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Transistors

t was just over ten years ago, on June 30th 1948, that the Bell Telephone ,aboratories announced the invention of the transistor. Bardeen and 3rattain, in the course of fundamental research into the electrical properies of solids, discovered that a metal point upon a germanium crystal vhen carrying forward current could influence the reverse current in a imilar point contact nearby. As a result of this observation, Shockley, vho had initiated and directed the research programme which led to the ransistor, developed a new theory of conduction in semiconductors, in vhich he postulated the junction transistor many months before the first one was made. In recognition of their work in this field these three shared the 1956 Nobel Prize in Physics.

Semiconductors, which have electrical properties intermediate between those of metals and insulators, rely for their conductivity on the presence of current carrying electrons or holes, the density of which may be less than one current carrier for every 10^9 atoms. The number of current carriers can be controlled by varying the number of impurity atoms in the semiconductor, using metallurgical techniques. More important, the current flowing through a semiconductor can be controlled by changing its electronic structure, e.g. by the application of a potential which may cause the injection or extraction of carriers, or by the generation of carriers by infra-red radiation.

All device development is dependent on the properties of the starting materials which are available, and it was for this reason that nearly all the transistors up until 1955 used germanium as the basic material. It was not until the silicon metallurgical techniques improved that silicon devices, with their potentially higher power handling ability and higher operating

temperature, were produced. The metallurgy of the Group III-V compounds (e.g., gallium arsenide, indium antimonide) is still under development, and for this reason very few devices using these compounds are available. The high quality of the semiconducting crystals, associated with the techniques of solid state diffusion, has made it possible to increase the cut off frequency of germanium diffused base transistors to 1,000 megacycles, and the power handling ability of silicon transistors to greater than 70 watts.

A new electronic era started with the invention of the transistor and many different types of semiconductor devices (e.g. high frequency transistors, power transistors, switching transistors and diodes, photo transistors, power rectifiers, microwave mixers) have been developed having some advantages over vacuum tubes, such as conservation of space, weight and power, with possibly greater reliability. Originally it was thought that transistors might replace vacuum tubes; this has not been the case so far, but they have made it possible for us to go beyond some of the practical limits set by vacuum tubes; in fact they have been used for the development of new equipments, and computors, data handling equipment and electronic telephone exchanges account for a large proportion of the transistors used to-day. The production of transistors in the U.K is less than 10% of that in the U.S.A, which was 29 million units in 1957, and it is forecast that it will exceed 250 million units by 1965.

With the development of very high frequency transistors and microwave diodes for use in parametric amplifiers, it is expected that semiconductor devices will play an important role in the communications of the future.

W. E. COPSEY

METALLURGY OF SEMICONDUCTORS, IN PARTICULAR GERMANIUM AND SILICON

By A. J. GOSS, Ph.D, B.Sc.

id state devices are becoming of increasing importance in the world of tronics, augmenting, and to some extent replacing, valves, with which the ineer has become relatively conversant. New techniques are involved in the paration of semiconductors, not the least important of which may be termed miconductor metallurgy." These processes of material preparation such as ting, alloying, polishing, etching, surface examination and crystallo- phic control are metallurgical methods applied and extended to semi- ductors, and, as such, are considerably removed from normal electronic ponent technology. The purpose of this article, therefore, is to give the rs of semiconductor devices some insight into the many problems and rare asures of dealing with the basic semiconductor material and at the same e providing sufficient references for more detailed examination of particular ects of the work.

TERIALS

semiconductor materials at present dominating the scene are manium (Ge) and silicon (Si), although there are many other potentially ful semiconducting elements and compounds which have been investi- ted. An indication of the scale of commercial semiconductor activity is en by the current annual production, which is of the order of 100,000 lbs. germanium(1) and 20,000 lbs. of silicon(2). As far as is known, no signifi- nt quantity of any of the complex semiconductors is being used, but it uld be unwise, however, to disregard completely consideration of these. r example, the Group III-Group V materials, in particular indium timonide (InSb), gallium arsenide (GaAs) and other combinations such silicon carbide (SiC) and Ge-Si alloys, possess unique properties, but the ficulties associated with the preparation of these materials are erently so much greater than for the pure elements, that their investiga- n has been limited, to a large extent, to research work. A brief, readable view of intermetallic semiconductors by Minden(3), and more compre- nsive studies by Pincherle and Radcliffe(4), and Cunnell and Saker(5) are ilable. As a result, of course, of the demand for germanium and silicon, ge scale commercial effort has gone into the problems of producing em in semiconductor grade, while the complex semiconductors are, in

many cases, only available in the chemically pure elemental state, because of the small requirements. The present review will, therefore, deal mainly with germanium and silicon.

The solid of the semiconductor may be considered in some respects as analogous to the vacuum(6) or gas(7) of the valve. Electrons can move freely in a vacuum or in a highly perfect crystal. Hence the basic requirement for high purity and perfection of semiconductor single crystals. It should be pointed out that the term single crystal has a scientific connotation distinct from the popular one. A crystal might be visualized as having distinct and regular faces but in fact the macroscopic surface is unimportant and in metals and semiconductors the single crystal surface is often apparently curved. A single crystal is defined as a volume in which the atoms of the crystal are on one regular network throughout, oriented in one particular crystalline direction. In practice, deviations from absolute perfection occur which are of the order of seconds of arc for the best crystals(8). When a specific crystal face is of importance in semiconductor metallurgy, the external specimen face may be made to coincide with the crystal plane by suitable specimen preparation.

PREPARATION OF PURE SEMICONDUCTORS

Basic material for the semiconductor, using the term now to apply to germanium and silicon in particular, is prepared by chemical and metallurgical manufacturers in various parts of the world. In the United Kingdom, Johnson Matthey have prepared large quantities of germanium dioxide from flue dusts. Germanium originating in the Belgian Congo is refined for Union Miniere in Belgium with an output(9) of the order of 50,000 lbs. per annum. The final product is specified in terms of its electrical resistivity (50 ohm cm. or 30 ohm cm.) to indicate its purity to the purchaser. In the United States the Eagle Picher Co. and Sylvania Electric Products Inc. are large producers of germanium. Silicon of semiconductor grade, i.e. the very highest purity, was at one time available only from Du Pont (U.S.A) and they are still producing very large quantities, but alternative supplies are now available, e.g. from Pechiney in France and, more recently, from I.C.I in England. The difficulties in preparing semiconductor grade materials make the costs high. At present germanium sells at 3s. per grm. (density 5·3, 16s. per c.c.) and silicon sells at 5s. 3d. per grm. (density 2·3, 12s. 9d. per c.c.).

Elements required for preparation of other semiconductors are purchased, in as pure state as possible, from the usual manufacturers or agents. Johnson Matthey of London, for example, can provide a wide range of pure elements. In general such elements have to be further purified before they can be used to prepare crystals.

Purity is certainly one key to the semiconductor problem. This may be

-emphasized by a calculation in terms of the electrical resistivity of the miconductor. Free electrical carriers are generated in the form of electron-ole pairs by the heat vibration in the semiconductor lattice so that the urest germanium would be 55 ohm cm. and the purest silicon would be 50,000 ohm cm. resistivity at room temperature. In addition it has been emonstrated(11) that, for group IV elements (Ge and Si in particular), ch atom of a group V impurity (e.g. Sb, As, or P) can contribute an ectron and each atom of a group III impurity (e.g. B, Al or Ga) a hole absence of an electron. Each hole or electron can behave as a free harge carrier. Then such free carriers from impurities give extrinsic onduction, in addition to the intrinsic conduction brought about by ermal generation. It is possible to calculate the approximate purities ith respect to group III and V elements which must be achieved in order have control over the extrinsic (impurity) conduction. Taking a mplified picture,

$$\frac{1}{\ } = \sigma_n = ne\mu_n \text{ for n-type (electron)} \qquad (1)$$

nd

$$\frac{1}{\rho_p} = \sigma_p = pe\mu_p \text{ for p-type (hole)} \qquad (2)$$

here

ρ = resistivity ohm cm.

σ = conductivity ohm^{-1} cm.$^{-1}$

n, p = number of free carriers cm.$^{-3}$

e = electronic charge = $1{\cdot}6 \times 10^{-19}$ coulombs

μ = mobility cm.^{2} volt^{-1} sec^{-1}

nd the subscript n refers to n-type and p to p-type

hen for example

1 5 ohm cm. n-type germanium, to calculate n, using Equation (1).

$$\frac{1}{5} = 0{\cdot}2 = n \times 1{\cdot}6 \times 10^{-19} \times 3600 \text{ ohm}^{-1} \text{ cm.}^{-1}$$

$$\therefore n = 3 \times 10^{14} \text{ Electrons cm.}^{-3}$$

ince there are 4×10^{22} germanium atoms per c.c. it can be seen that an npurity of one part in 10^8 of group V element will be detectable. For 00 ohm cm. p-type silicon, to calculate p, using Equation (2).

$$\frac{1}{100} = 0{\cdot}01 = p \times 1{\cdot}6 \times 10^{-19} \times 480 \text{ ohm}^{-1} \text{ cm.}^{-1}$$

$$\therefore p = 1{\cdot}3 \times 10^{14} \text{ holes cm.}^{-3}$$

number (approximately 10^{15} cm.$^{-3}$) of free carriers present at room temperature.

Before leaving the subject of preparation of pure semiconductors it should be pointed out that an inescapable problem associated with semiconductors is that of impurity determination. While the final assessment of material may be made on grown crystals, a need arises for earlier measurement to check on the purification processes, and then all the most refined tests for trace impurities are called for. Some discussion of these problems has been given by James([12]).

PREPARATION OF THE SINGLE CRYSTAL SEMICONDUCTOR

Having purified the semiconductor it is now necessary to prepare the pure material in an ideal form, i.e. in the single crystal state for experimental or device use. There are many methods of growing single crystals: the most comprehensive published reviews([26, 27]) deal with non metals as well as metals. A summary on crystals growing of metals by Holden([28]) is more directly applicable to semiconductor work. The method used for preparation of semiconductor single crystals is, almost invariably, that of solidification of the molten material. In effect, temperature conditions are controlled to allow the melt to solidify slowly on to a seed of single crystal. Of the classic methods, the ones in use are the horizontal technique after Goetz([29]), and the vertical pulling technique after Czochralski ([30]). The horizontal method is preferred for bulk material preparation because, in the author's opinion, of one overwhelming advantage—that it can provide large ingots of uniform resistivity along the length([15, 18]). This, coupled with fully automatic growth procedure, makes for high quality semiconductor available at low cost. The vertical pulling technique does have some advantages and is at present largely used for silicon because no satisfactory crucible is available for horizontal silicon crystal growing. The advantages of these two techniques have been discussed elsewhere([18]).

The horizontal technique used in the Marconi Research Laboratories for germanium will be briefly described. In this type of apparatus, Fig. 1, the quartz furnace tube is heated by a temperature-controlled platinum furnace, and most favourable growth conditions are achieved by water-cooled muffles at the ends of the furnace. Close control of the temperatures is essential for production of high quality ingots. Zone refined germanium, ideal in shape and size of course, fits into carbonized quartz boats, together with a seed crystal. With the tube filled with inert gas, the furnace is brought into position to melt part of the seed and join it on to the zone-refined ingot. An automatic traverse then passes the liquid zone through

he whole length of the ingot resulting in one single crystal. It may be een in Fig. 1 that the quartz tube, crucible and germanium are all tilted a slight angle (about 5°) which is necessary to keep a constant ingot ross-section[31]. In the simplest case, when high purity crystals are equired, no impurity (so-called "dope") is added. When a particular esistivity of germanium is required a suitable weight of germanium-npurity alloy can be conveniently placed so that it becomes part of the nolten zone, and hence dopes the whole ingot as the molten zone is swept long. Very uniform resistivities, ± 5%, are obtained for 85% of the rystal length, as discussed in detail by Cressell and Powell[18].

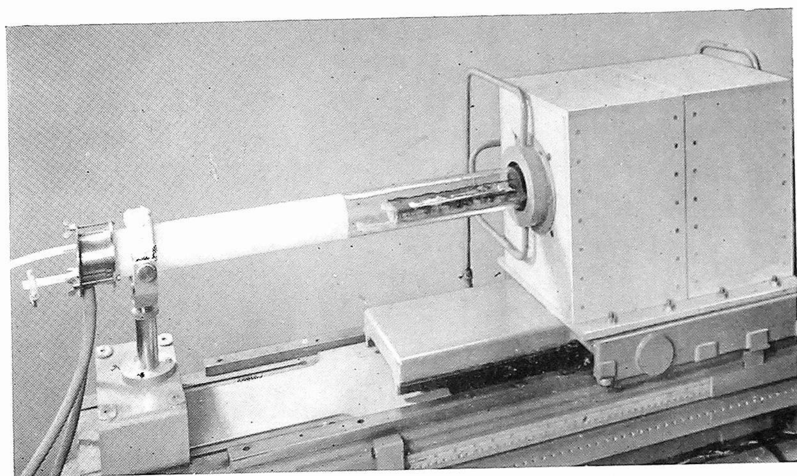

Fig. 1. Single crystal furnace for germanium

The vertical technique, correctly called crystal pulling, is advantageous in that the crystal solidifies without contact to the crucible holding the melt, and hence silicon crystals are successfully pulled. (The method is also used for germanium and other semiconductors, e.g. InSb.) Other advantages of crystal pulling are the symmetrical shape, the large cross-section and the convenience of single and double doping, i.e. the preparation of p/n and multiple p/n structures in the crystal. But the inherent disadvantage remains, in that as the melt is progressively solidified the impurity in the semiconductor steadily concentrates and a normal freezing distribution occurs[15]. Hence, except for boron doped silicon in which segregation is negligible, there will be a variation of approximately 50% in the resistivity for the first half of the crystal and then even more rapid changes towards the tip. Some compensation for this increasing concentration of impurity along the crystal length may be obtained, for example by changing the growth rate (ref. 32, p.101), or by diluting the melt[33, 34], or by vacuum reduction of impurity[35]. The crystal pulling technique appears to lack the beautiful simplicity which characterizes the horizontal method.

The type of apparatus used for silicon crystal pulling in this laboratory is shown in Fig. 2 and the crystal growing operation may be briefly described as follows. The high purity silicon is placed in a pure quartz crucible which fits into a graphite susceptor. This assembly is surrounded by an inert gas atmosphere in a quartz envelope (Fig. 2) while RF power at 400 kc/s heats the graphite susceptor and thus melts the silicon. Temperature in the system is adjusted so that a single crystal seed, about

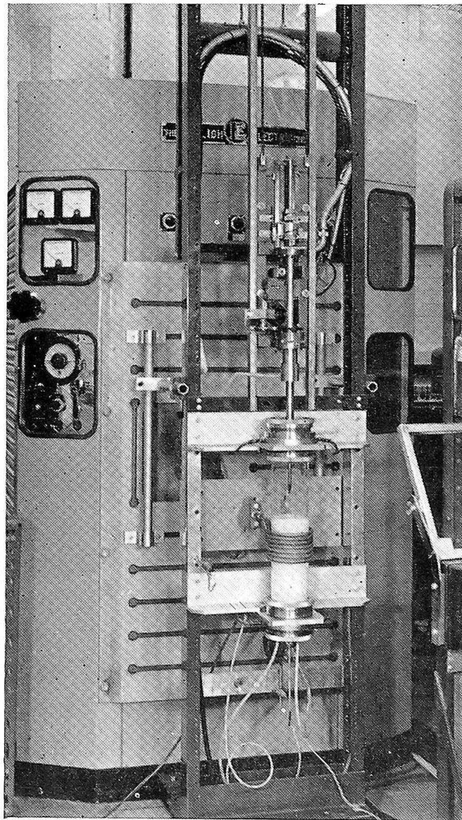

Fig. 2. Single crystal furnace for silicon

0·5 × 0·5 cm., can be dipped into the melt, brought into thermal equilibrium and then pulled out at about 10 cm/h, so growing a silicon crystal 75 g. in weight. Crystal dimensions can be controlled by adjustment of temperature, or pull rate, or rotation rate of the seed crystal (the seed and growing crystal are rotated about the growth axis to homogenize growth conditions)[36]. Dope can be conveniently added by dropping it into the melt before or during the crystal growth. By successive doping, say n- and then p-type added to a p-type melt, it is possible to grow crystals with a p-n-p structure suitable for transistors. A most comprehensive review of germanium crystal pulling, theory and practice is given in ref. 32.

Crystals of germanium grown in the horizontal apparatus may be several llogrammes in weight, those grown in the crystal puller are, in general, naller although crystals of germanium 6 inches and of silicon 4 inches in ameter have been grown[37]. Silicon crystal pullers similar in performance that shown in Fig. 2 may have direct heating[38] or vacuum[35] enclosures istead of RF heating and gas ambient. The relative merits of these ethods are still under discussion. A major problem associated with ne choice of a crystal puller is that of the reactivity of liquid silicon. he silica (SiO_2) crucible surface is dissolved by molten silicon and hence xygen is detected in the silicon crystal[39]. Not only is this oxygen itself eleterious but it is indicative of other impurities so dissolved. To over-ome such problems there is now available very high purity silica synthe-zed from semiconductor grade materials[40], and even better, there is ne use of the floating zone technique with wider application to crystal rowing. It is possible by this method to prepare long single crystals of omogeneous high resistivity silicon[22] without contamination from silica. great deal of this work is in the experimental stage, so that its impact n silicon technology cannot yet be assessed.

Other methods of producing single crystals are mainly of academic nterest. For some semiconductor compounds, e.g. lead selenide (Pb Se), rowth from the vapour can be used to prepare very fine crystals with cm. dimensions[41]. Great experimental care is necessary to produce uch large crystals from the vapour and similar precautions would appear o be necessary to grow semiconductor crystals from solution in a metal. No recrystallization processes occur in germanium or silicon nor can apour or electrolytic deposition provide significant single crystals.

Hence, to summarize, semiconductor single crystals are usually prepared rom the melt with elements added as necessary to provide the electrical onductivity required. This is most readily accomplished for germanium y the horizontal technique and, for silicon, with greater difficulty and xpense, by the vertical technique.

EVALUATION OF THE SINGLE CRYSTAL

The single crystal semiconductor has to be evaluated in terms of certain physical and electrical properties. Firstly, the single crystal nature of the ngot has to be verified and subsequently checked for microscopic imperfec-tions by measurement of the dislocation density in the crystal, as described below. Then the electrical characteristics of the semiconductor, namely the conductivity type (n or p), the resistivity, the concentrations of free carriers and the lifetime of injected carriers should also be examined (ref. 34, chapter 20). The evaluation of material will, needless to say, depend on time, tests available and final material use.

The orientation of a single crystal is the relationship between the crystallographic axes and the specimen. It is usual to grow crystals with axial symmetry, e.g. [100] or [111]. Pulled single crystals then have growth faces indicative of this symmetry(36). In most cases a visual examination of the exterior of the ingot will reveal imperfections in the crystal structure, which can be confirmed by chemical etching or X-ray methods, if necessary. Assuming the crystal to be free of major flaws such as twins or lineage (see ref. 42 for definitions) then microscopic defects in the crystal lattice known as dislocations can be quantitatively revealed. These dislocations are discontinuities in the atomic arrangement of the crystal and, therefore, on a very fine scale. They can be made visible because the strained region associated with a dislocation is thousands of lattice cells in extent. This strained region can be shown up by its differential chemical etching—hence etch pits (Fig. 3)—or by special X-ray study of crystal

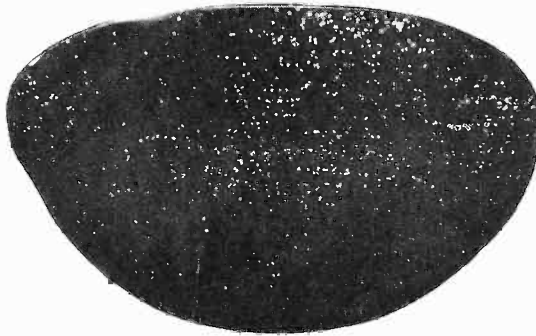

Fig. 3. Dislocation etch pits on germanium

perfection(44) or by "decoration" with impurity(45). A fairly consistent picture of dislocations, in particular edge dislocations, is obtained by these methods and a density of dislocations (ρ) can be stated. For example, in the specimen of Fig. 3, $\rho = 10^2$ cm.$^{-2}$. Germanium crystals with densities of dislocations 10^6 to 10^4 cm.$^{-2}$ were common(44), but improved methods have produced material with approximately 10 cm.$^{-2}$ while a special technique for producing silicon crystals a few grammes in weight without dislocations has recently been published(46). It must be stated, however, that correlation between electrical properties of semiconductors and the density of dislocations has been disappointing. Nevertheless, the observation of a very rapid movement of impurities along edge dislocations(45) makes them of increased importance in devices prepared by diffusion in the solid state.

