing

Portsmouth Polytechnic, 4 p.m.

South Western Section

Monday, 2nd February

JOINT MEETING WITH IEE AND R.AE.S.

Concorde in Airline Service

By J. Romeril (*British Airways*)

University of Bristol, 6 p.m. (Tea 5.30 p.m.)

Thursday, 5th February

JOINT MEETING WITH IEE

Digital Switching

By G. N. Lawrence
(*GEC Telecommunications Ltd.*)

Plymouth Polytechnic, 7 p.m. (Tea 6.30 p.m.)

Tuesday, 16th March

JOINT MEETING WITH IEE

Some Aspects of Telecommunications Engineering

By T. M. Coleman and J. Little (*Post Office*) Techno Centre, Swindon, 7 p.m.

Wednesday, 24th March

JOINT MEETING WITH IEE

Applications of Microprocessors

By Dr. B. A. White and R. Lipczynski (*Bath University*)

Canteen, Westinghouse Brake & Signal Co., Chippenham, 6 p.m. (Tea 5.30 p.m.)

South Wales Section

Wednesday, 11th February

JOINT MEETING WITH IEE

Facsimile Transmission over the Telephone Network

By J. P. Basgallop (*P.O. Telecommunications H.Q.*)

Department of Applied Physics and Electronics, UWIST, Cardiff, 6.30 p.m. Buffet after lecture.

Wednesday, 10th March

Wave Generation and Shaping

By W. A. Evans (*University College, Swansea*)

Department of Applied Physics and Electronics, UWIST, Cardiff, 6.30 p.m. (Tea 5.30 p.m.)

Beds & Herts Section

Tuesday, 17th February

The Role of Night Vision Sensors as Flying and Target Acquisition Aids in Future Military Aircraft

By D. E. Humphreys (*RAE Farnborough*)

Mander College, Bedford, 7.45 p.m.

East Anglian Section

Thursday, 26th February

JOINT MEETING WITH IEE

Digital Transmitters above 100 Megabits per second

By P. R. Rowbotham (*Post Office Research Establishment, Martlesham*)

University Engineering Laboratories, Trumpington Street, Cambridge, 6 p.m. (Tea 5.30 p.m.)

South Midlands Section

Tuesday, 17th February

Digital Transmission Radio Relay Systems

By E. S. Doe (*P.O. Telecommunications Development Dept.*)

Golden Valley Hotel, Cheltenham, 7.30 p.m.

Wednesday, 17th March

Electronics in Motor Vehicles

By L. Phoenix (*Lucas Electrical Co.*) Foley Arms Hotel, Malvern, 7.30 p.m.

West Midlands Section

Thursday, 26th February

JOINT MEETING WITH IPOEE AND IEE

Teletext

By B. Pike (*Pye*)

P.O. Training Centre, Stone, Staffs., 7 p.m. (Tea 6.30 p.m.)

Tuesday, 2nd March

An Introduction to Microprocessors

By F. Arthur and D. R. H. Baggs (*City of Birmingham Polytechnic*)

City of Birmingham Polytechnic, 7 p.m. (Tea at 6.30 p.m.)

Tuesday, 16th March

JOINT MEETING WITH IEE

Computerised Telephone System

Speaker to be announced

Lanchester Polytechnic, Coventry

East Midlands Section

Tuesday, 3rd February

JOINT MEETING WITH IEE

Progression of Control and Control Techniques

By J. R. Wooton (*Marconi Radar Systems*)

Lecture Theatre J.002, Edward Herbert Building, Loughborough University of Technology, 7 p.m. (Tea 6.30 p.m.)

Thursday, 11th March

JOINT MEETING WITH IOP

Acoustical Holography

By Professor J. W. R. Griffiths (*Loughborough University of Technology*) Lecture Theatre W.001, Loughborough University of Technology, 7 p.m. (Tea 6.30 p.m.)

Merseyside Section

Wednesday, 11th February

Electronics in Oceanography

By A. J. Harrison (*Bidston Observatory*)

Bidston Observatory, Birkenhead, 7 p.m. (Tea 6.30 p.m.)

Wednesday, 10th March

Electronic Calculators and their Development

By I. Jennings (*Texas Instruments*)

Department of Electrical Engineering and Electronics, University of Liverpool, 7 p.m. (Tea 6.30 p.m.)

Yorkshire Section

Thursday, 19th February

JOINT MEETING WITH IEE

Minicomputer Architecture

By R. H. Brunsill (*Teesside Polytechnic*)

York College of Further Education, 7 p.m.

Wednesday, 24th March

The Impact of Digital Electronics on TV Illustration

By A. A. Trainer (*ITN*)

Yorkshire TV Studios, Leeds, 7.30 p.m.

North Eastern Section

Monday, 2nd February

JOINT MEETING WITH IEE

Charge Coupled Devices

By D. J. Birt (*GEC*)

Merz Court, University of Newcastle-upon-Tyne, 6.15 p.m. (Tea 5.30 p.m.)

Wednesday, 3rd March

JOINT MEETING WITH BRITISH COMPUTER SOCIETY

Privacy and Security of Information systems

By C. P. Marks (*President, BCS*)

University of Newcastle-Upon-Tyne, 7 p.m. (Tea 6.30 p.m.)

North Western Section

Thursday, 12th February

Railway Control Systems

By Dr. Merryweather (*Cambridge CAD*)

UMIST, 6.15 p.m. (Light Refreshments 5.45 p.m.)

Wednesday, 31st March

JOINT MEETING WITH IEE

Ceefax

By a speaker from the BBC Research Department

University of Manchester Institute of Science and Technology

Northern Ireland Section

Tuesday, 10th February

Kilroot Power Station

By J. McIlwaine

Ashby Institute, Stranmillis Road, Belfast, 6.30 p.m.

Thursday, 12th February

JOINT MEETING WITH I PROD E

Fuel Resources in Northern Ireland

By D. McVitty (*Department of Commerce*)

Ulster Polytechnic, 7.30 p.m.

Tuesday, 17th February

Film: The Social Computer

Ashby Institute, Stranmillis Road, Belfast, 6.30 p.m.

Tuesday, 2nd March

Space Heating

By D. E. Shackleton

Coleraine Technical College, 7.30 p.m.

Tuesday, 9th March

Recent Development in Northern Ireland's Telecommunications System

By H. W. Topping and N. D. Beck

Lecture to mark the centenary of the invention of the telephone

Ashby Institute, Stranmillis Road, Belfast, 6.30 p.m.

Wednesday, 10th March

Megaw Memorial Prize Lectures

Ashby Institute, Stranmillis Road, Belfast, 6.30 p.m.

Tuesday, 16th March

Nuclear Propulsion in Submarines

By Lt.- Com. J. P. Bullard

Ashby Institute, Stranmillis Road, Belfast, 6.30 p.m.