The electrical measurements on the single crystal semiconductor are obviously of importance but it would be inappropriate to refer to them in any detail in the present metallurgical context. The thermo-electric effect

used to check the n- or p-type predominance in the material. Hot and ld probes, connected in series with a galvanometer, are pressed on to e specimen. The positive or negative nature of the majority carriers is dicated by the corresponding galvanometer deflection. Precise data are btained from resistivity measurements, made with a combination of rrent and voltage probes by one of a number of available methods(36). rom these resistivity measurements the number of uncompensated ajority carriers can be calculated. However, for a complete determination the numbers of donors and acceptors, a low temperature Hall effect easurement has to be made (34, 47). Finally, a most important parameter the minority carrier lifetime. Lifetime is a measure of the time for which rrent carriers injected by electrical contacts or by incident light remain e in the semiconductor, and lifetime is, therefore, vital for particular vice applications. Details of measurement of lifetimes are given in unter(34).

Other measurements on semiconductors can, of course, give further formation about the material, e.g. infra-red absorption has been shown) to indicate the presence of oxygen in silicon, which can play an portant part in its electrical characteristics. But such other measureents are seldom used on routine basis and the performance of the device self provides the final material check.

ETALLURGY OF DEVICES

hile a homogeneous single crystal semiconductor is essential for fundaental measurements and also for some device fabrication, semiconductor vices in general consist of single crystal material of more than one conictivity type. The simplest example is the p-n (or n-p) junction, i.e. ode. The next stage is the three layer transistor structure, the n-p-n r p-n-p), and more recently four layer structures, e.g. n-p-n-p with yratron characteristics, have been developed. This further stage of miconductor metallurgy may be called device metallurgy in which gions of single crystal are controlled in conductivity type and in resisvity. An account of the principles, metallurgy and applications of p-n nctions has been given (48) (also in ref. 34, chapter 7) and a recent R.E publication (49) gives comprehensive up-to-date surveys and many ferences. A few examples are described below to typify the metallurgy. he number of ways of forming localized regions of controlled resistivity almost as numerous as the types of devices so made but three broad assifications can be given.

) DEVICES FORMED DURING CRYSTAL GROWTH

he first and most obvious method of junction preparation is by addition dope to the melt, and hence to the crystal, in the crystal puller. Con-

siderable theory and some experimental results that are obtained with such transient changes in impurity concentration are dealt with in Transistor Technology, Volume 1 [32]. Doping a p-type melt with n-type impurity can thus produce a p-n junction and by double doping, a p-n-p junction. Only one such junction can normally be so prepared in one pulled crystal, unless evaporation of the impurity [35] can be used to recover the original p-type melt. An alternative technique has been tried [50] in which two melts, one p-type and one n-type, are used sequentially.

The grown junction can be sliced into many sections, each section being an individual device. These devices have to be mounted, with electrical contacts, surfaces prepared and the whole suitably encapsulated. Needless to say many problems have to be overcome in these processes, but the final product can be a silicon grown junction (n-p-n) transistor with 150 mW dissipation. In grown junction transistors the thickness of the base region, i.e. the p-region in an n-p-n, cannot be readily controlled below 0·0005 inches thickness, thus setting an upper limit of about 10 Mc/s to the operating frequency. The lack of control of base thickness is largely due to the time constants involved in mixing the dope in the melt.

Other variations in the crystal-growing procedure may be used to produce junctions in a crystal. By changing growth rate [51] or seed rotation rate [52] the relative segregation of two impurities can be modified so that the crystal changes conductivity type while a short length of crystal is grown. However, the control of base width would appear to be even more difficult than in double doping. Finally a crystal growing trick which can be used to give more abrupt junctions is sometimes used. This is "melt-back" in which a layer of crystal is melted off while the added impurity is being mixed in the melt and then crystal growth is continued from the doped melt.

(*b*) DEVICES FORMED AFTER CRYSTAL GROWTH BY ALLOYING

After the single crystal has been grown and cut into sections, regions of p- and n-type may be conveniently formed by local melting and solidification in contact with a suitable alloying material. For example, a thin layer of indium metal placed on an n-type germanium crystal will, when heated, melt and then dissolve some germanium. On cooling, germanium heavily doped with indium is frozen out and grows as a p-type layer of single crystal on the original germanium. In this way very large area p-n junction germanium rectifiers are made such as the English Electric Valve Co. VA710, 120 amp rating, which was developed from a research design prepared at Marconi Research Laboratories. Alloying to silicon presents much greater difficulties. For example, on cooling alloyed silicon differences in thermal expansion are greater than those for the corresponding germanium unit, so that greater stresses are set up and cracking

occurs. However, such difficulties can be overcome and large area silicon diodes such as the Siemens-Schukert Si 150 handling 200 amps have been made.

By duplicating the alloying it is apparent that n-p-n or p-n-p structures can be made. Close control of the alloying temperatures will be necessary to give control of the base layer thickness and even so the ultimate frequency of alloyed devices is not appreciably higher than grown junction devices. A significant improvement is made by the newer technique of diffusion.

(c) DEVICES FORMED AFTER CRYSTAL GROWTH BY DIFFUSION

In the last few years significant gains have been achieved by application of another solid state phenomenon, namely diffusion, to device preparation. The resistivity regions are obtained by diffusion of the impurity into the solid single crystal, as has been summarized by Smits ([53]). Thus from an atmosphere of arsenic vapour, arsenic will diffuse into p-type germanium, the penetration of the arsenic depending on temperatures and pressures used. For example, on 1 ohm cm. germanium the p-n junction due to arsenic would be approximately 10^{-4} cm. (i.e. 4×10^{-5} inches) below the surface after one hour at 700°C in a closed system. It is obvious, therefore, that thin layers may be better controlled by diffusion than by alloying, and hence transistors operating to 1000 Mc/s appear possible([54]). Naturally, these gains are not made without some disadvantages arising. The high temperatures necessary to get finite diffusion distances in reasonable intervals of time are responsible for degradation of other semiconductor properties, e.g. lifetime is shortened. If the effective base thickness is reduced to produce a high frequency device, then the dimensions of other parts of the device must also be reduced, so that, for example, emitter and base connections of area 0·002 inches × 0·0005 inches have to be prepared. However, the techniques necessary to deal with these problems are being found and high frequency devices, such as the germanium high-frequency transistor being developed at Marconi Research Laboratories, are becoming available.

(d) OTHER DEVICE TECHNIQUES

Combinations of the three methods given above are sometimes advantageous and in fact it is difficult to specify for some methods of device preparation the relative importance of individual effects. There are a few other rather specialized devices, in particular the surface barrier transistor. In this high frequency transistor small electroplated contacts are used to provide the junction regions. Refs. 34 and 49 refer to the whole range of device production methods.

It would be unfair to give any impression that the device is completed

when three or more resistivity layers have been prepared. The subsequent treatment is equally if not more difficult if first grade transistors are to be produced.

SUMMARY

The metallurgical processes used on the raw semiconductor through to the working device are briefly outlined. Some of the difficulties which arise have been pointed out and some of the new techniques which have been used to overcome these difficulties have been described. In order to give an overall picture of the metallurgy some oversimplification has been necessary and therefore references have been provided, to standard works as far as possible, which give detailed descriptions.

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BOOK REVIEW

A FIRST COURSE IN TELEVISION *by "Decibel,"* pp. 149

Sir Isaac Pitman and Sons, Ltd. Price 15s.

Introductory books on television published in recent years are sufficiently numerous to provide a very wide choice to the prospective reader. One book that is likely to stand high in order of merit is that now under review, written by an author who is responsible for an ever-popular volume of similar standard on wireless.

"Decibel" has an attractive style for the beginner and introduces each subject with a direct approach that dispenses with "padding" and is adequately explicit. The standpoint adopted is distinctly contemporary, although the scanning disc and mirror drum have been imported to aid in the explanation of scanning systems.

The main subjects for which this book will be read are each dealt with in a separate chapter; namely, the vision signal, basic circuits and principles, video frequency amplifiers, wave-form generators, and picture tubes with their associated circuits. Within the limit set by the size of the book, these chapters are well done. Chapter VIII on the reception of television signals is likely to prove disappointing as containing far too little information on actual receiver circuits. This position is not retrieved by the insertion, at the *end* of the chapter, of a diagram and eleven lines of description of the cascode r.f. amplifier. The outline of the picture noise limiter, although correct so far as it goes, fails to have much meaning unless there is an indication to the reader that the noise diode is *in series* with the signal channel.

Television cameras are, on the whole, well treated, the iconoscope being described in sufficient detail to provide an example of general principles. The description of the image orthicon, however, could well have included a note on the nature of the returning amplitude modulated beam to the first dynode. This essential feature of the image orthicon tube is not illustrated in the diagrams and can only be deduced from the description. Incidentally, the sensitivity of the image orthicon is not merely "comparable to that of the human eye," but is much greater.

These minor shortcomings do not obscure the merit of this volume: it is a valuable and up-to-date contribution to the elementary literature on the television art.

THE EFFECTS OF SEED ROTATION ON SILICON CRYSTALS

By A. J. GOSS, Ph.D, B.Sc, and R. E. ADLINGTON, B.Sc, A.Inst.P.

Single crystals of silicon have been pulled in an argon atmosphere from a quartz crucible using seed rotation rates from 0 to 200 r.p.m. The effect of rotation on crystal pulling, the growth interface, dislocations, etching, resistivity, 9μ absorption data and heat treatment of the crystal, are given. A mechanical model of stirring in the melt is described and the results are discussed in relation to the model.

INTRODUCTION

The technique of pulling metal crystals from a melt dates from a 1917 publication by Czochralski(1). There are, however, several other methods(2) which have many advantages over crystal pulling for the preparation of most metal crystals. Crystal pulling, therefore, has been of minor scientific interest until the last decade and the advent of new semiconductor devices. At the present time a considerable quantity, i.e. thousands of kilogrammes, of germanium is being prepared in single crystal form by crystal pulling, although the horizontal technique of zone melting (3, 4, 5) would seem preferable. However, for silicon, crystal pulling is of very considerable importance since the horizontal technique is complicated by the reaction between molten silicon and crucible materials(6). Since the properties of the semiconductor silicon are, to a degree, governed by the growth process, the study of growth parameters is important. The rotation of the seed and crystal, which is normally employed during crystal pulling, is dealt with in detail in the present paper.

Little general discussion of the effects of seed rotation has been published. Some of the important features have been emphasized, in particular by Burton *et al.* (7, 8). Their theory is built on a picture of a narrow layer ($\sim 10^{-2}$ cm.) of melt immediately adjacent to the growing interface through which impurity diffuses, with a thoroughly mixed melt beyond the narrow layer. The experimental results obtained by Burton *et al.*(8) for germanium confirmed the expected effects on the segregation of impurities during the growth process of (a) change of growth rate and (b) change of rotation rate. Thus in a slowly stirred melt an increase in growth rate results in a considerable increase in K (K = the effective segregation coefficient, $K < 1$), and in a rapidly stirred homogenized melt increase in K with growth rate is small. Hall (1953)(9) has suggested that K is changed as well as the mixing in the melt. He observed that a change in rotation rate from

60 to 360 r.p.m. did not appear to have much effect compared with a change in growth rate. More recently, experimental work has been described by Bridgers[10] in which the change in K was successfully used to make multiple p-n structures.

In silicon the effects of stirring have raised other problems. Rotation was reported by Hannay *et al.*[11] to give trapping in silicon crystals and subsequently Fuller *et al.*[12] reported heat treatment effects. The work of Kaiser and his associates has now given a clear picture of oxygen entering the rotated silicon crystal, resulting in optical absorption (e.g. at 9·05μ) and also in heat treatment properties of the silicon. In particular Kaiser and Keck (1957)[13] have stated that the 9μ absorption decreases with the diameter of the silicon crystal and similarly with the rotation rate. Fuller and Logan 1957[14] have reported the corresponding changes for heat treatment. Finally the oxygen content of the silicon has been demonstrated[15] to be a controlling agent in silicon etch pit formation.

In the experiments reported in this paper, the rate of seed rotation has been varied from zero to 200 r.p.m. and the effects on five crystal characteristics have been examined and correlated. The results obtained are shown to fit a proposed model of stirring in the melt.

CRYSTAL GROWING APPARATUS

The silicon crystals have been grown in crystal pullers designed and built in these laboratories. The essential features of the crystal pullers will be described in order that, where relevant, these features may be taken into account. The pulling chamber is a 10 cm. diameter quartz tube, 45 cm. in height, the upper half transparent and the lower half translucent. The tube is sealed to water-cooled stainless-steel ends, by silicone and neoprene O-rings. Inside the quartz chamber, quartz shields and supports are used to hold a stationary graphite (Atomic Energy grade) susceptor, 5·2 cm. in diameter, at the centre of the system. The high purity quartz crucible (Thermal Syndicate C2 type) fits inside the graphite susceptor. Argon of 99·95% purity has been used for most of the experiments, flowing through the chamber at about 2 litres/min.

The susceptor is heated by RF power at 400 kc/s from a 25 kW English Electric generator. Through the lower stainless-steel end plate a thermocouple (Pt/PtRh) is fitted which measures a susceptor temperature. Manual or servo mechanism (Honeywell Brown: Integra, Leeds and Northrup equipment) may then be used for temperature control. The crystal pulling shaft, made of stainless-steel, passes through a Wilson-seal in the upper stainless-steel end plate. A molybdenum reflector is fitted in the top of the pulling chamber to protect the upper end plate from radiation. The crystal pulling motion is obtained from a 16 thread per cm. screw driven through a gearbox by a Velodyne[16] motor-generator.

Rotation of the pulling shaft is either by a small A.C motor or another Velodyne unit, the latter being used for wide ranges of rotation rate. No crucible rotation has been used. Dope is added to the melt from tilting pans feeding into quartz guide tubes.

As far as possible investigations involving change of the seed rotation rate have been made with the minimum number of changes of other variables in the system. In critical experiments, e.g. to compare rotation and non-rotation, the changes in rotation rate have been made during the growth of one crystal.

GROWTH PROCEDURE AND EFFECTS OF STIRRING

The silicon is placed in a clean quartz crucible in the graphite susceptor, and the system is flushed with argon. The susceptor is heated by RF power to about 200°C above its temperature for crystal pulling, melting being completed in twelve minutes. The power is reduced and five minutes

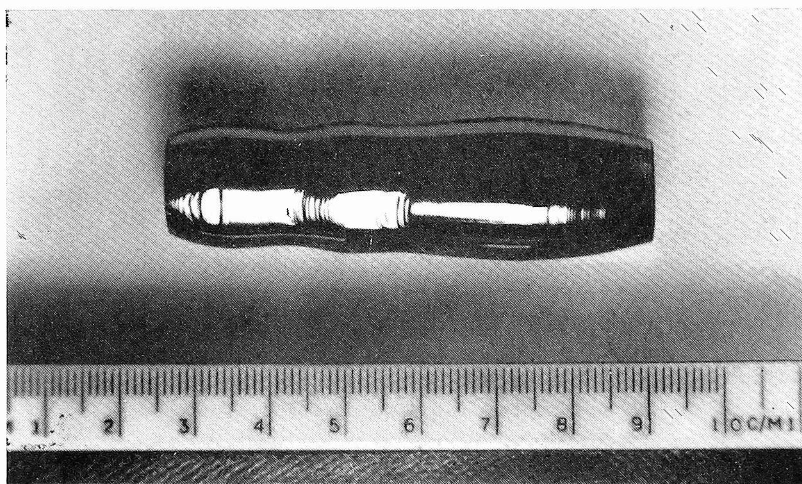

Fig. 1. Silicon crystal showing wide (fast rotation) and narrow (slow rotation) growth flats

allowed for temperatures to steady. The seed, heated by juxtaposition to the melt, is dipped in. Observation of the appearance of the pulling interface (similar in nature to that reported by Marshall and Wickham, 1958)([17]) enables the temperature to be adjusted to give smooth seeding on. According to the rate of stirring with the usual pulling rates of 0·0025 to 0·0006 cm./sec., the temperature is then adjusted to give the required ingot, normally 1·5 to 2·0 cm. diameter with 35 to 50 gm. melts.

The effects of fast stirring are immediately apparent during crystal growing and emphasize that several parameters are inevitably changed by increasing the rotation rate. Thus an increase of rotation rate, while a uniform crystal is being grown, results in the crystal diameter increasing

and, conversely, a decrease in rotation rate results in the crystal diameter decreasing. Marked effects are observed for changes of from 10 to 80 r.p.m. Changes of rotation rate from 3 to 30 r.p.m. or from 80 to 160 r.p.m. have less effect. The external surface of the crystal is also modified by the stirring rate. Wide growth flats ({111} facets) appear for fast rotation and, subsequently, narrow growth flats appear for slow rotation. An example is shown in Fig. 1. Various sizes of growth flats have been obtained in other pulling systems, i.e. wide growth flats have been obtained in a thermally insulated growing chamber and very narrow growth flats have been obtained in a crystal puller with reduced heat insulation. It is felt therefore, that wide growth flats correspond to a low temperature gradient in the melt, adjacent to the growth interface. This would confirm the increase of crystal diameter with stirring, and is in agreement, as shown below, with interface shapes. It should be pointed out that with fast rotation a slightly higher susceptor temperature (approximately 5°C) has to be used and it must be assumed therefore that greater heat loss from the melt then occurs.

EXPERIMENTS ON ROTATION

GROWTH INTERFACE SHAPE

Crystals were grown, as described above, with uniform pulling and seed rotation rates. The size, shape and weight, etc., of crystals were standardized as far as possible. After approximately one third of the length of each crystal had been pulled, dope was added to the melt to delineate the junction. It was known from doping successively at short time intervals that the time constant for dope to reach the complete growth face was of the order of seconds. Hence the p-n junction made by doping the melt

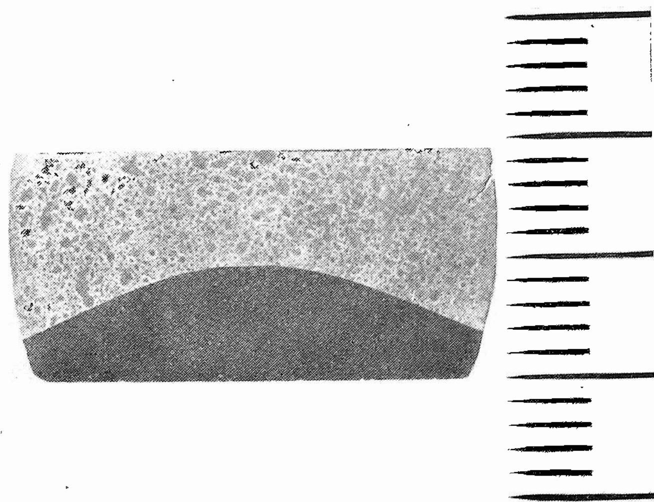

Fig. 2. Growth interface. Mag. × 3

did give a true macroscopic picture of the interface shape. After the crystal had been pulled it was sectioned longitudinally and the p-n junction stained([18]), photographed (Fig. 2) and measured.

Results are shown in Figs. 3 and 4. With a crystal pulling rate of 0·0012 cm./sec., rotation rates of 3 to 80 r.p.m. were used, while with a crystal pulling rate of 0·0006 cm./sec. the rotation rates were 3 to 200 r.p.m. The interface deflection is the distance, in mm., of the maximum depression

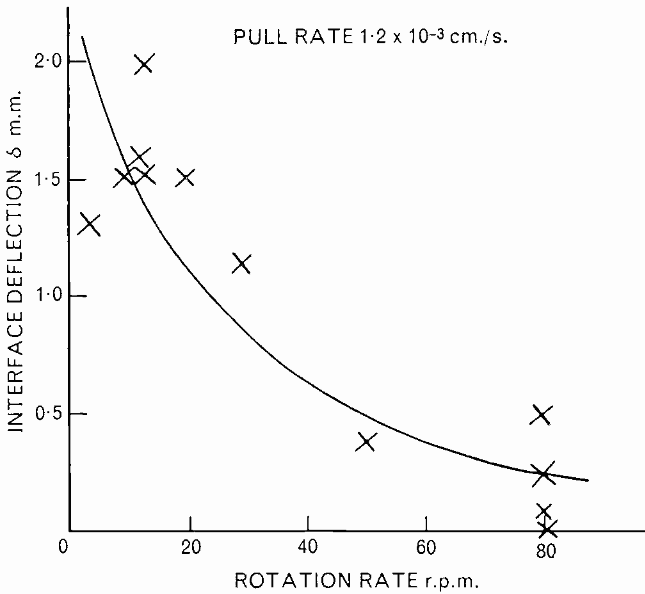

Fig. 3. The effect of seed rotation on the interface shape for $1{\cdot}2 \times 10^{-3}$ cm./sec. pull rate

of the centre of the growing interface below the periphery (Fig. 2). Figs. 3 and 4 giving rotation rate versus interface deflection show data for crystals of average diameter 19 mm. It may be seen that for rotation rates above 50 r.p.m. the interface is appreciably flattened. The same effect has been confirmed for other pulling rates in the range 0·002 to 0·003 cm./sec. With a pulling rate of 0·0025 cm./sec. and slow seed rotation the interface was almost flat while fast rotation caused a reverse curvature.

DISLOCATIONS AND ETCHING

The distribution and density of edge type dislocations as revealed by chemical etching have been studied on (111) cross sections of crystals pulled at various rotation rates. The size and shape of the crystals were kept as uniform as possible. The specimens were ground with alumina A.0 grade 303, and then etched in one part hydrofluoric acid (40%) with five parts nitric acid (95%) to give a polished surface. They were then

etched in SD1 [19] for a few minutes when etch pits, usually very small in size, formed at the edge dislocations. To enlarge these pits the specimens were left for sixteen hours in the Dash (1956) [20] etch and to confirm that these large etch pits developed at the termination of edge dislocations with the surface, the copper decoration techniques of Dash were also followed.

After etching, the specimens were photographed and a typical etch pit

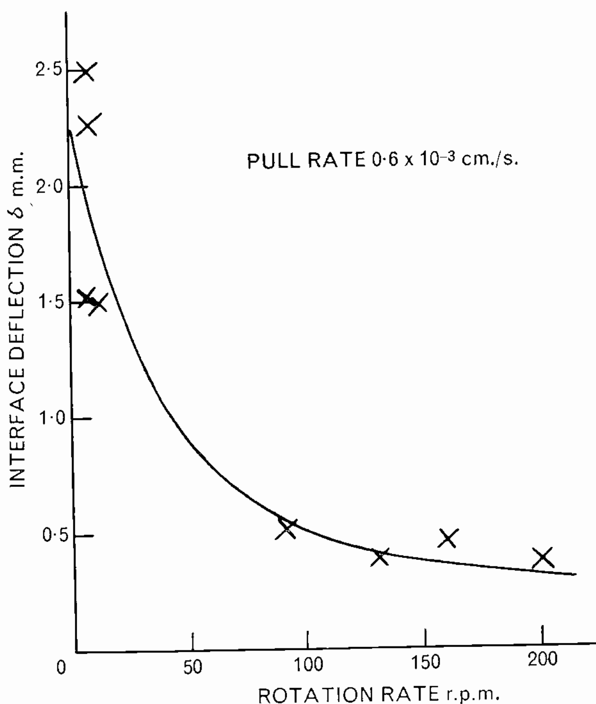

Fig. 4. The effect of seed rotation on the interface shape for 0·6 × 10⁻³ cm./sec. pull rate

pattern on a (111) cross-section is shown in Fig. 5, where the edge dislocations have been caused by slip on the three symmetrical (111) planes. Due to the non-uniform distribution of the etch pits, there was a large range of dislocation densities, in some cases $10\text{-}10^3/\text{cm.}^2$ on each cross section and this made the correlation with rotation rate somewhat difficult. However, when the photographs of the etched specimens were arranged in order of decreasing etch pit density as judged by several observers, the faster rotation rate crystals were seen to have the lower density.

The effects of rotation rate, resistivity value and conductivity type on the background and etch pit etching rate of (111) cross sections of single

crystal silicon have been studied. Fast and slow rotated specimens of high (> 10 ohm cm.) and low (< 1 ohm cm.) resistivity, p- and n-type, were etched together, using the etch described above. With regard to the background it was found that p-type silicon etched faster than n-type, and p-type appeared dull whereas the n-type remained brightly polished. Etch pit sizes were obtained ranging from 6×10^{-2} mm. for slow rotation, low resistivity p-type to $1{\cdot}5 \times 10^{-2}$ mm. for high rotation, low resistivity

Fig. 5. Edge dislocation etch pits on a (111) silicon cross section. Mag. × 4

n-type silicon. Although there was some variation in pit size over each cross section, a comparison between the specimens gave some general results which can be summarized as follows.

1. Etch pits on slow rotated silicon etch faster than those on fast rotated material of similar resistivity and conductivity type as stated by Logan and Peters (1957)([15]).
2. Etch pits on p-type silicon etch faster than those on n-type of similar resistivity and rotation rate.
3. Etch pits on low resistivity p-type silicon etch faster than those on high resistivity p-type of similar rotation rate.

RESISTIVITY

The resistivity in a pulled silicon crystal containing a dominant added impurity follows the segregation relationship of a normal freeze([4]). This segregation, considering $K < 1$, involves a build up of impurity in a layer of melt adjacent to the interface, as considered by Burton *et al.* (1953)([7, 8]). Effective segregation will be influenced by sweeping the melt over this high concentration region, i.e. K will depend on melt mixing. Hence

irring can be expected to affect K and also possibly to redistribute npurity. Changes of K for longitudinal sections, resulting from changes n rotation rate, have been given by Burton *et al.* (1953)([8]) and Bridgers 1956)([10]) but transverse variations in resistivity do not appear to have een reported. Crystals have therefore been grown with various rotation ates and the distribution of gallium impurity has been followed by esistivity measurements.

Crystals were pulled as described above. After a uniform 1 cm. length ad been grown without rotation a pellet of tin-gallium dope was added. The crystal was grown a further 1 cm. without rotation and then subsequently rotated at 10, 30 or 80 r.p.m. Tin-gallium alloy dope was used to nsure that the dope sank immediately. The doped crystal was about ohm cm. resistivity, and no effects of the tin could be observed in eparate experiments. A central longitudinal section was cut from the rystal and then separate longitudinal strips, 2 to 3 mm. in width, cut from his section. Resistivity measurements were made with a two probe unit vith 3 mm. probe spacing. Five or more curves were obtained for each rystal and have been checked with single probe measurements. Fig. 6 hows two sample curves of resistivity along the length of crystals for -30 r.p.m. and for 0-80 r.p.m.

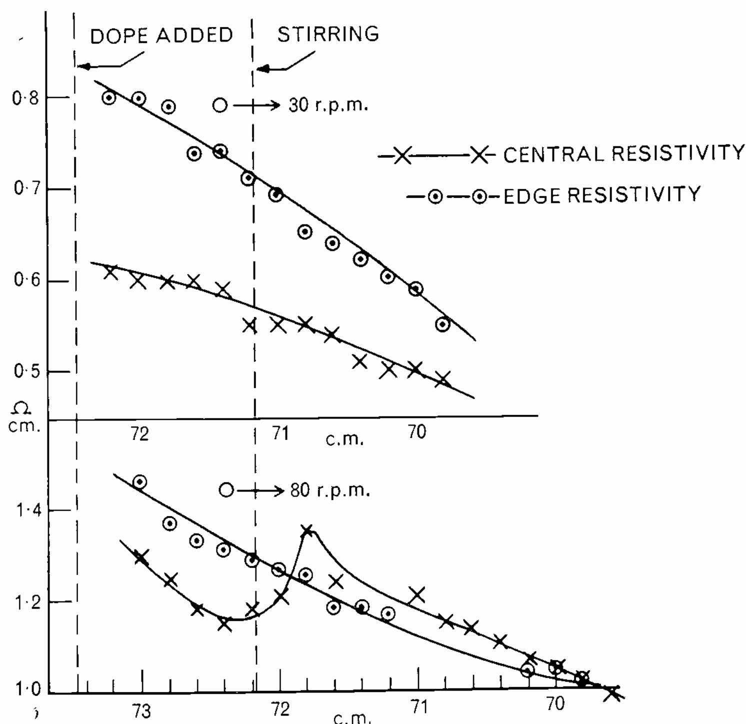

Fig. 6. The effect of seed rotation on the resistivity of gallium doped silicon

Quite a sharp interface was formed where dope was added without stirring. In the unstirred region the impurity concentration varied considerably. Slow stirring appeared to reduce the variation in concentration, but the outside of the crystal was always of higher resistivity. The effect of stirring at 80 r.p.m. was very marked (Fig. 6). The centre of the crystal increased in resistivity from 1·2 to 1·4 ohm cm., but sections 1 to 3 mm. from the edge of the crystal did not. A change in segregation coefficient

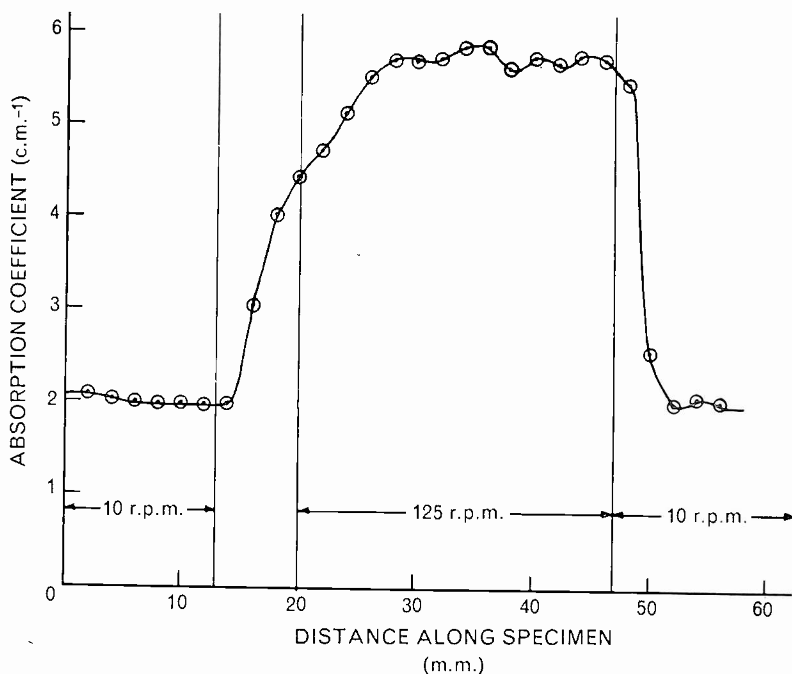

Fig. 7. The effect of seed rotation on the 9μ absorption in a silicon crystal along the growth axis

corresponding to a resistivity change of 20% might be anticipated from the curves given by Burton *et al.* (1953)([8]). Having established fast rotation, the crystal grew with more uniform transverse resistivity, approximately ± 5% across the interface, within the limits of experimental measurement.

9μ ABSORPTION

From the recent work of Kaiser, Keck and Lange (1956) ([21]) it is now well established that oxygen is introduced into pulled silicon crystals due to the reduction of quartz crucibles by the silicon melt. The concentration and distribution of the oxygen in the silicon depends upon various growth parameters including the crystal diameter and rotation rate, the temperature distribution in the melt and the gaseous ambient or vacuum in the

ystem. The concentration of oxygen is determined by measuring its 9μ nfra-red absorption coefficient. This absorption band has been related by Hrostowski (1957)[22] to a silicon-oxygen molecular vibration from bservations of isotopic shifts on the substitution of 0^{18} for 0^{16}, and calibrated by vacuum fusion gas analysis[13].

In the present experiments 9μ absorption data were obtained from ransmission measurements using an S3A Grubb-Parsons infra-red pectrometer. Strain free specimens, with carrier concentrations less than 10^{15} cm.$^{-3}$ from more than twenty (111) grown silicon crystals, were used. Measurements were made every 2 mm. along the length on longitudinal entre sections, with faces ground parallel and optically polished. A range f diameters were studied for crystals, grown as described above, with arious crystal rotation rates, up to 160 r.p.m.

The effect of seed rotation rate is illustrated in Fig. 7. The rotation rate vas changed from 10 to 125 r.p.m. and then after 3 cm. had been grown, lecreased to 10 r.p.m. The 9μ absorption coefficient can be seen to change rom 2 cm.$^{-1}$ to 5·7 cm.$^{-1}$ over the region in which the rotation rate was ncreased, and to revert to 2 cm.$^{-1}$ when the rate was reduced. By taking nto account the diameters of the crystals, the relationship between the μ absorption and the rotation rate up to 160 r.p.m. can be accurately hown. Fig. 8 shows data for three diameters, in which absorption rises

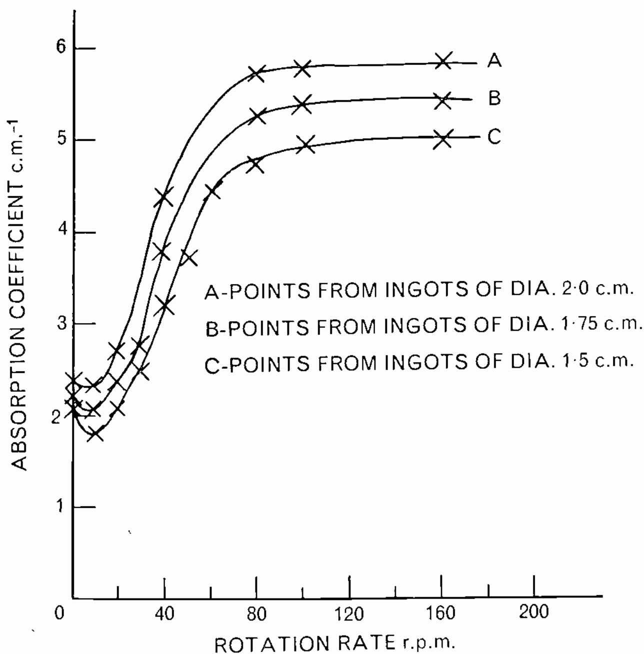

Fig. 8. The effect of seed rotation on the 9μ absorption for three crystal diameters

from about 2 cm.$^{-1}$ at low rotation rates to 6 cm.$^{-1}$ at 160 r.p.m. As shown by Kaiser and Keck (1957)[13] this corresponds to a range of oxygen content of four to sixteen parts in 10^6 by weight. Slow rotation, 10 r.p.m., is seen to reduce the 9μ absorption below that for zero rotation for crystal diameters less than 2 cm. A linear relationship is shown to exist (Fig. 9) between the 9μ absorption at the centre of a crystal and the diameter over the range considered, for both slow and fast rotation rates.

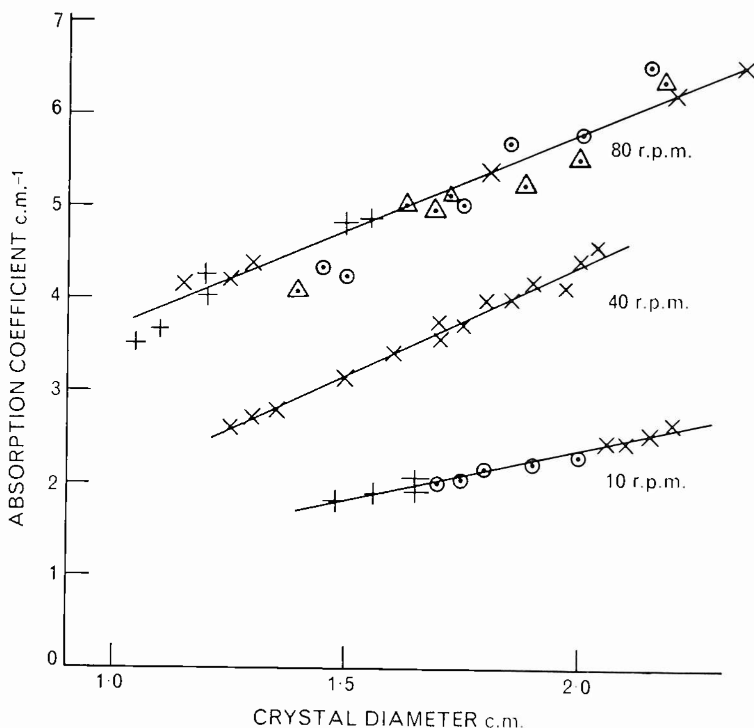

Fig. 9. The effect of crystal diameter on the 9μ absorption for three rotation rates

Measurements have also been made of the variation of 9μ absorption perpendicular to the length of the crystal, for fast and slow rotation rates. 9μ absorption is a maximum at the centre and decreases outwards, being about 5% less for silicon 1 mm. from the edge, and considerably reduced in the skin. Kaiser and Keck (1957)[13] suggest that this lack of oxygen is due to evaporation of SiO from the surface of the melt.

These observations on 9μ absorption do no apply to the last few cm. of the silicon crystal, where growth conditions, melt size, etc., are rapidly changing.

HEAT TREATMENT

Heat treatment of rotated silicon crystals was pointed out by Fuller *et al.* (1955)[12] and a comprehensive study of heat treatment was published by Fuller and Logan in 1957[14]. They have stated that heat treatment at low temperatures which gives rise to donors in the silicon is related to the rotation rate and to the crystal diameter. An increasing number of donors, N_D, was found with increasing rotation rate and crystal diameter. In the present experiments the principal effort has been made to study the results of change of rotation rate and in so doing the importance of crystal diameter had become apparent. The extremely close correlation between 9μ absorption and heat treatment measurements has provided valuable confirmation of results.

Heat treatment has been carried out on specimens from crystals prepared by the standard techniques described earlier. The range 400-500°C has been explored and the maximum increase in N_D was found at 450°C. Experiments have been carried out in chemically clean conditions, using quartz apparatus and argon atmosphere. Two probe resistivity measurements at room temperature have been used to evaluate N_D with a background acceptor level of 5×10^{13}/cm.³. Results were estimated to be accurate to ± 10%.

The increase in donors, N_D, for various rotation rates as a result of a standard heat treatment of 24 h. at 450°C are given in Table 1. The results have been taken for specimens of 1·5 to 2·0 cm. in diameter.

TABLE I

Rotation Rate r.p.m.	Donor increase/cm.³ (24 h. at 450°C)
0–10	$0{\cdot}5 \times 10^{13}$ to 3×10^{13}
40	$1{\cdot}0 \times 10^{14}$ to 15×10^{14}
80–160	$0{\cdot}8 \times 10^{15}$ to 15×10^{15}

For ranges 0-10 and 80-160 r.p.m. any systematic change of N_D is masked by other variables. Fig. 10 shows the relationship between N_D and the crystal diameter for seven crystals grown with rotation rates $\geqslant$ 80 r.p.m. For any one crystal a single line of points is frequently obtained and an exponential function of crystal diameter can be made to fit the correspond-

ing values of N_D. However, due to variation from melt to melt, the overall average data is as represented in Fig. 10.

A set of curves for N_D, 9μ absorption and crystal diameter for a typical crystal is shown in Fig. 11. The increase in N_D, and in absorption at the large cross section is interrupted by a non-rotated section of crystal, with immediate reduction in both parameters. But the curves also contain an anomaly in the *reduction* of N_D and absorption over the length 3-4 cm.,

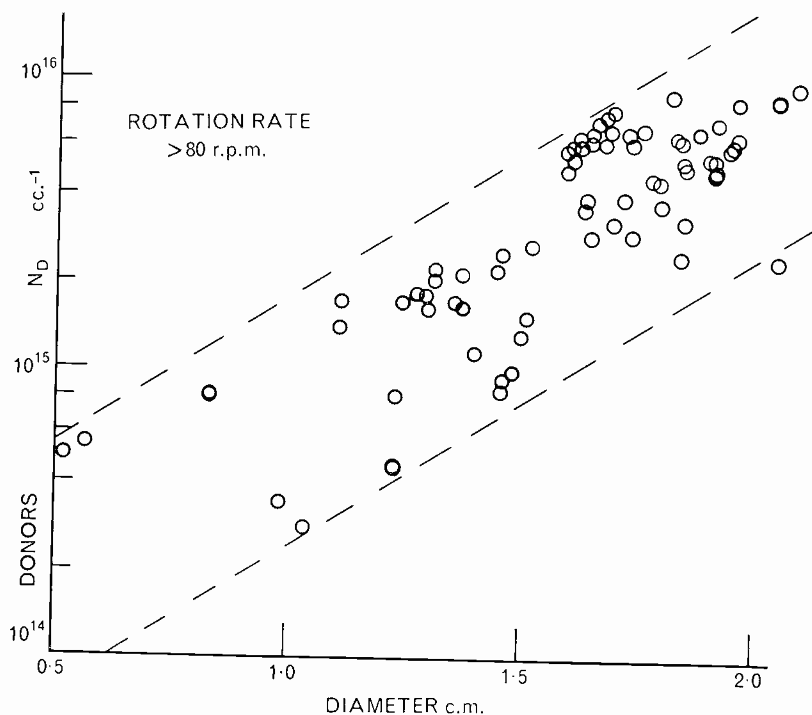

Fig. 10. The effect of crystal diameter on the donor production for a heat treatment of 24 hours at 450°C for rotation rates ≫ 80 r.p.m.

in which the crystal diameter is increasing. Such anomalies are probably due to random instabilities in the system.

From consistent measurements in several ingots with slow and fast rotation rates it is estimated that for fast rotated material N_D during the growth process, i.e. heat treatment in growth, is about 2×10^{14}/cm.^{3}. All fast rotated crystals of normal diameter, 1·5-2 cm., must have had this treatment.

A MODEL OF ROTATION IN THE MELT

The results of experiments, as given above, may be more readily appreciated by first discussing the flow movements in the melt. A mechanical model

has been of particular assistance in giving visual evidence of these movements. For the model an actual quartz crucible has been used, with bottom heat. Water in the crucible has been "doped" with drops of potassium permanganate solution while the crystal has been simulated by brass rods, of various diameters, rotated with a Velodyne motor-generator. The movements of the dye could be observed with and without crystal rotation. Since the viscosity of liquid silicon is not known, glycerine and water-

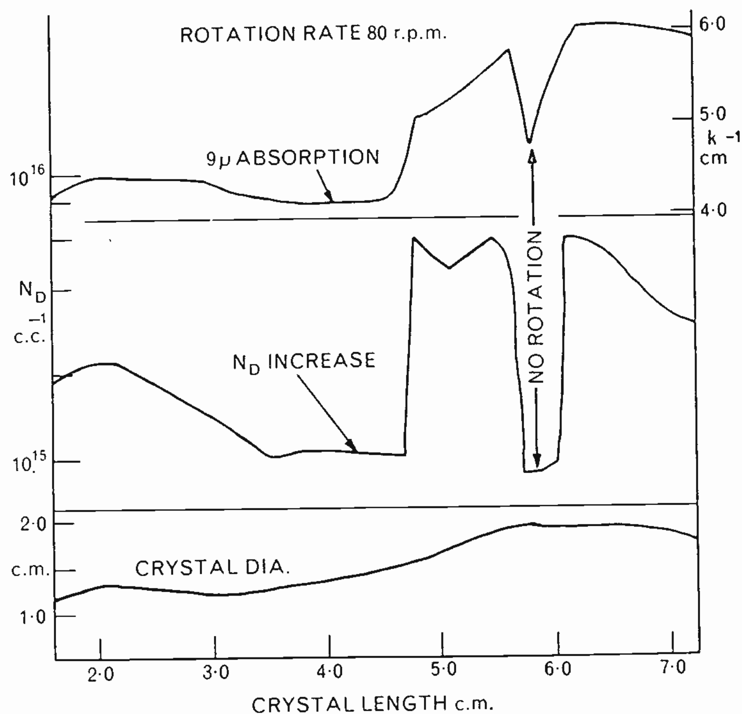

Fig. 11. 9μ absorption, heat treatment, and crystal diameter for a silicon crystal grown at 80 r.p.m.

glycerine mixtures were also tried to provide a range of viscosities for the model. The essential features of the melt circulation remained the same, although with changed time constants. The water model is felt to be a very reasonable one and the glycerine experiments confirm the results.

With no seed rotation, thermal effects in the melt are observed. The melt rises at the edge, the hottest part of the system, and the introduction of a cold crystal gives an immediate downward flow in the centre of the melt, which continues even with a warm crystal. If slow stirring say 10 r.p.m. is switched on, then there are no marked changes in the flow system. The edge of the melt is not rotated and downward central flow continues. Without thermal stirring, dope dropped into a water "melt"

with crystal rotation at 20 r.p.m. is incompletely mixed even in one minute. Thus thermal stirring is important with slow rotation rates. With fast rotation rates a marked change in stirring occurs. At 60 r.p.m. a central vortex forms which is very stable, rising rapidly and continuously underneath the crystal. Dope is swept rapidly up from the bottom of the melt to the underside of the crystal and then out sideways. Fig. 12 shows potassium permanganate "dope" rising under the "crystal" a few seconds

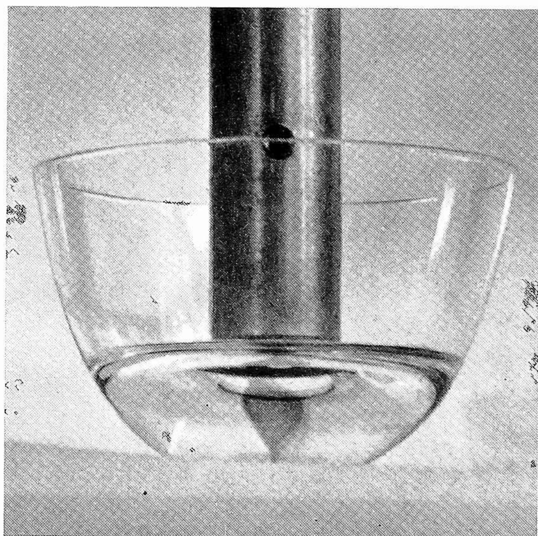

Fig. 12. Model showing central vortex at a "seed" rotation rate of 70 r.p.m.

after doping the (water) melt. Vortex action is introduced in the range 30-60 r.p.m. and, naturally, is enhanced by larger crystals.

Flow due to a rotating disc has been the subject of several mathematical treatments. The case of rotation of an infinite flat disc has been calculated by Cochran (1934)([23]). Streamlines of flow bounded by a single disc for the conditions in which the angular velocity of the fluid is a maximum at the disc have been given by Batchelor (1951)([24]). He shows the disc acting as a centrifugal fan, throwing fluid out in a radial direction and drawing it up axially, as observed in the present model.

It should be noted that crucible rotation, from evidence of the model, gives quite different modes of liquid flow from those described here for seed rotation.

RESULTS COMPARED WITH THE MODEL

(a) GROWTH INTERFACE SHAPE AND DISLOCATIONS

In the model slow stirring was seen to have little effect on the circulation of the liquid. Thermal stirring thus predominates and the associated

mperature gradients in the melt give rise to a curved growth interface, observed for slow growth rates. Rosi (1958)([25]) has made temperature easurements in silicon melts and found temperature differences of 0°C vertically and 40°C radially. The curved interface and curved othermals must result in thermal stresses in the pulled crystal. Higher slocation densities, as have been observed, would therefore be anticipated ith slow seed rotation and curved interfaces.

Since at rotation rates in excess of 60 r.p.m. mechanical stirring of the elt takes over, temperature gradients are reduced. This reduction in radient is shown in crystal pulling effects (e.g. Fig. 2 growth facets) and terface flattening (Figs. 3 and 4) with the same crystal pulling rate. e. 0·0012 cm./sec. Fewer dislocations are therefore observed with fast otation. A similar modification in the growth interface shape and associated duction in the dislocation density may be made by increasing the pulling te from 0·0006 to 0·0025 cm./sec. With a pulling rate of 0·0025 cm./sec. e effect of fast seed rotation on interface shape is in the same sense as at described in Figs. 3 and 4. Since the slow rotated interface is almost at the fast rotated interface is now curved in the reverse direction to at shown in Fig. 1.

Silicon crystals with edge dislocation densities of approximately 0/cm.^{2} have been obtained by using flat interfaces, coincident with (111) lanes. This is analogous to the growth of low dislocation density ger-anium crystals using controlled growth on (111) planes in a horizontal pparatus by Cressell and Powell (1957)([5]) in this laboratory.

)) RESISTIVITY

hermal stirring alone has been responsible for the movement of gallium ope into the non-rotated crystals, and hence resistivity variations across he growth interface are to be expected. Fig. 6 is indicative of such ariations and very large random changes in resistivity in separate lements have also been observed. While some improvement may occur ith rotation rates of 10 and 30 r.p.m. there is still a considerable radial pread in resistivity with gallium concentrated in the centre of the inter-ace. The immediate effect of fast rotation (80 r.p.m.) seen in Fig. 6 can e related to the vortex sweeping up under the crystal and then out side-ays, levelling out the impurity concentration as it sweeps over the iffusion layer. Hence the impurity level is modified, K changing from hat for static to that for dynamic conditions and a marked increase of niformity in resistivity is obtained. The effects of rotation rate on egregation along crystals of germanium, have been discussed in detail y Burton *et al.* (1953)([7,8]) and by Bridgers (1956)([10]).

Data in Fig. 6 show that, for fast rotation, while the centre changes esistivity, the edge of the crystal (1-3 mm. depth) is not affected. It might

be suggested that heat treatment could be responsible for the change in resistivity. However, measurements of 9μ absorption 1 mm. from the edge of the crystal show only a small change in oxygen concentration as compared with the centre of the crystal. In addition the change in resistivity observed corresponds to a decrease of approximately 2×10^{15} acceptors/cm.^{3} whereas careful measurements in several crystals indicate an increase of only approximately 2×10^{14} donors/cm.^{3} during growth of fast rotated silicon crystals of normal diameter.

(*c*) 9μ ABSORPTION AND HEAT TREATMENT

The effects of seed rotation on the oxygen concentration, and hence the heat treatment effects in silicon crystals, can be partly explained in terms of the results seen in the model. At zero rotation the melt is circulated by thermal stirring and oxygen rich silicon is supplied from the walls of the crucible to the crystal interface giving an oxygen concentration of four parts in 10^6 by weight in the crystal, and a donor increase of the order of 10^{13}/cm.^{3} for a twenty-four hour heat treatment at 450°C.

A minimum oxygen concentration occurs at 10 r.p.m. for crystal diameters below 2 cm. (Fig. 8). At this rotation rate, the oxygen is still being transported by thermal stirring, the slow rotation of the seed only stirring the melt in the immediate vicinity of the crystal. This small mechanical stirring allows more oxygen to evaporate from the surface than with zero rotation and so the melt is diluted at the growth interface. This minimum in the oxygen concentration is not substantiated by the heat treatment measurements since other variables in the apparatus mask the results and limit them to an accuracy of $\pm$ 10%. However, Domenicali *et al.* (1957)([26]) reported a greater donor increase in a 3-4 r.p.m. rotated crystal than in 12-20 r.p.m. rotated crystals.

For seed rotations between 20 and 80 r.p.m. the mechanical stirring of the melt becomes increasingly important as seen by the rising vortex under the "crystal" in the model. Hence melt containing higher oxygen concentration reaches the growth interface and a rapid rise occurs in the oxygen content in the crystal (Fig. 8). The increase in donors from 10^{13} to 10^{16}/cm.^{3} emphasizes further the effects of seed rotation in the range 20-80 r.p.m.

Between 80 r.p.m. and 160 r.p.m. the 9μ absorption curve begins to flatten out (Fig. 8) and little change is seen in the production of donors by heat treatment (Table 1). Over this range, the melt and the crystal are becoming saturated with oxygen and due to the rapid stirring there is probably a large increase in the surface evaporation of oxygen.

With the increasing crystal diameter both 9μ absorption and donor production increase for both slow and fast rotation rates (Figs. 9 and 10). These effects are chiefly due to the decreasing influence which the evapora-

ion of SiO from the melt surface has on the oxygen concentration at the growth interface ([13]). Above 30 r.p.m. these effects also depend upon the vortex action which increases with crystal diameter, as shown in the model, supplying more oxygen to the interface.

CONCLUSION

Three ranges of rotation rate, namely 0 to approximately 20 r.p.m., 20 to 60 r.p.m. and 60 to 200 r.p.m., have been found to be of importance in the present experimental arrangement.

(*a*) With seed rotation rate less than approximately 20 r.p.m., the fluid movement in the molten silicon appears to be largely due to thermal stirring. The resultant conditions, in particular the temperature gradients, are such that the growth interface is curved and dislocations ranging in density from 10^2-10^4/cm.^{2} are formed, with the growth rate of 0·0012 cm./sec.[1]. The resistivity varies considerably in a radial direction and oxygen reaches the growth interface in appreciable concentrations, as would be expected in view of the thermal stirring.

(*b*) Transition from thermal to mechanical stirring in the melt takes place in the range from approximately 20 to 60 r.p.m., giving rise to changes in the various measured parameters. In particular the oxygen concentration increases by a factor three and donors due to heat treatment increase by about three orders of magnitude.

(*c*) With fast rotation rates, i.e. approximately 60 r.p.m. and above, rapid mechanical stirring dominates the liquid flow pattern. The temperatures in the melt are modified so that the growth interface is flattened and dislocations appear in reduced numbers, of the order of 10-10^3/cm.^{2} with the same growth rate, i.e. 0·0012 cm./sec. Melt mixing results in a more uniform radial resistivity but at the same time oxygen rich melt is brought up to the interface and considerable 9μ absorption is therefore observed. Heat treatment data support the optical absorption data in every detail.

ACKNOWLEDGMENTS

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BOOK REVIEW

BIBLIOGRAFIA MARCONIANA (In Italian)

Compiled by Giovanni Di Benedetto. Published as a supplement to "La Ricerca Scientifica," 1958, by the Italian National Council of Research. Price 2,000 Lire (approx. 24s.)

This unique bibliography comprises two main sections. The first deals with publications in the form of scientific papers, articles, letters, interviews, etc., for which Guglielmo Marconi himself was primarily responsible. The second section deals with papers, books and articles written about Marconi; these range from "Keeping House for a Genius" by his beautiful wife, Marchesa Cristina Marconi, to "A Caustic Summary of Wireless Telegraphy Invention" by Professor Sylvanus P. Thompson. In addition, more than twenty pages are devoted to a brief but very useful personal history of Marconi.

The most striking thing about this bibliography is the care with which every piece of information has been numbered and placed in chronological order and, from the historical point of view, it is a real joy to use. The publication concludes with an Alphabetical Index of names of authors and organizations as well as pseudonyms; Signor Di Benedetto achieves the spectacular feat of finding a reference under every letter of the alphabet—yes X for Ximenes.

The foreword is written by General Prof. Luigi Sacco, well known in international radio affairs and Trustee of the Marconi Foundation. One must be tolerant of the flowery language he uses when he writes of a fellow Italian who achieved world-wide fame but one boggles at his suggestion that Marconi discovered the ionospheric medium in 1901 and the tropospheric medium in 1930; it would be more correct to say that Marconi demonstrated that radio waves

ould be propagated to distances which vere thought to be impossible at the time, but left the scientists and physicists to heorize upon the propagation medium.

General Sacco writes of the three great oads taken by radio but the reader is left n doubt whether he refers to ground-wave, ropospheric and ionospheric propagation—ong, medium and short wavelengths—or possibly communication, broadcast and adar.

There are always better ways of doing a job and Signor Di Benedetto's work is no exception but credit must be freely given to him for the masterly manner in which he has tackled a vast subject and achieved such a great measure of success. Historians of the future will have cause to be grateful to the Italian National Council of Research for sponsoring the work and it is a pity that such a monumental publication should not have been given a suitable stiff cover to grace the shelves of Technical Libraries.

A few statistics will serve to demonstrate Guglielmo Marconi's status and, at the same time, give an idea of the magnitude of Signor Di Benedetto's task. The references number in all 2,662, of which Marconi himself was primarily responsible for 223. Of the 2,439 references relating to Marconi, 865, many in the form of obituaries, were written after his death in July 1937. Many of the references have useful informative notes appended, and some of the titles in lesser known languages are translated into Italian. A list of the honours, decorations and awards bestowed upon Marconi occupies three pages. Lastly, Signor Di Benedetto personally scrutinized the relevant literature in 31 libraries in Italy.

Now for the inevitable criticisms. How annoying it is to find oneself reading a page in the middle of the book (243 pages in all) without the section to which the page refers being indicated on one side of the page or the other! The Contents page states that the Alphabetical Index includes "persons referred to" and "the more important subjects," but these have in fact not been included—Kemp, Paget and the like, inseparable from the history of Marconi, are not listed in the index, neither is a reference given to the Yacht *Elettra* on board which much radio history was made; surely this gallant but ill-fated vessel deserved special mention.

Mistakes? Yes, there are a few mistakes not all of which are typographical. In two places entries should read "Wireless Telegraph and Signal Co. Ltd." (the first name of Marconi's Wireless Telegraph Co. Ltd.) and not "Wireless Telegraph Trading Signal Co. Ltd." On page 35 the entry for March 26th, 1930, says the distance from Genova to Sydney is 14,000 miles and that impulses transmitted by Marconi from the Yacht *Elettra* to Sydney travelled at a speed of 180 miles per second—the statement would seem to need slight revision. The Irish will probably take exception to the spelling of Ballycastle and, of course, the name Davis Jameson on page 14 should read Jameson Davis.

One last complaint—the brief history of Marconi is confused in one particular respect after 1931. The words "short-wave" are used in places where "microwave" would have been more correct; in other places the significance of the note is lost because the word "microwave" has been omitted.

Both General Sacco and Signor Di Benedetto are careful to point out that all available literature, whether it be adverse criticism or not, has been included. In the main this declared policy has been well executed but there are a few minor omissions.

A well-informed reader will have no difficulty in discerning that Solari's "Storia della Radio" is quoted verbatim in some parts of Signor Di Benedetto's personal history of Marconi, but nevertheless it serves a very useful purpose and makes interesting reading.

As a final summing up of the *Bibliografia Marconiana* it can be said that it is a most important contribution to the history of radio and the Italian National Council of Research and Signor Di Benedetto are both to be congratulated upon its publication.

TRANSISTOR LINE DEFLECTION CIRCUITS FOR TELEVISION

By P. B. HELSDON, A.M.Brit.I.R.E, M.I.R.E.

The conventional shunt diode energy recovery system used for transistor line scan generators is very efficient, but due to the hole-storage effect it is often difficult to obtain the required small flyback time. Retrace driven circuits avoid this problem but require about twice the transistor volt-ampere rating for a given scanning energy. The use of automatic phase control and reverse base current drive applied to the shunt diode circuit allows the production of saw-tooth currents sufficient to scan a full sized picture tube to normal television standards.

The generation of a saw-tooth current in deflector coils involves the repeated storage and removal of a large amount of energy. For example, in the case of a 70° tube operating at an anode potential of 14 kV, the energy required to deflect the beam from its central position to one side amounts to about 950 micro-Joules. If this energy were to be removed by dissipating it in a resistance the power required would be 19 watts. By making use of a principle disclosed by A. D. Blumlein(1) in 1932 the stored energy can be recovered and recirculated at each cycle. With circuits using this method the power source has only to supply the small amount of energy lost in the deflector coil resistance and other unavoidable circuit losses.

These energy recovery systems fall into two main types. Conventional valve circuits generally use a "series efficiency diode," whereas transistor scan generators usually take the form having a "shunt efficiency diode." Valves work well at high voltages and medium currents, transistors however have limited voltage ratings, but operate at comparatively high currents. The series diode returns energy to the valve circuit in the form of extra or "boosted" HT voltage, which suits valves. A shunt diode returns current directly to the supply, i.e. it recharges the battery or reservoir capacitor, so that the mean supply current is much less than the peak current passed by the transistor.

THE TRANSISTOR AS A SWITCH

In these high efficiency circuits the valve or transistor is usually operated in a manner simulating a switch. A perfect switch of course dissipates no power. Within its ratings a transistor makes a very good switch, so long as the operating speed is not too high. A p-n-p transistor in the grounded

mitter connection can be switched off by driving the base a fraction of a olt positive. At collector voltages below the breakdown point only the eakage and saturation currents then flow. These are small at room emperature but can be expected to double for every 9°C rise.

If the transistor is switched on by the application of a negative base ias current of sufficient magnitude, the collector will conduct fully for oltages of the order of one volt. In comparison, most valves have a "bottoming" voltage about fifty times greater.

THE SHUNT EFFICIENCY DIODE CIRCUIT

A transistor version of the Blumlein energy recovery system was first lescribed by G. C. Sziklai([2]) in 1953. This circuit is intrinsically very fficient, but as will be shown, certain practical difficulties are encountered. Fig. 1 shows the basic circuit and waveforms. The transistor V_1 acts as a witch closed for the scan period T_2 and open for the flyback period T_1 During T_2 a nearly linear current builds up in the scanning coils L_1. At he beginning of T_1 this current continues to flow into the flyback capacitor

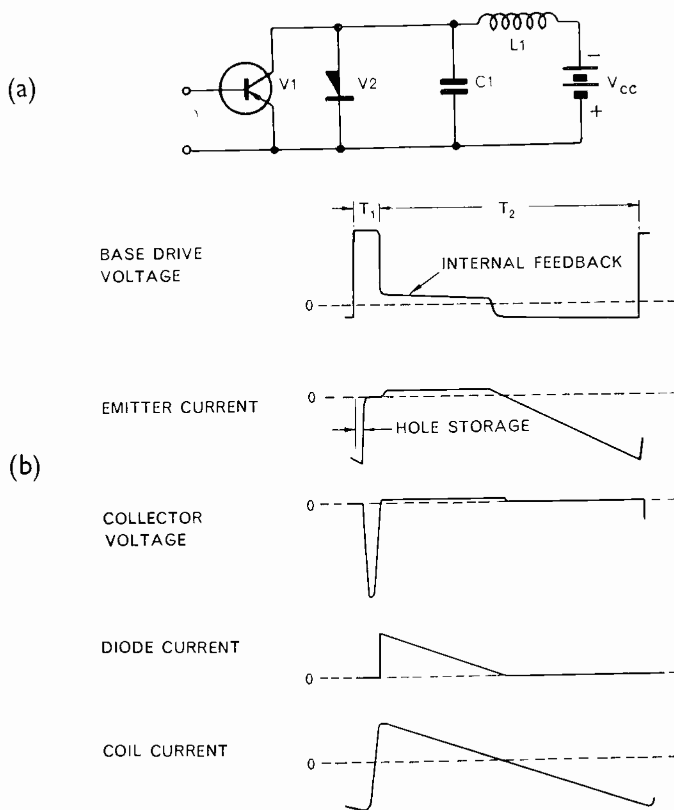


Fig. 1. (a) Basic energy recovery system using a shunt diode and (b) characteristic waveforms

C_1. Now C_1 is chosen to resonate with L_1 so that the current goes through half a cycle of oscillation in the period T_1. This ensures that the current in L_1 at the end of T_1 is equal but opposite in direction to its value at the end of T_2. During T_1 the voltage across C_1 rises to a maximum negative value, as the current in L_1 passes through zero, and then falls to zero sinusoidally.

If the transistor were a good bi-directional device the shunt diode would not be necessary, but in practice transistors are only poorly bi-directional. At the beginning of T_2 the decaying current in L_1 generates a positive voltage which when it equals the battery voltage causes the diode to conduct. The constant battery voltage then causes the current to decay in a near linear manner until the diode cuts off as the current passes through zero at the middle of T_2. The current builds up again in the opposite direction through V_1 as before. It will be noticed that the battery is charged during the first half of T_2 by the diode current, and discharged through V_1 in the latter half of T_2, the mean battery current being zero. In practice, resistive losses in the components cause the mean diode current to be reduced so that the battery has to supply a small nett current, and the diode ceases to conduct before the middle of T_2. A derivation of the necessary circuit constants can be found in Appendix A on page 63.

LOW ENERGY EXPERIMENTAL CIRCUIT

A simple experimental circuit is shown in Fig. 2. This, like the others that follow, is intended only to illustrate the basic operation and does not represent a finished design. All the low energy experimental circuits

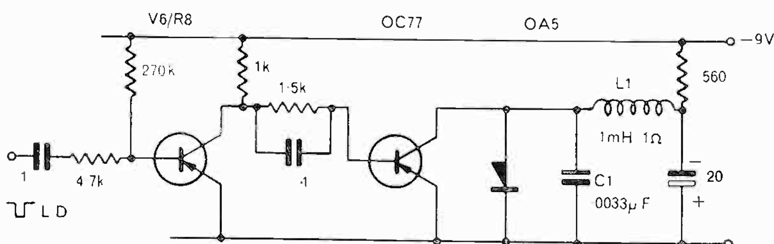


Fig. 2. Experimental shunt diode circuit for low level operation

described were adjusted to give a saw-tooth current of 150 mA p.p into a 1mH coil, with a flyback time of 8μS on the 405 line system. Performance figures are shown in the Table on page 48. Line drive pulses switch the V6/R8 from saturation to cut-off. Inverted pulses at the base of the OC77 drive it to saturation during the scan period T_2, and cut-off for the flyback period T_1. It is fully bottomed so that collector dissipation is

minimized. Collector current of the OC77 rises to a maximum at the end of T_2 and the base region accumulates a large store of holes. The flyback proper cannot start until most of these holes have been abstracted since the collector continues to conduct while holes are stored in the base region. Holes are rapidly removed by driving the base positive. Even so about 3μS is lost from the available flyback time, and necessitates the use of a smaller value for the flyback capacitor so that the resonant flyback is completed within the available time T_1. This results in a proportionate increase in the peak flyback voltage. An improved technique for dealing with the hole-storage problem is described below in regard to the design of higher energy scanning circuits.

RETRACE DRIVEN CIRCUITS

Circuits have also been proposed which overcome the problem of hole-storage by making the transistor conduct during the flyback period. Due to a self-commutating action, a rapid fall in collector current is no longer necessary.

A scanning system of this type was described by W. B. Guggi[3] in 1956. No complete analysis of this circuit appears to have been published, so there follows below a short description of the circuit action, and a derivation of the necessary circuit constants. The latter can be found in Appendix B on page 64.

BASIC OPERATION OF THE GUGGI CIRCUIT

Fig. 3 shows the basic circuit and waveforms. V_1 is a transistor which acts as a switch, closed throughout both T_1 the flyback period and T_p the positive scan period but open during the negative scan period T_n. As shown in Appendix B, the period T_p must be roughly four times T_n. During T_1 and T_p the battery and the charge on the large reservoir capacitor C_2 cause a current to flow in the large storage inductor L_2. In the off period T_n this current continues to flow through L_2, but is switched via the diode V_2 into the flyback capacitor C_1. This almost constant current charges C_1 to a high voltage by the end of T_n. The diode is cut off and the scan current in the deflector coils L_1 is reversed quickly during T_1 when the transistor switches the highly charged C_1 across L_1. The value of C_1 is chosen so that its charge drops to zero in the flyback period. At the beginning of T_p the decaying current in L_1 develops a reverse voltage which when it equals the voltage maintained by the reservoir capacitor C_2 causes the diode V_2 to conduct. The positive current in L_1 then decays in a near linear manner until it reaches zero, recharging C_2 in the process. At this instant the transistor must be switched off. The circulating current in the storage inductor L_2 switches

itself through V_2 and recharges C_1 as before. The substantially constant voltage on the reservoir capacitor can now build up a negative going linear rise of current in L_1, this current passing through the diode V_2 backwards by subtraction from the L_2 current. Obviously the current in L_2 must be at least equal to the peak value of the negative current in L_1 at the end of T_n, otherwise the diode would cut-off before the end of the scan.

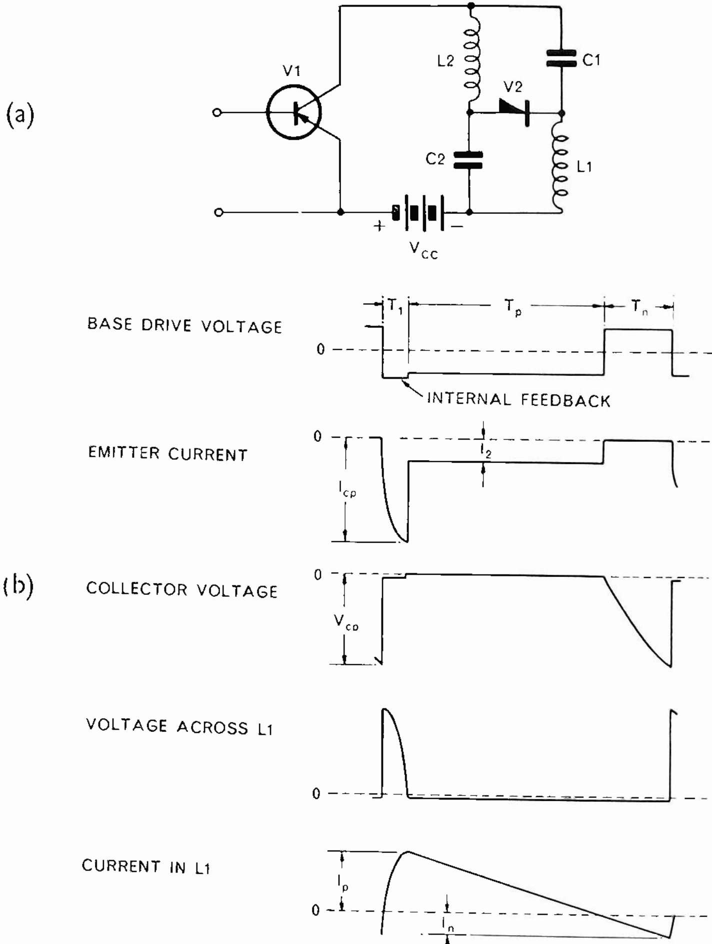


Fig. 3. (a) Basic retrace driven system by W. B. Guggi and (b) relevant waveforms

The energy stored by L_1 at the end of T_n is recovered and added to that provided by the flyback capacitor C_1. Consequently C_1 does not have to store all the energy required per scan, i.e. the peak voltage required is reduced.

The initial collector current at the beginning of T_1 is the sum of the circulating current in L_2 and the peak negative scan current I_n. These

[cu]rrents are in opposition so if they are equal their sum is zero. Since the [co]llector current starts at zero it is obvious that its peak value at the end [of] T_1 must be equal to the peak to peak value of the scanning current in [L]. Alternatively, the peak collector current at the end of T_1 is the sum [of] the circulating current I_2 and the peak positive scan current I_p, which [as] $I_2 = I_n$ gives the same result, since I_2 cannot change much in the short [fl]yback period T_1.

[T]he simplified analysis in Appendix B shows that the nett result is a [re]duction of about 14% in the necessary transistor peak volt-amps for a [g]iven scanning power. This advantage tends to be offset by the necessary [fa]ctor of safety which requires the circulating current in the storage [in]ductor to be somewhat larger than the peak negative scanning current. [A]lso the analysis here neglects the fact that the flyback period encom[p]asses more than a quarter cycle of oscillation, which would necessitate [a] reduced value for C_1 and consequently a higher voltage for the required [en]ergy.

The mean battery supply current is a function only of the transistor [p]eak current rating and the television standards. The battery voltage, [h]owever, is a function of circuit losses. A resistance free circuit would [r]equire zero battery volts once the reservoir capacitor were charged.

[E]XPERIMENTAL GUGGI CIRCUIT

[T]he circuit is shown in Fig. 4. The first transistor is driven by line drive [p]ulses and produces a negative going saw-tooth at the collector; it is

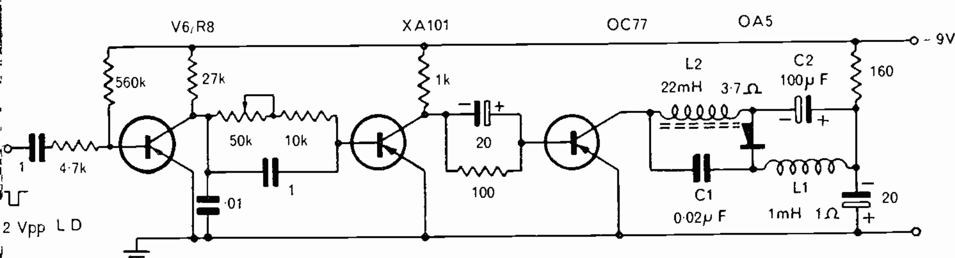


Fig. 4. Simple experimental retrace circuit (after W. B. Guggi)

[b]ottomed during the flyback and cut-off during the saw-tooth run-down. [A]n adjustable auto-bias network in the base circuit of the second transistor [k]eeps it cut-off for both the flyback period and a large predetermined part [o]f the run-down period. Once in conduction it soon bottoms. The resulting [s]tretched line drive pulse at the second collector, in conjunction with the [n]ext auto-bias network in the following base circuit, provides the specially

timed driving waveform for the output transistor. The output transistor is bottomed during the flyback period and about 80% of the scan period; it is then cut off for the remainder of the time (T_n). The theoretical value for T_n is 18μS and the measured value was 15μS. This discrepancy may be an experimental error. Hole-storage in the output stage is not a problem so it was unnecessary to pulse the base heavily positive. The negative swing had to be increased to give the double collector current required in comparison with the shunt diode circuit.

Comparison of equation (11) in Appendix B and equation (4) in Appendix A (neglecting hole-storage) shows that the Guggi circuit requires a collector peak volt-ampere rating of nearly twice that for the shunt diode circuit. The Guggi system gains an advantage in this respect, however, when the hole-storage delay in the shunt diode circuit exceeds half the allowable flyback period in simple circuits not using automatic phase control.

The Guggi circuit is intrinsically efficient and it does avoid the hole-storage problem. The power supply required, however, is a low voltage, high current one.

The simple experimental circuit described above was unsatisfactory in that the switch-off transition was slow, since it was derived from a slowly falling saw-tooth waveform.

A scanning current saw-tooth with a sinusoidal component for flat-face correction can be obtained by giving the reservoir capacitor C_2 a suitable value. Linearity otherwise is a function of the deflector coil time constant included in which is the diode forward resistance. The diode resistance is a function of current and rises to a maximum as the current passes through a minimum at the juncture of T_p and T_n. This rise in diode resistance can cause an inflection in the saw-tooth at this juncture. Reduction of the inflection can be obtained by switching the transistor off a little before the deflector coil current reaches zero, and by using a high conductance diode.

A NEW FLYBACK DRIVEN CIRCUIT

This circuit[4] was devised to obtain a more useful ratio between the required battery voltage and the peak collector voltage rating. It also eliminates the hole-storage problem while at the same time utilizing the normal line drive pulse timings.

The circuit can be designed to operate directly from the normal transistor HT supply voltage. The supply current is typically about one quarter that for the Guggi circuit for the same scanning current. Energy recovery is not inherent, as in the previous circuits, but can be incorporated if required.

ASIC OPERATION OF THE NEW CIRCUIT

he basic circuit and associated waveforms are shown in Fig. 5. It will be en that the transistor V_1 acts as a switch which is closed for the flyback riod T_1 (or slightly more) and open throughout the remainder of the an period T_2. The values of L_1 and C_1 are chosen so that C_1 is discharged mpletely through L_1 in the period T_1, so that all the energy acquired y C_1 during the previous period is transferred to the deflection coils L_1. t the end of period T_1 the decreasing current in L_1 generates a negative oltage which when it equals the steady D.C. voltage maintained by the rge reservoir capacitor C_2, causes the diode V_2 to conduct. Now the alues of C_2 and R_2 are chosen so that the voltage developed across C_2,

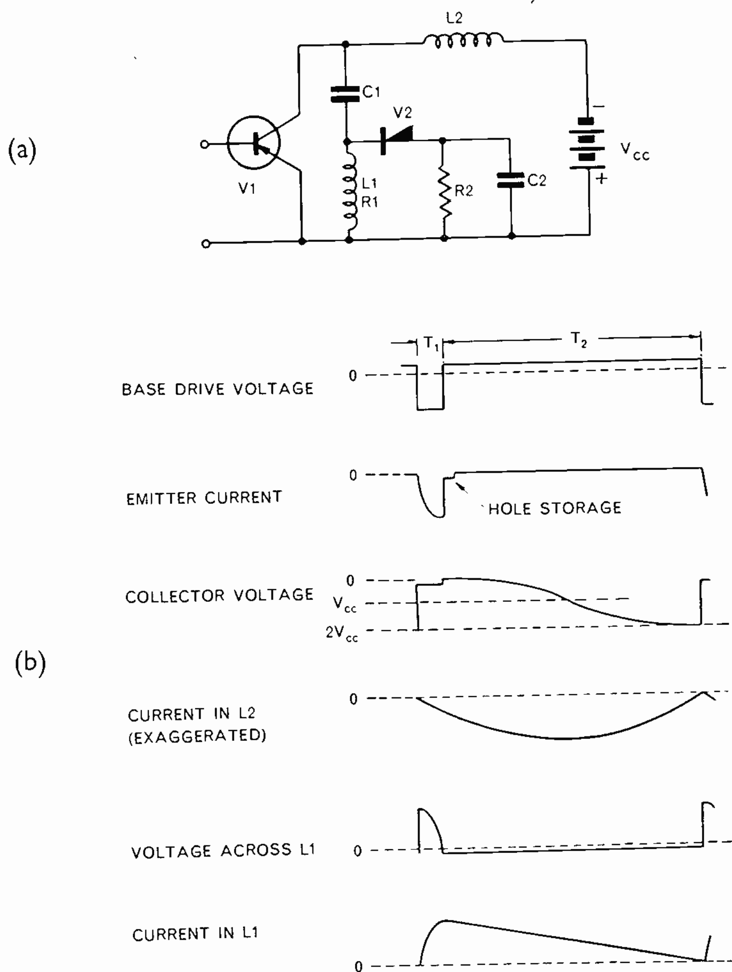


Fig. 5. (a) Elementary form of a flyback driven system and (b) associated waveforms

by the pulsating current from V_2, is substantially constant. This constant voltage causes the current in L_1 to decay in an exponential manner. If the deflection coils have negligible resistive losses, the exponential decay becomes a substantially linear saw-tooth suitable for television applications. The value of R_2 is chosen so that the current in L_1 decays to nearly zero at the end of the scan period T_2.

The capacitor C_1 is completely discharged at the end of period T_1 so that the inductance L_2 has the full battery voltage V_{cc} impressed across it throughout the period T_1 and the beginning of T_2. This causes an increasing current to build up in L_2. Now the value of L_2 is chosen to resonate with C_1 at half the frequency given by the reciprocal of $T_1 + T_2$. This causes the voltage across C_1 to build up in a sinusoidal manner which reaches a peak value, equal to twice the battery voltage, at the end of period T_2. Thus the flyback voltage applied to the deflection coils L_1 at the beginning of T_1 is equal to twice the battery voltage (neglecting losses). The current in L_2 varies sinusoidally, reaching a peak about half way through T_2 and decaying to nearly zero at the end of T_2. It is possible to make L_2 much larger. The build up of voltage across C_1 during T_2 is then more linear and the current in L_2 approximates to a parabolic waveform. The sinusoidal mode of operation is believed to be the most efficient.

The end of period T_1 can be delayed slightly, by hole-storage for example, without materially affecting the operation of the circuit.

The experimental circuit is shown in Fig. 8. Corresponding performance figures are given in the Table. Hole-storage in the output stage is not a problem so it was not necessary to pulse the base heavily positive.

The switching transient losses often associated with transistors are minimized in this circuit, since the build up of collector voltage after the switch-off point at the beginning of T_2 is slow. The build up of current during T_1 is also fairly slow.

Comparison of equation (3) in Appendix C and equation (4) in Appendix A, shows that the new circuit requires a peak collector current twice as great as for the shunt diode circuit, other things being equal. The new circuit gains an advantage in this respect, however, when the hole-storage delay in simple circuits exceeds half the allowable flyback period. Another point in favour of the new circuit is that the peak collector current is required only for the short flyback period so that the mean dissipation is reduced.

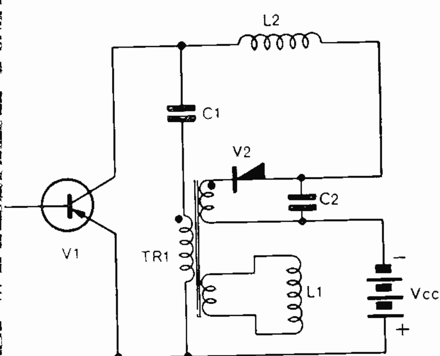
The battery voltage required is half the peak collector voltage rating and corresponds to normal practice for other transistor circuits. The value of C_2 can be reduced so that the current in L_1 during period T_2 has a sinusoidal component superimposed on the saw-tooth, and is suitable for "flat-face" correction.

In a practical circuit the deflection coils would need to be connected

a a transformer to eliminate the DC component of the saw-tooth rrent and allow the injection of the conventional centring current.

Improved circuits, not yet engineered, are shown in Figs. 6 and 7. In ese the power previously wasted in the resistance R_2 is added to the HT pply, thus improving the efficiency. Alternatively, the resistance R_2 n be replaced by some other circuit that requires a low voltage, high urrent supply.

In the proposed circuit of Fig. 6 the transformer TR_1 is chosen to have ratio so that the average current passed by V_2 equals that required by 2. In the circuit of Fig. 7 the transformer TR_1 is chosen to have a ratio



ig. 6. Voltage saving version of the flyback driven system

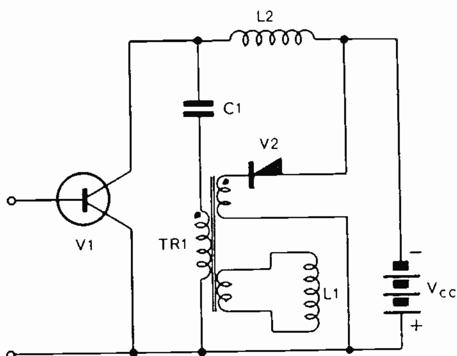


Fig. 7. Current economizing form of the flyback driven system

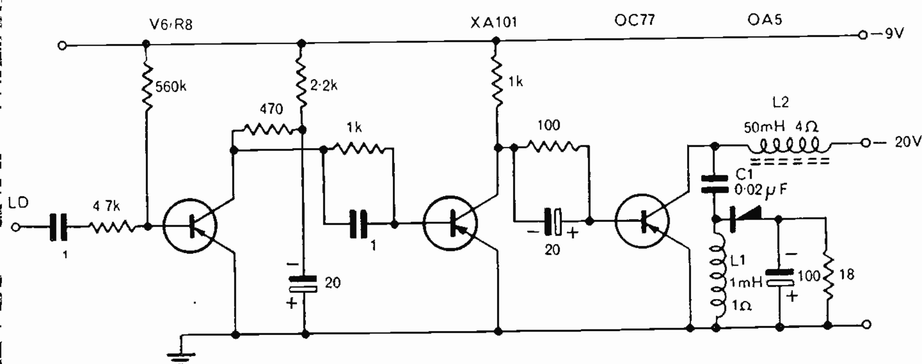


Fig. 8. Low energy experimental flyback driven scanning generator

o that the voltage across the secondary connected to V_2 during the period V_2 is equal to the battery voltage V_{cc}. This should result in a considerable aving of current.

Circuit	Emitter current peak	Collector voltage peak	Collector V.A peak	Diode current peak	Input voltage D.C.	Input current D.C.	Power Input D.C.	Power Output D.C.	Hole storage delay	Power input from 24 V supply
	mA	V	V.A	mA	V	mA	mW	mW	μS	mW
Shunt-diode Fig. 2	+18 −70	50	3·5	+68	1·8	11·5	21	—	3	277
Guggi Fig. 4	−190	31	5·9	+120	1·3	48·5	63	—	—	1,160
New Fly-back Fig. 8	−180	40	7·2	+150	20	9	180	110 mW (1·4V 78mA)	—	216

Performance of experimental circuits designed to produce 150mA p.p. in 1mH deflector coils and adjusted to have a flyback time of 8 μS on the 405 line system.

HIGHER ENERGY SCANNING

The experimental circuits described so far operate at a low level, producing only sufficient energy to scan a 1 inch Vidicon camera tube. These low energy circuits can of course be used in conjunction with scan magnification[5, 6] to provide normal line deflection in a full sized picture tube. It is doubtful if scan magnification can be applied to camera tubes, such as the image-orthicon which requires scanning energy at about the same level as a conventional picture tube.

The choice of which basic circuit to use for the production of higher energy scanning depends upon the rating of available transistors and the effect of hole storage. We have seen that when hole storage can be neglected the shunt diode circuit demands a transistor peak volt-ampere rating of only about half that required by the retrace driven type of circuit. Hole storage delay can be eliminated by a method described by H. C. Goodrich[7]. This uses an automatic phase-lock system which allows one to adjust the timing of the flyback, so that it falls within the blanking period as required.

The deflection of a 70° picture tube operating at 14 kV was the design aim for the experimental circuit to be described. Under these conditions and with standard deflector coils this tube was known to require a half-angle deflection energy of 945 micro-Joules.

om Appendix A the necessary transistor volt-ampere rating is given by

$$V_{cp}\, I_{cp} = \frac{2\pi J}{T_1} \quad \text{(neglecting losses)}$$

This can be made a minimum by allowing the flyback time T_1 to equal e blanking interval of 14μS less the time taken for hole storage decay. lowing an estimated 3μS for hole storage decay, T_1 becomes 11μS. The quired collector V.A rating is then 560 V.A. Now a 2N174 power transis- r is rated at 80 Volts and 13 Amps giving 1040 V.A which is ample. iere are numerous germanium power rectifiers with similar ratings which n be used as the shunt diode.

Samples of the 2N174 were not at the time available so some OC16 ınsistors were tested as substitutes, for experimental purposes only. ɔrmal ratings for an OC16 are 32 V_p and $3A_p$ giving 96 V.A which is ıdequate. Out of fourteen samples tested, ten were found to have a llector break-down voltage greater than 80V. Collector cut-off current ɔtted against collector voltage for temperatures of 20°C and 70°C · sample No. 5 are shown in Fig. 9. It will be seen that the breakdown

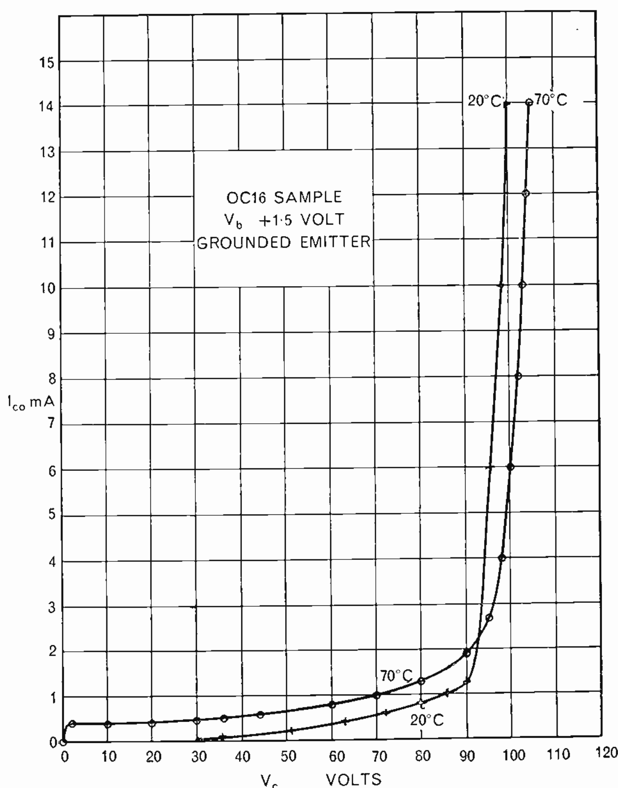


Fig. 9. Collector breakdown characteristics of a sample OC16 power transistor (not necessarily typical)

voltage increases with temperature and above 95 V the collector current falls as the temperature rises. This unexpected result can be explained by the fact that the mean free distance of a current carrier within the depletion layer falls as the temperature rises. Consequently it has less time to gather the momentum required to initiate current multiplication by collision ionization.

The normal doubling of the saturation component of the current every 9°C can be seen at the lower collector voltages, but this is swamped by the large leakage current above 50 V, and by the even larger ionization current above 90 V.

Base driving voltage and current required to obtain collector currents up to 9 A are shown in Fig. 10. It will be seen that the current gain

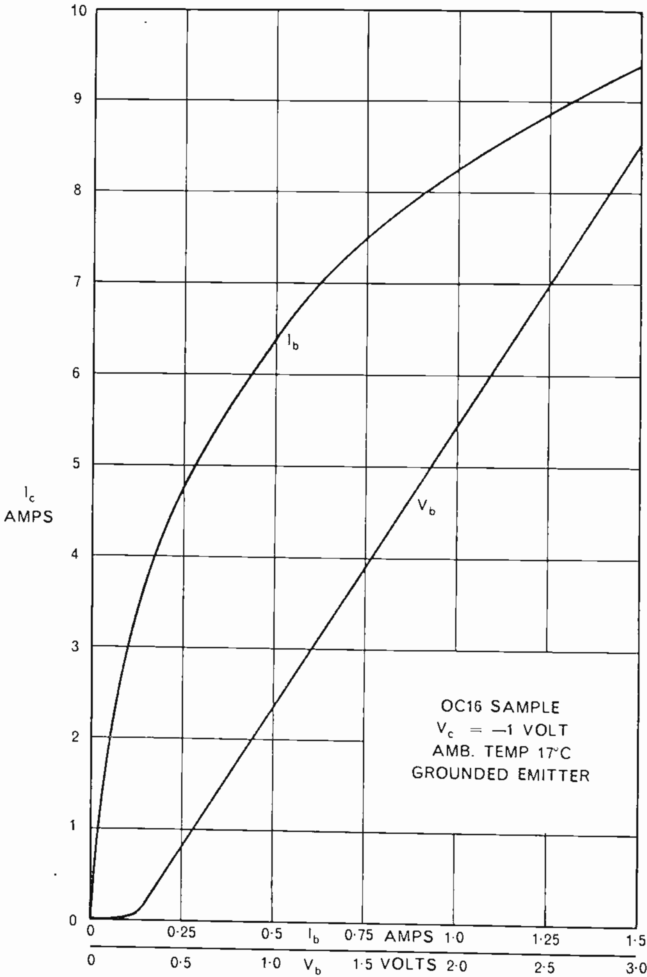


Fig. 10. Transfer characteristics of a sample OC16 power transistor (not necessarily typical)

racteristic up to the normal 3 A is very linear, but to obtain 8·5 A, ase driving voltage of −3 V at 1·1 A is required. A 2N174 at the same lector current would require only −·9 V at ·34 A. If we choose a working k current of 8 A at 70 V, the required 560 V.A will be obtained. A table shunt diode is the GEX541 which is rated at 80 V and 8 A with propriate cooling. Both transistor and diode must be mounted on a bstantial heat-sink. The diode stud is connected to the cathode so that can be directly connected to the chassis heat sink, but the transistor ist be insulated with the usual mica washers. The measured total sipation in the output transistor was 11 W, but a lower value should be ained using a 2N174. A theoretical calculation of transistor dissipation line scan service has been given by G. Schiess and W. Palmer(9).

EFLECTOR COIL CIRCUIT CONSTANTS

e inductance required for the deflector coil is given by

$$L = \frac{V_{cp}\, T_1}{I_{cp}\, \pi}$$

$$L = \frac{70\,.\,11}{10^6\,.\,8\,.\,\pi}$$

$$= 30{\cdot}5\mu\text{H}$$

yback capacitance is given by

$$C = \frac{I_{cp}\, T_1}{V_{cp}\, \pi}$$

$$= \frac{8\,.\,11}{10^6\,.\,70\,\pi}$$

$$= 0{\cdot}4\mu\text{F}$$

ttery voltage less the bottoming voltage is

$$V_{cc} = \frac{2\, T_1\, V_{cp}}{\pi\, T_2}$$

$$= \frac{2\,.\,11\,.\,70}{\pi\, 87}$$

$$= 5{\cdot}7 \text{ Volts}$$

If the collector bottoms at −0·7 V the required battery voltage will be 6·4 V.

A ready made deflector coil was available with an inductance of 114μH d the coils in series. By reconnecting these in parallel an inductance of ·5μH was obtained. To minimize losses a 0·5μF mica heavy duty capacitor

was used connected across the coils as the energy storage flyback capacito
Power was obtained from a 6 V lead-acid accumulator, by-passed by
bank of electrolytic capacitors totalling ·024F. This large value wa
required to obtain the necessary low internal series resistance and t
keep the ripple current per section within reason, because some 16 Amp
p.p. of saw-tooth current at 10 kc/s was to circulate. The use of 6 V instea
of the estimated 6·4 V partly explains the failure to fully scan the 70° tub
while operating at 14 kV. Fig. 11 is a photograph of the screen showin
the system working at 10 kV. Linearity was corrected by the use of th
Mullard shorted turn method([8]).

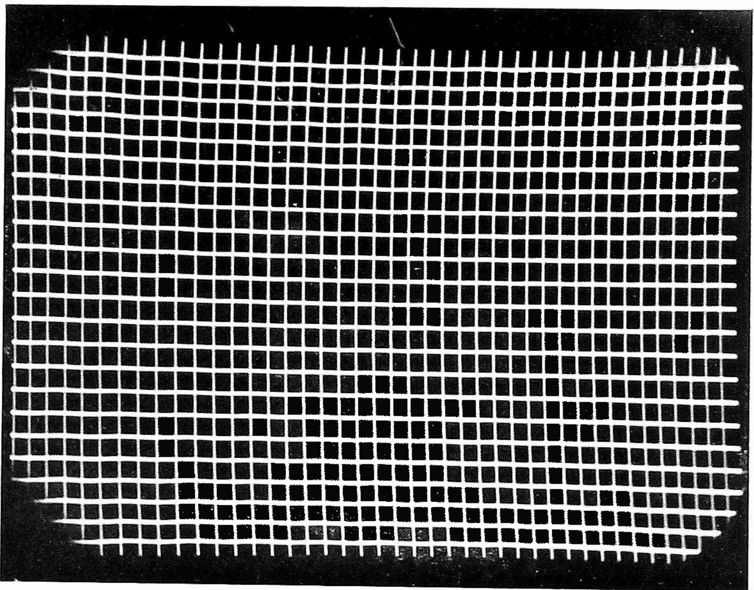


Fig. 11. Raster obtained using the high energy experimental circuit to scan a 70° tube operating at 10 kV

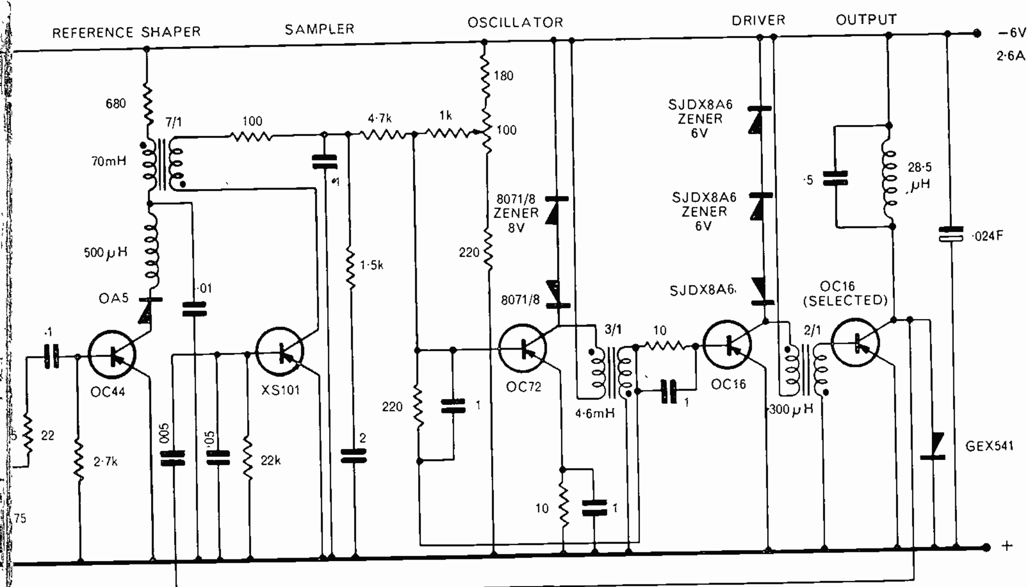
BASE DRIVING CONDITIONS

The complete circuit diagram is shown in Fig. 12 and the relevant wave-
form of each stage in Fig. 13. It will be seen that the output stage need
only be switched on for the latter 54μS of the scan since the shunt diode
carries the current for the first 30μS and both are off for the flyback perio
of 14μS.

Transformer coupling is used to obtain the conditions necessary fo
fast switching and to save driver current, also to ensure that the transisto
is cut off if the drive should fail. It was found under dynamic condition
that just over −2·5 V forward base drive was sufficient to keep the output
collector bottomed up to the end of the scan. Allowing −1 volt for the
driver collector there remains 5 V for the primary, so that a step dow

io of 2/1 is required. This calls for a driver load current of 0·55 A plus primary magnetizing current. This is well within the rating of the 16 driver transistor.

Energy built up in the core of the driver transformer due to the flow of gnetizing current must be removed during the off period. There are a mber of ways in which this stored energy can be dealt with. For ample, a storage capacitor and shunt diode as in the deflector coil case l return the energy to the battery. Or a capacitor-resistance network



g. 12. High energy experimental circuit using the shunt diode system and incorporating automatic phase-lock

n be made to dissipate the energy. In either case the capacitor has to uild up sinusoidally a peak voltage which, referred to the secondary, ves a base peak positive voltage of

$$V_{\mathrm{boff}} = -V_{\mathrm{bon}} \frac{\pi}{2} \frac{T_{\mathrm{on}}}{T_{\mathrm{off}}}$$

Now since this peak positive base voltage is effectively added to the eak negative collector voltage, it is an advantage to minimize it by aking the off period T_{off} as long as possible. By switching the base on ust before the diode ceases conduction the ratio of on to off times of the river can be made 2/1 instead of the usual 10/1.

Another way to deal with the stored energy is to use a catching diode

connected between the driver collector and a reference voltage which i
larger than the battery voltage by a suitable amount.

When the catching voltage is three times the battery voltage the catch
ing diode will conduct automatically for a time equal to half the on perioc
Referred to the secondary this will give a square positive off-pulse with
peak amplitude of only twice the negative on-pulse. It will be seen tha
this reduces the off-pulse by a factor of $2/\pi$. If the catching voltage is buil
up by a C.R network there is the possibility of a dangerous transien
condition while switching on, and a second battery is not always con
venient. A neat solution is to use Zener diodes to provide the catchin
voltage with another diode connected back to back as the catching diode
In the case of the driver, Fig. 12 shows that two 6 V Zener diodes are use
in series aiding with a third silicon diode in reverse, giving a total referenc
voltage (including the battery) of nominally 18·7 Volts. The actual voltag
was 21 V so the base is held positive for only 20μS, but remains cut-of

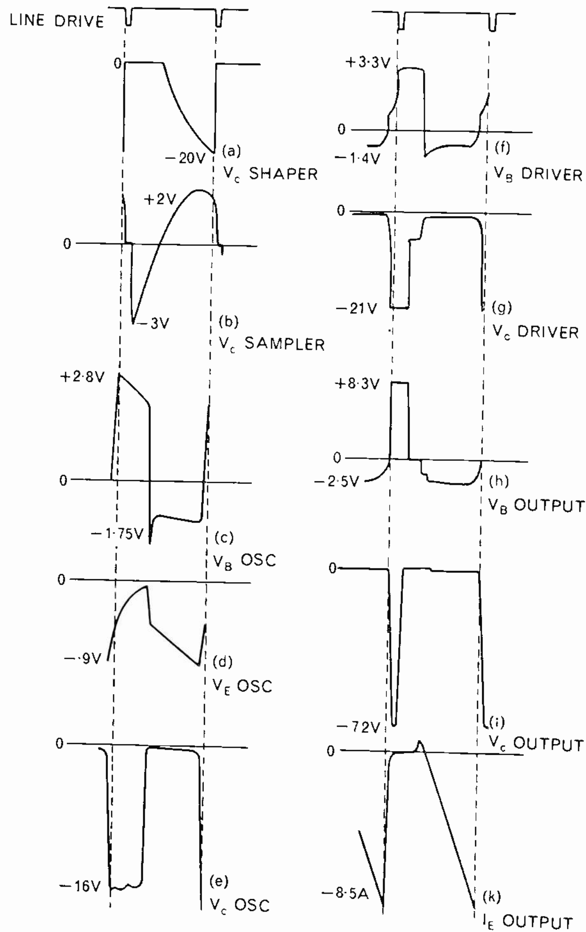


Fig. 13. Waveforms occurring in the high energy scanning generator

ice there is no forward bias until the start of the on-period as shown in g. 13. The use of a catching diode instead of the usual driver flyback pacitor is of vital importance when the problem of hole storage is nsidered as shown below.

RANSISTOR TRANSIENT RESPONSE

minimize dissipation the transistor should be fully bottomed throught the on period. Under static conditions this can be obtained by plying a forward bias current equal to

$$I_b = \frac{I_{cp}}{\bar{\alpha}_e}$$

Where I_{cp} is the peak collector current and $\bar{\alpha}_e$ is the large signal current in. Complete cut-off is ensured also if the base is driven a volt or two sitive.

The transition from on to off is characterized by an initial delay[10] fore the collector current starts to fall. This delay is caused by holes ored in the base region due to any excess of the previous base current er the minimum value required for bottoming as given above. This cess base current is necessary as a factor of safety. The hole storage delay this and previous stages is completely taken up by the automatic phase ntrol system and can therefore be neglected.

After the initial delay the collector current decays in a way determined the transistor high frequency response, the base driving waveform and e external circuit constants. Transient dissipation will be minimized if e collector current decays to a low value before the voltage across the back capacitor has had time to build up to a significant value. In this se, the flyback capacitor is effectively a short circuit during the collector rrent decay time so that Miller effect will not be significant. Collector rrent decay is then determined only by the transistor high-frequency sponse and the base driving conditions.

The short-circuit current transfer characteristic of a grounded emitter ansistor is given by

$$i_c = i_b \left[\frac{\alpha_e}{1 + j\dfrac{f}{f_{\alpha e}}} \right]$$

here $f_{\alpha e}$ is the frequency at which the grounded emitter low frequency rrent gain α_e is reduced 3 dB.

For a step of base current $\triangle i_b$ the collector current will therefore hange according to

$$i_c = \triangle i_b\, \alpha_e \left[1 - e^{-\frac{t}{T\alpha_e}} \right]$$

where $T_{\alpha e}$ the grounded emitter time constant, is

$$T_{\alpha e} = \frac{1}{2\pi f_{\alpha e}}$$

and the time t is considered to start after the initial hole-storage dela
which as mentioned above can be neglected.

If the step reduces the base current to zero the time taken for th
collector current to fall to 10% of its initial value will be $2{\cdot}3\ T_{\alpha e}$. Nov
$f_{\alpha e}$ of the OC16 at the high current levels used is about 19 kc/s, so the tim
taken by the collector current to fall to 10% for a reduction of base bia
to zero will be about 20μS. Since we require the collector current to deca
in less than 3μS it would seem impractical to employ audio-frequenc
transistors such as the OC16. During the collector current decay period
however, it is possible to draw a positive base current so that the ste
in base current can be larger than the previous steady negative value
Under these conditions the collector current can be made to decay to zer
in a nearly linear manner in a time much shorter than $T_{\alpha e}$. When th
decay time t_d is made less than 10% of $T_{\alpha e}$ in this way the required bas
current step approximates to

$$\triangle i_b = \frac{I_{cp}\, T_{\alpha e}}{\bar{\alpha}_e\, t_d}$$

Now $f_{\alpha e}\, \alpha_e = f_e$
which is the grounded emitter current gain bandwidth factor.

therefore

$$\frac{T_{\alpha e}}{\alpha_e} = T_e$$

the equivalent time constant, and so

$$t_d = \frac{I_{cp}\, T_e}{\triangle i_b} \text{ approx. (assuming } \bar{\alpha}_e = \alpha_e\text{)}$$

consequently, if the base current step were made equal to the initia
collector current, the decay time would approximate to the groundec
emitter current gain-bandwidth factor time constant.

$$T_e = \frac{1}{2\pi f_e} = \frac{A}{2\pi f_{\alpha b}\, \alpha_b}$$

Where A is the diffusion constant equal to $1{\cdot}22$.

For an OC16 the grounded base cut-off frequency $f_{\alpha b}$ is 200 kc/s and a
the high current levels used $\alpha_b = 0{\cdot}9$, so that the collector current decay
time would be 1·1μS. This probably represents a lower limit for practica
circuits since it is difficult to generate the high positive drive curren
demanded.

The driver stage was designed to give a negative base current of 1·5 A
d a positive base current of 2 A, giving a step change of 3·5 A. Large
nal current gain of the output transistor at the peak collector current
8·5 A was $\bar{\alpha}_e = 7{\cdot}7$ so that the decay time can be calculated from

$$8{\cdot}5 = 3{\cdot}5 \,.\, 7{\cdot}7 \left[1 - e^{-\frac{t_d}{8\cdot4}}\right]$$

since $T_{\alpha_e} = 8{\cdot}4\mu S$
Solving for the decay time t_d gives

$$t_d = 3{\cdot}2\mu S$$

The decay time measured was 3μS, which with the resonant flyback
ne of 11μS, gives the required total time of 14μS to fit into the normal
anking interval.

An examination of the driver stage circuit will show that during the
period a constant base driving voltage is produced, whereas during the
cay time a constant base current is maintained. The time constant of
e decay is almost independent of any time variables as shown above,
t the time "constant" applicable during the build up of collector current
der the influence of the constant base voltage is a function of the
stantaneous emitter current. This non linear behaviour under constant
se driving voltage conditions makes the calculation of the collector
rrent build up time difficult.

For equivalent ultimate steady state conditions a constant voltage
itch-on step will produce a faster rise of collector current than the
uivalent switch-on constant current step. With a constant switch-on
ltage step the initial base current will exceed the final base current in
e ratio of

$$\frac{\bar{R}_{b'e} + R_{bb'}}{R_{bb'}}$$

ecause $\bar{R}_{b'e}$ (the large signal value of $R_{b'e}$) is short circuited by the
ffusion capacitance $C_{b'e}$ at the instant of switching. Whereas of course
e equivalent constant base current step has the same value as the final
rrent continuously. This initial kick of base current causes the collector
rrent to rise faster than under constant base current conditions for
hich the rise time is $2{\cdot}3\ T_{\alpha_e} = 20\mu S$. This is sufficiently fast to follow
e required linear rise of collector current during the latter 54μS of the
an.

RIVER STAGE

he driver stage is required to give a constant voltage pulse of −2·5 V at
-1·5 A for the latter 54μS and a constant current of +2 A during the
μS decay period, followed by a small positive voltage for the remaining

41μS of the scan. These are all referred to the secondary of the transforme connected to the output stage base.

To obtain fast clean transitions it was found essential to wind th coupling transformer in a multifilar manner on a ferrite core. Leakag inductance was then a minimum. In addition the driver base circu includes an equalizer C.R network to speed up the switch-on since th natural collector current rise time was too slow to achieve bottomin from the start of the on period. Also the techniques of constant voltag on-drive and constant positive current off-drive are used to obtain fas transitions for minimum transient dissipation.

The constant current switching off-drive of 2 A to the output stage bas is derived from the continuing transformer magnetizing current built u during the previous on period. Referred to the primary of the 2/1 rati transformer this calls for a peak magnetizing current of 1 A. The o period of the driver stage is 58μS, and the battery voltage less the bottomin voltage, i.e. the primary voltage, is 5 V, so the required primary inductanc is given by

$$L_{\text{pri.}} = \frac{V_{\text{pri.}}\, T_{\text{on}}}{I_{\text{p. mag.}}} = \frac{5\ .\ 58}{10^{6}\ .\ 1}$$

therefore $L_{\text{pri.}} = 290\mu\text{H}$

The value used was 300μH.

The fact that the continuing magnetizing current is required as th positive base switching current explains the necessity of using the Zene and catching diode de-magnetizing combination. If a capacitor-diode o capacitor-resistance network were used a part of the circulating magneti ing current would flow into the capacitor instead of the transistor bas thus prolonging the decay time of the collector current. The circulatin magnetizing current does not flow into the catching diode until the end o the decay period. During the decay period the base input impedance is a low as in the normal on and bottomed condition and the input voltage doe not rise to the level corresponding to the Zener diode breakdown voltag until the collector current has practically ceased.

BLOCKING OSCILLATOR

The blocking oscillator is designed to use the same fast switching tech niques to drive itself and the base of the driver stage. In addition a equalizing network is used in each base circuit and the emitter circuit t speed up the rise in collector current. The 3/1 blocking oscillator trans former has a primary voltage during the 63μS on period of 5 volts an therefore provides a secondary forward driving voltage of $-1{\cdot}66$ V This is larger than the ultimate forward base bias of $-0{\cdot}9$ V required b the driver and the excess is dropped across the 10 ohm base circuit resisto

During the switch-on transition, however, the full secondary voltage is applied through the 1μF capacitor shunting the resistor so the rise time of the driver collector current is reduced to a few microseconds. The equalizer time constant of 10μS was chosen to be longer than the switching time but shorter than the on period for optimum results. The 220 ohm resistor shunted by a 0·1μF capacitor in the base circuit of the OC72 blocking oscillator serves the same purposes, but here the value of the capacitor must lie between special limits.

If the capacitor is too large the driver base becomes negative and conducts before the oscillator base at the time when the voltage maintained by the Zener diode collapses and overshoots due to stray capacity. The driver base then catches the overshoot before it can again switch on the oscillator. This condition will cause a slow switch-on. Alternatively, if the capacitor is too small the oscillator base voltage will decay from positive to negative before the end of the Zener controlled period. This will result in a premature and slow switch-on. The optimum value of capacitor allows the base voltage during the off period to decay by an amount slightly more than the normal forward base bias. This decay towards a less positive voltage is assisted by the 1,000 ohm resistor which is returned to an adjustable negative voltage provided by the potentiometer chain from the 6 Volt supply.

The on period of the oscillator is determined by the time taken for the emitter voltage to rise to the base voltage. The base voltage during the on period is set by the primary voltage and transformer ratio in conjunction with the potentiometer voltage and the associated resistance network. Emitter voltage is developed across the 10 ohm resistance by the flow of emitter current. This current consists of a steady component due to the transformer secondary load and a rising component which is the primary magnetizing current. When the rising magnetizing current causes the emitter voltage to nearly equal the base voltage the transistor cuts off. The collector voltage then increases until it is caught at the level at which the Zener diode breaks down. The catching diode continues to conduct until the circulating magnetizing current has decayed to zero. During this time the secondary voltage is positive and all transistors cut off. When the Zener voltage collapses the stray capacity causes an overshoot which rapidly switches the oscillator on. It will be noticed that the on period is controlled by the potentiometer. The peak value of the magnetizing current is also directly proportional to the on period. Now since the off period is also directly proportional to the peak value of the magnetizing current the ratio of on to off will be independent of the potentiometer voltage and hence the frequency. In other words the potentiometer controls the frequency but the on/off ratio is almost constant. This is another advantage obtained by the use of the Zener reference diodes.

It will be noticed that the operation of the blocking oscillator is substantially independent of the transistor characteristics. The on/off ratio and output are mainly determined by circuit constants, but the frequency is dependent on the loading to some degree.

The 4·7K resistance also connected to the oscillator base is returned to the automatic phase lock circuit. Under locked conditions the blocking oscillator phase is maintained just sufficiently in advance of the output stage flyback pulse to compensate for the overall delay due to hole-storage. The operation of the phase lock circuit is assisted by designing the blocking oscillator circuit so that the mean base voltage over the cycle is substantially zero.

AUTOMATIC PHASE LOCK

Automatic phase lock systems comprise a phase comparitor stage in which the phase of the output of the controlled oscillator system is compared with the phase of an external reference signal. Any difference in phase, lagging or leading, produces a D.C. control voltage the polarity and amplitude of which change accordingly. If the phase is correct, the D.C. output is ideally zero. An incorrect phase produces a polarity of D.C. in the direction necessary to momentarily change the frequency of the oscillator until it is in phase.

These A.P.L. systems can take many forms. The best form for a particular application depends upon the required operating conditions, such as noise on the reference signal. A television camera channel is driven from noise free and uniform line drive pulses, so that the usual receiver problems of noise and double frequency frame synchronizing pulses do not arise. The only requirements left are that the flyback pulse should fall within the blanking period, the pull-in range be sufficient for normal mains frequency variations and that the circuit should be safe in the event of failure of the line drive pulses.

The fail safe requirement can be met by using the deflector coil flyback voltage as the gating pulse and by selecting a circuit which gives zero output when the phase is right. The oscillator then operates close to the correct frequency in the absence of line drive pulses.

Basically the comparitor consists of a switch which is closed by the tip of the flyback pulse and which samples the instantaneous value of the reference waveform. The samples are integrated in a storage capacitor to give the D.C. used to control the oscillator. To obtain good phase control in the locked condition the rate of change of the reference waveform should be a maximum and its amplitude pass through zero near the centre of the blanking interval. In the locked condition the shape of the rest of the reference signal is immaterial.

Pull-in range is determined by the peak value of the low difference

equency signal developed by the integrating capacitor. For a given fference frequency out of lock the peak value of the integrated samples ill be greatest for a small capacitor and a full square waveform reference gnal. A minimum value for the capacitor is set by the necessity to filter it the waveform fed back from the blocking oscillator and to smooth out ight phase modulation effects in the line drive pulses.

An approximation to the ideal reference waveform is produced by the aping circuit used. So that the deflector coil flyback pulse shall be ntred in blanking the line drive reference pulse is delayed by partial tegration. This operation is performed by the complementary network hich also acts as the normal 75 ohm termination. The shaping amplifier thereby switched into the conducting state for about 7μS at the centre the blanking interval.

The poor rise time resulting from this method of delay necessitates the e of a high frequency transistor type OC44 as the amplifier. If the delay ere produced by a delay line so that the rise times were preserved, an idio frequency transistor type OC72 could be used.

During the conduction period the 0·01μF capacitor in the collector rcuit is discharged through the 500μH inductance. Energy gained by the ductance recharges the capacitor again with an equal but opposite iarge. Reversal of the current flow in the inductance is prevented by the ocking diode in series with the collector.

The collector is bottomed throughout the conduction period and cut off r the rest of the cycle. Neglecting for the moment the 680 ohm resistor, e voltage across the primary of the transformer is now the battery oltage plus the capacitor voltage. Current in the primary builds up nusoidally and decays to zero again during the off period, and in so oing again reverses the charge on the capacitor leaving it charged to vice the battery voltage. At the end of the second cycle the capacitor left with a charge of three times the battery voltage. This building up rocess continues until the energy lost per cycle due to flow of current rough the 680 ohm resistor and other circuit losses equals the energy ained per cycle from the battery. In this circuit the peak to peak voltage eveloped across the capacitor is about six times the battery voltage. nly the negative half cycle appears at the collector because the diode locks for the positive half cycle.

If it were not for the 680 ohm resistor, the waveform across the primary ould consist of a fast half cosine during the conduction period and a ow half cosine of appropriate phase during the remaining part of the ycle. The resistor adds a small exponential component during the longer eriod. Its presence limits the current that could flow under fault conditions nd the peak collector voltage during normal operation to safe values.

Sampling of the voltage at the secondary of the 7/1 step down trans-

former is carried out by a symmetrical transistor type XS101. A step down transformer is used to provide a low impedance source and so the sampling transistor can have its emitter at earth potential. This simplifies the base drive circuit which consists of a ten to one capacitor potentiometer connected to the deflector coil. A transistor used in this way can provide an efficient switch for voltages of either polarity, but the base must be driven more positive than the most positive collector voltage to ensure cut off. The collector waveform has a peak to peak value of 5 Volts and the base is therefore driven with one eleventh of the flyback voltage, i.e., about 6·5 Volts peak. After rectification at the base this provides the necessary + 6 Volts of hold-off bias.

Integration of the sampled reference waveform is accomplished by the 0·1μF capacitor. An anti-hunt network consisting of a 2μF capacitor in series with a 1,500 ohm resistor is connected across the main integrating capacitor. The best anti-hunt circuit values were determined experimentally by driving the reference waveform generator with blanking instead of line drive pulses. The long frame blanking pulse set up a transient disturbance in the phase of the oscillator. Without the anti-hunt network the disturbance took the form of a damped oscillatory wave which continued for about forty lines. The values chosen reduced the visible effect in the picture to a small initial displacement of about 1% of the line width, which died out exponentially in a few lines.

With standard 405 line drive pulses the pull in range was + 220 c/s and − 320 c/s. When locked in, the potentiometer in the base circuit of the oscillator can control the phase of the flyback pulse so it can be made to appear on either side of the blanking pulse or be properly coinsident at will. There is a phase drift for a few minutes while the transistors warm up after first switching on. This is probably due to the heavy dissipation in the output stage reflecting a changing load back to the oscillator. This effect could probably be minimized by the use of the more efficient 2N174 transistors which also require less driving power.

This A.P.L circuit is not designed to operate from combined synchronizing pulses, but nevertheless, while doing so, the visible disturbance after the frame pulses is well within domestic receiver standards.

ACKNOWLEDGMENTS

The writer wishes to acknowledge helpful discussion on the subject of transistor behaviour with Mr. I. G. Cressel and his staff, especially, Mr. L. De Tullio.

APPENDIX A

[illegible]ALYSIS OF THE SHUNT EFFICIENCY DIODE CIRCUIT

Using the symbols as follows:

L_Y inductance of deflection coils
R_Y resistance of deflection coils
C_1 capacitance of flyback capacitor
T_1 flyback period
T_2 forward scan period
V_b battery voltage
V_{cm} peak collector voltage
I_{cm} peak collector current
J energy in Joules for half deflection angle
I_b mean battery current
$V_b I_b = W_{dc}$ power input or dissipation in R_Y

Neglecting hole storage and assuming that $\frac{L_Y}{R_Y}$ is much greater than T_1 let

$$\frac{1}{2T_1} = \frac{1}{2\pi\sqrt{L_Y C_1}}$$

so that $C_1 = \frac{T_1^2}{\pi^2 L_Y}$ (1)

and $V_{cm} = \frac{I_{cm} T_1}{\pi C_1}$ or $C_1 = \frac{I_{cm} T_1}{V_{cm} \pi}$

Hence $V_{cm} = \frac{I_{cm} \pi L_Y}{T_1}$ or $L_Y = \frac{V_{cm} T_1}{I_{cm} \pi}$ (2)

and $V_b = \frac{L_Y 2 I_{cm}}{T_2}$

Consequently $V_b = \frac{2 T_1 V_{cm}}{\pi T_2}$ (3)

In a typical case, $\frac{T_1}{T_2} = \frac{1}{10}$ approx.

Therefore the required battery voltage is less than one-[illegible]th of the peak collector voltage rating when T_1 is reduced to [illegible] for hole storage.

Also $\frac{1}{2} L_Y I_{cm}^2 = J$

With (2) $V_{cm} I_{cm} = \frac{2\pi J}{T_1}$ (4)

This determines the required transistor peak ratings when T_1 is a reduced value to allow for hole storage.

APPENDIX B

ANALYSIS OF THE GUGGI CIRCUIT

Keeping the symbols as used in Appendix A and introducing:

L_2 = inductance of charging inductor
R_2 = resistance of charging inductor
C_2 = reservoir capacitor
T_p = positive scan period
T_n = negative scan period
V_2 = voltage maintained by C_2
I_p = peak current in L_1 at beginning of T_p
I_n = peak current in L_1 at the end of T_n
I_2 = current in L_2
I_{pp} = $I_p + I_n$
T_2 = $T_p + T_n = 11 T_1$

This analysis assumed that $\frac{L_1}{R_1}$ and $\frac{L_2}{R_2}$ are each much greater than T_2.

During T_1 the current in L_1 passes through slightly more than a quarter cycle of oscillation, since it starts off from a negative value. This, however can be neglected and T_1 assumed to be a quarter of a cycle exactly.

$$\text{Let } 4\,T_1 = 2\pi\sqrt{L_1 C_1}$$

$$L_1 C_1 = \frac{4\,T_1^2}{\pi^2} \quad (1)$$

Now I_2 can be assumed to be constant and equal to I_n.

The charge accumulated by C_1 in the period T_n is given by:

$$C_1 V_{cp} = I_n T_n' \quad (2)$$

At the end of T_1 the voltage across C_1 has fallen to zero so that the energy in L_1 at that instant is equal to the sum of the energies acquired by both L_1 and C_1 during T_n.

$$\frac{1}{2} L_1 I_n^2 + \frac{1}{2} C_1 V_{cp}^2 = \frac{1}{2} L_1 I_p^2 \quad (3)$$

Now $\quad I_p = I_{pp} - I_n$

and $\quad I_n = \frac{I_{pp} T_n}{T_2} \quad (4)$

so $\quad I_p = I_{pp}\left(1 - \frac{T_n}{T_2}\right) \quad (5)$

From (2) $C_1 V_{cp}^2 = \frac{I_n^2 T_n^2}{C_1}$

om (4) $C_1 V_{cp}^2 = \frac{I_{pp}^2 T_n^4}{T_2^2 C_1}$ (6)

om (3) (4) (5) and (6)

$$\frac{L_1 I_{pp}^2 T_n^2}{T_2^2} + \frac{I_{pp}^2 T_n^4}{T_2^2 C_1} = L_1 I_{pp}^2 \left(1 - \frac{T_n}{T_2}\right)^2$$

$$\frac{T_n^4}{T_2^2 L_1 C_1} + \frac{2 T_n}{T_2} - 1 = 0$$

om (1) $\frac{T_n^4 \pi^2}{T_2^2 4 T_1^2} + \frac{2 T_n}{T_2} - 1 = 0$ (7)

This quartic has to be solved to find T_n

r television applications where $T_2 = 11 T_1$ a reasonable approximation equation (7) is given by

$$T_n = \frac{T_2}{5} \quad (8)$$

$$\text{Now } J = \frac{1}{2} L_1 \left(\frac{I_{pp}}{2}\right)^2$$

$$\text{or } I_{pp} = \sqrt{\frac{8J}{L_1}} \quad (9)$$

om (3) (4) and (5)

$$\frac{L_1 I_{pp}^2 T_n^2}{T_2^2} + C_1 V_{cp}^2 = L_1 I_{pp}^2 \left(1 - \frac{T_n}{T_2}\right)^2$$

$$C_1 V_{cp}^2 = L_1 I_{pp}^2 \left(1 - \frac{2 T_n}{T_2}\right)$$

om (8) and (9)

$$C_1 V_{cp}^2 = \frac{24}{5} J$$

om (2) (4) and (8)

$$I_{pp} V_{cp} = 120 \frac{J}{T_2}$$

Now $I_{cp} = I_2 + I_p = I_n + I_p = I_{pp}$ (10)

suming that $I_2 = I_n$ is a constant during T_1.

$$V_{cp} I_{cp} = 120 \frac{J}{T_2}$$

former is carried out by a symmetrical transistor type XS101. A step down transformer is used to provide a low impedance source and so the sampling transistor can have its emitter at earth potential. This simplifies the base drive circuit which consists of a ten to one capacitor potentiometer connected to the deflector coil. A transistor used in this way can provide an efficient switch for voltages of either polarity, but the base must be driven more positive than the most positive collector voltage to ensure cut off. The collector waveform has a peak to peak value of 5 Volts and the base is therefore driven with one eleventh of the flyback voltage, i.e., about 6·5 Volts peak. After rectification at the base this provides the necessary + 6 Volts of hold-off bias.

Integration of the sampled reference waveform is accomplished by the 0·1μF capacitor. An anti-hunt network consisting of a 2μF capacitor in series with a 1,500 ohm resistor is connected across the main integrating capacitor. The best anti-hunt circuit values were determined experimentally by driving the reference waveform generator with blanking instead of line drive pulses. The long frame blanking pulse set up a transient disturbance in the phase of the oscillator. Without the anti-hunt network the disturbance took the form of a damped oscillatory wave which continued for about forty lines. The values chosen reduced the visible effect in the picture to a small initial displacement of about 1% of the line width, which died out exponentially in a few lines.

With standard 405 line drive pulses the pull in range was + 220 c/s and − 320 c/s. When locked in, the potentiometer in the base circuit of the oscillator can control the phase of the flyback pulse so it can be made to appear on either side of the blanking pulse or be properly coinsident at will. There is a phase drift for a few minutes while the transistors warm up after first switching on. This is probably due to the heavy dissipation in the output stage reflecting a changing load back to the oscillator. This effect could probably be minimized by the use of the more efficient 2N174 transistors which also require less driving power.

This A.P.L circuit is not designed to operate from combined synchronizing pulses, but nevertheless, while doing so, the visible disturbance after the frame pulses is well within domestic receiver standards.

ACKNOWLEDGMENTS

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APPENDIX A

LYSIS OF THE SHUNT EFFICIENCY DIODE CIRCUIT

Jsing the symbols as follows:

L_1 = inductance of deflection coils
R_1 = resistance of deflection coils
C_1 = capacitance of flyback capacitor
T_1 = flyback period
T_2 = forward scan period
V_{cc} = battery voltage
V_{cp} = peak collector voltage
I_{cp} = peak collector current
J = energy in Joules for half deflection angle
I_{cc} = mean battery current
W_r = W_{cc} = power input or dissipation in R_1

lecting hole storage and assuming that $\frac{L_1}{R_1}$ is much greater than T_2, let:

$$\frac{1}{2T_1} = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

that $C_1 = \frac{T_1{}^2}{\pi^2 L_1}$ (1)

w $V_{cp} = \frac{I_{cp}\, T_1}{\pi\, C_1}$ or $C_1 = \frac{I_{cp}\, T_1}{V_{cp}\, \pi}$

refore $V_{cp} = \frac{I_{cp}\, \pi\, L_1}{T_1}$ or $L_1 = \frac{V_{cp}\, T_1}{I_{cp}\, \pi}$ (2)

w $V_{cc} = \frac{L_1\, 2\, I_{cp}}{T_2}$

sequently $V_{cc} = \frac{2\, T_1\, V_{cp}}{\pi\, T_2}$ (3)

w in television $\frac{T_1}{T_2} = \frac{1}{10}$ approx.

Therefore the required battery voltage is less than one fifteenth of the k collector voltage rating, when T_1 is reduced to allow for hole storage.

w $\frac{1}{2}\, L_1\, I_{cp}{}^2 = J$

With (2) $V_{cp}\, I_{cp} = \frac{2\pi\, J}{T_1}$ (4)

This determines the required transistor peak ratings when T_1 is a uced value to allow for hole storage.

APPENDIX B

ANALYSIS OF THE GUGGI CIRCUIT

Keeping the symbols as used in Appendix A and introducing:

L_2 = inductance of charging inductor
R_2 = resistance of charging inductor
C_2 = reservoir capacitor
T_p = positive scan period
T_n = negative scan period
V_2 = voltage maintained by C_2
I_p = peak current in L_1 at beginning of T_p
I_n = peak current in L_1 at the end of T_n
I_2 = current in L_2
I_{pp} = $I_p + I_n$
T_2 = $T_p + T_n = 11 T_1$

This analysis assumed that $\frac{L_1}{R_1}$ and $\frac{L_2}{R_2}$ are each much greater than T_2.

During T_1 the current in L_1 passes through slightly more than a quarter cycle of oscillation, since it starts off from a negative value. This, however, can be neglected and T_1 assumed to be a quarter of a cycle exactly.

$$\text{Let } 4\,T_1 = 2\pi\sqrt{L_1 C_1}$$

$$L_1 C_1 = \frac{4\,T_1^2}{\pi^2} \qquad (1)$$

Now I_2 can be assumed to be constant and equal to I_n.

The charge accumulated by C_1 in the period T_n is given by:

$$C_1 V_{cp} = I_n T_n' \qquad (2)$$

At the end of T_1 the voltage across C_1 has fallen to zero so that the energy in L_1 at that instant is equal to the sum of the energies acquired by both L_1 and C_1 during T_n.

$$\frac{1}{2} L_1 I_n^2 + \frac{1}{2} C_1 V_{cp}^2 = \frac{1}{2} L_1 I_p^2 \qquad (3)$$

Now $\quad I_p = I_{pp} - I_n$

and $\quad I_n = \frac{I_{pp} T_n}{T_2} \qquad (4)$

so $\quad I_p = I_{pp}\left(1 - \frac{T_n}{T_2}\right) \qquad (5)$

From (2) $C_1 V_{cp}^2 = \frac{I_n^2 T_n^2}{C_1}$

om (4) $C_1 V_{cp}^2 = \dfrac{I_{pp}^2 T_n^4}{T_2^2 C_1}$ (6)

om (3) (4) (5) and (6)

$$\frac{L_1 I_{pp}^2 T_n^2}{T_2^2} + \frac{I_{pp}^2 T_n^4}{T_2^2 C_1} = L_1 I_{pp}^2 \left(1 - \frac{T_n}{T_2}\right)^2$$

$$\frac{T_n^4}{T_2^2 L_1 C_1} + \frac{2 T_n}{T_2} - 1 = 0$$

om (1) $\dfrac{T_n^4 \pi^2}{T_2^2 4 T_1^2} + \dfrac{2 T_n}{T_2} - 1 = 0$ (7)

This quartic has to be solved to find T_n

r television applications where $T_2 = 11 T_1$ a reasonable approximation equation (7) is given by

$$T_n = \frac{T_2}{5} \quad (8)$$

$$\text{Now } J = \frac{1}{2} L_1 \left(\frac{I_{pp}}{2}\right)^2$$

$$\text{or } I_{pp} = \sqrt{\frac{8J}{L_1}} \quad (9)$$

om (3) (4) and (5)

$$\frac{L_1 I_{pp}^2 T_n^2}{T_2^2} + C_1 V_{cp}^2 = L_1 I_{pp}^2 \left(1 - \frac{T_n}{T_2}\right)^2$$

$$C_1 V_{cp}^2 = L_1 I_{pp}^2 \left(1 - \frac{2 T_n}{T_2}\right)$$

om (8) and (9)

$$C_1 V_{cp}^2 = \frac{24}{5} J$$

om (2) (4) and (8)

$$I_{pp} V_{cp} = 120 \frac{J}{T_2}$$

Now $I_{cp} = I_2 + I_p = I_n + I_p = I_{pp}$ (10)

ssuming that $I_2 = I_n$ is a constant during T_1.

$$V_{cp} I_{cp} = 120 \frac{J}{T_2}$$

or $$V_{cp}\, I_{cp} = \frac{3 \cdot 5\, \pi J}{T_1} \text{ approx.} \tag{11}$$

From (2) (4) and (8) $$C_1 = \frac{I_{cp}\, T_2}{25\, V_{cp}} \tag{12}$$

From (1) $$L_1 = \frac{10\, T_1^2\, V_{cp}}{T_2\, I_{cp}} \text{ approx.} \tag{13}$$

If the natural period of $L_2\, C_1$ were four times T_n, the current in L_2 would fall to zero at the end of T_n. But we require this current to be equal to I_n at the end of T_n, without having an excessive value at the end of T_p. This calls for a large value for L_2. If we make the natural period eight times T_n, the current will drop to $0 \cdot 707$ of its peak value.

Let $$8\, T_n = 2\pi \sqrt{L_2\, C_1}$$

or $$L_2 = \frac{16\, T_n^2}{\pi^2\, C_1}$$

From (8) and (12) $$L_2 = \frac{1 \cdot 6\, T_2\, V_{cp}}{I_{cp}} \text{ approx.} \tag{14}$$

In the absence of resistive losses the sawtooth current in L_1 is the linear part of a sine wave, the period of which is determined by $L_1\, C_2$. For the sinusoidal component to be less than 1% the period should be greater than 12 times T_2 or 132 times T_1. Now the period of $C_1\, L_1$ is 4 times T_1 so that C_2 is given by:

$$C_2 = C_1 \left(\frac{132}{4}\right)^2$$

or $C_2 = 1000\, C_1$ approx. (15)

Now $$I_{cc} = I_{pp} \frac{2\, T_1}{\pi\, T_2} + I_n \left(\frac{T_2 - T_n}{T_2}\right)$$

From (4) and (8) $$I_{cc} = I_{pp} \left[\frac{2\, T_1}{\pi\, T_2} + \frac{4}{25}\right]$$

From (10) $$I_{cc} = I_{cp} \left[\frac{2\, T_1}{\pi\, T_2} + \frac{4}{25}\right]$$

When $T_2 = 11\, T_1$

$$I_{cc} = \frac{I_{cp}}{4 \cdot 6} \text{ approx.} \tag{16}$$

A sawtooth linearity of 5% will be obtained when $\frac{L_1}{R_1} = 10\, T_2$. It seems

onable to make R_2 such a value that the power lost in R_1 and R_2 are al. The total power lost must be supplied by the battery.

refore $I_{cc} V_{cc} = \frac{2 I_{pp}^2 R_1}{3}$ (neglecting I_n)

m (16) $V_{cc} = \frac{3 I_{cp} L_1}{10 T_2}$

m (13) $V_{cc} = \frac{3 V_{cp} T_1^2}{T_2^2}$

When $T_2 = 11 T_1$

$$V_{cc} = \frac{V_{cp}}{40} \text{ approx.} \tag{17}$$

$V_2 = \frac{L_1 I_{pp}}{T_2}$

m (13) $V_2 = \frac{10 T_1^2 V_{cp}}{T_2^2}$

hat $V_2 = \frac{V_{cp}}{12}$ approx. (18)

nmarizing:

$$T_n = \frac{T_2}{5} \text{ approx.}$$

$$V_{cp} I_{cp} = 120 \frac{J}{T_2} = \frac{3\cdot5 \pi J}{T_1} \text{ approx.}$$

$C_1 = \frac{I_{cp} T_2}{25 V_{cp}} = \frac{T_1 I_{cp}}{2\cdot27 V_{cp}}$ approx.

$L_1 = \frac{10 T_1^2 V_{cp}}{T_2 I_{cp}} = \frac{0\cdot91 T_1 V_{cp}}{I_{cp}}$ approx.

$L_2 = \frac{1\cdot6 T_2 V_{cp}}{I_{cp}} = 19 L_1$ approx.

$C_2 = 1000 C_1$ approx.

$I_{cc} = \frac{I_{cp}}{4\cdot6}$ approx. (for 5% linearity)

$$V_{cc} = \frac{V_{cp}}{40} \text{ approx.}$$

$$V_2 = \frac{V_{cp}}{12} \text{ approx.}$$

APPENDIX C

ANALYSIS OF THE NEW FLYBACK DRIVEN CIRCUIT

Using the same symbols as in Appendices A and B, excepting for the following redefinitions.

L_2 = inductance of charging inductor
R_2 = diode load resistance
C_2 = reservoir capacitor R_2
V_r = mean voltage maintained by C_2

Assuming that $\frac{L_1}{R_1}$ is much greater than T_2, let:

$$\frac{1}{4\,T_1} = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

or

$$C_1 = \frac{4\,T_1^2}{\pi^2 L_1} \tag{1}$$

Now due to the D.C. component produced by this circuit, the energy stored in the deflector coils at the end of T_1 is four times that required to deflect the beam from its central rest position to one side, i.e., through half the full deflection angle.

$$4J = \frac{1}{2} L_1 I_{cp}^2 \tag{2}$$

Also $4J = \frac{1}{2} C_1 V_{cp}^2$ neglecting the small loss in R_1

From (1 and 2) $$V_{cp} I_{cp} = \frac{4J\pi}{T_1} \tag{3}$$

This determines the required transistor ratings.

Now $\frac{1}{2} C_1 V_{cp}^2 = \frac{1}{2} L_1 I_{cp}^2$

Therefore $$L_1 = C_1 \frac{V_{cp}^2}{I_{cp}^2} \tag{4}$$

rom (1) $L_1 = \dfrac{2\,T_1\,V_{cp}}{\pi\,I_{cp}}$ (5)

rom (4) $C_1 = \dfrac{I_{cp}\,2\,T_1}{V_{cp}\,\pi}$ (6)

As shown in Appendix B. for 1% sinusoidal non-linearity the value of is given by

$$C_2 = 1000\,C_1 \text{ approx.}$$

This neglects the effect of the continuous discharge current through which tends to increase the non linearity. The value of C_2 is best ermined experimentally.

et $\dfrac{1}{2T_2} = \dfrac{1}{2\pi\sqrt{L_2C_1}}$ assuming $T_1 << T_2$

m (6) $L_2 = \dfrac{T_2^2\,V_{cp}}{2\pi\,T_1\,I_{cp}}$ (7)

w $V_r = \dfrac{L_1\,I_{cp}}{T_2}$

uming that current in $L_1 = 0$ at end of T_2 and neglecting I_{cc} flowing R_2 and the small loss in R_1.

The mean current flowing in R_2 is $\dfrac{I_{cp}}{2}$

erefore $R_2 = \dfrac{2\,L_1}{T_2}$

m (5) $R_2 = \dfrac{4\,T_1\,V_{cp}}{\pi\,T_2\,I_{cp}}$ (8)

Now $V_{cc} = \dfrac{V_{cp}}{2}$ (9)

The peak current in L_2 is given by $\dfrac{\pi\,I_{cc}}{2}$

Now $\dfrac{\pi\,I_{cc}}{2} = \dfrac{V_{cc}\,2\,T_2}{2\pi\,L_2}$

suming that T_1 is much less than T_2.

erefore $I_{cc} = \dfrac{V_{cc}\,2\,T_2}{\pi^2\,L_2}$

$$V_{cc} = \frac{V_{cp}}{40} \text{ approx.}$$

$$V_2 = \frac{V_{cp}}{12} \text{ approx.}$$

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ANALYSIS OF THE NEW FLYBACK DRIVEN CIRCUIT

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$$\frac{1}{4\,T_1} = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

or
$$C_1 = \frac{4\,T_1^2}{\pi^2 L_1} \tag{1}$$

Now due to the D.C. component produced by this circuit, the energy stored in the deflector coils at the end of T_1 is four times that required to deflect the beam from its central rest position to one side, i.e., through half the full deflection angle.

$$4J = \frac{1}{2} L_1 I_{cp}^2 \tag{2}$$

Also $4J = \frac{1}{2} C_1 V_{cp}^2$ neglecting the small loss in R_1

From (1 and 2) $$V_{cp} I_{cp} = \frac{4J\pi}{T_1} \tag{3}$$

This determines the required transistor ratings.

Now $\frac{1}{2} C_1 V_{cp}^2 = \frac{1}{2} L_1 I_{cp}^2$

Therefore $$L_1 = C_1 \frac{V_{cp}^2}{I_{cp}^2} \tag{4}$$

From (1) $L_1 = \frac{2\,T_1\,V_{cp}}{\pi\,I_{cp}}$ (5)

From (4) $C_1 = \frac{I_{cp}}{V_{cp}} \frac{2T_1}{\pi}$ (6)

As shown in Appendix B. for 1% sinusoidal non-linearity the value of is given by

$$C_2 = 1000\,C_1 \text{ approx.}$$

This neglects the effect of the continuous discharge current through $_2$, which tends to increase the non linearity. The value of C_2 is best etermined experimentally.

Let $\frac{1}{2T_2} = \frac{1}{2\pi\sqrt{L_2C_1}}$ assuming $T_1 << T_2$

rom (6) $L_2 = \frac{T_2^2\,V_{cp}}{2\pi\,T_1\,I_{cp}}$ (7)

ow $V_r = \frac{L_1\,I_{cp}}{T_2}$

ssuming that current in $L_1 = 0$ at end of T_2 and neglecting I_{cc} flowing R$_2$ and the small loss in R$_1$.

The mean current flowing in R$_2$ is $\frac{I_{cp}}{2}$

herefore $R_2 = \frac{2\,L_1}{T_2}$

rom (5) $R_2 = \frac{4\,T_1\,V_{cp}}{\pi\,T_2\,I_{cp}}$ (8)

Now $V_{cc} = \frac{V_{cp}}{2}$ (9)

The peak current in L$_2$ is given by $\frac{\pi\,I_{cc}}{2}$

Now $\frac{\pi\,I_{cc}}{2} = \frac{V_{cc}\,2\,T_2}{2\pi\,L_2}$

ssuming that T_1 is much less than T_2.

herefore $I_{cc} = \frac{V_{cc}\,2\,T_2}{\pi^2\,L_2}$

From (7) $I_{cc} = \dfrac{2T_1 I_{cp}}{\pi T_2}$ (10)

Summarizing:

$$V_{cp} I_{cp} = \frac{4\pi J}{T_1}$$

$$C_1 = \frac{2T_1 I_{cp}}{\pi V_{cp}}$$

$$L_1 = \frac{2T_1 V_{cp}}{\pi I_{cp}}$$

From (7) and (5) $L_2 = \dfrac{L_1 T_2^2}{4 T_1^2}$

$$C_2 = 10000\, C_1 \text{ approx. (empirical)}$$

$$R_2 = \frac{4 T_1 V_{cp}}{\pi T_2 I_{cp}}$$

$$V_{cc} = \frac{V_{cp}}{2}$$

From (10) $I_{cc} = \dfrac{I_{cp}}{17}$ approximately, when $T_2 = 11 T_1$

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BOOK REVIEWS

EQUENCY MODULATION *by L. B. Arguimban and R. D. Stuart*

thuen and Co. London. Price 8s. 6d.

authors of this very readable monoph have stressed the value of the concept nstantaneous frequency in dealing with blems arising in the application of uency modulation; indeed the alterna- approach by way of time and phase eives scant mention. Followers of the er school should not be deterred, for the hors handle their theme with skill and ity, and we cannot but be stimulated by insight gained from a different approach. s applies particularly when considering effects of interfering signals, especially in tion to bandwidth.

practical outlook is maintained throughout; detailed descriptions of the modes of operation of limiters and of several discriminators, including the locked-oscillator, are given, whilst the longest chapter, that on interference, is particularly recommended. A final short chapter deals with problems peculiar to television signals when transmitted by frequency modulation, and concludes that though improvement relative to amplitude modulation is possible, the cost in terms of channel bandwidth is too high for a broadcasting service.

The figures are excellent and full use is made of vector diagrams to clarify points under discussion.

LECOMMUNICATIONS PRINCIPLES *by R. N. Renton*, pp. 446

Isaac Pitman and Sons, Ltd. Price 45s.

s always an advantage for a student of a nical subject to have as a source of study omprehensive book covering all the ciples of his subject. The aim of the hor of the volume under review is to sent in a single volume all the "principles" uired by a student of telecommunications to the level required to pass Grade III he City and Guilds Examinations.

n the new edition the rationalized system I.K.S. units is used exclusively. No commises with the older C.G.S. electrognetic and electrostatic units has been de and it is refreshing to note that neither nparisons nor conversions are considered ween the two systems.

hroughout the text, large numbers of ked examples are given, these being luded at the end of each appropriate tion. A feature that is helpful to the nentary student is the appendix contain- mathematical notes relating to calculus ation, trigonometry and vectors to which can refer for revision purposes.

he treatment is adequate and effective covers not only principles but also lications. Although the d.c. circuit is well lt with, the notes could with advantage e included information on commercial stors having a negative temperature fficient, such as thermistors. These are, of course, finding increasing use in telecommunications equipment. The description of the series connection of electrolytic condensers when the operating voltage is higher than the individual rated voltages of the condensers, does not include a note on the use of a shunt resistance across each to carry the respective leakage currents which may be quite different.

The statement that in diversity reception the aerials are spaced from one another by 500 feet or more needs qualification. In practice, a spacing of $3\lambda - 7\lambda$ is found to be sufficient in most cases to prevent fading synchronization at the two aerials.

Chapter XIII on electronics is a valuable introduction to the subject but shows in Fig. 13.11 the triode electrodes mounted with their axes perpendicular to the stem and having connections from each end of the grid joined together and to the base in such a manner that they could be in contact with the anode cylinder. Other illustrations showing sectional views of valves are, however, sufficiently clear to correct any false impression that might be created. The part of this chapter dealing with the valve under dynamic conditions is admirable and presents an extremely clear picture of a valve in operation. Although the simple

continued

equivalent circuit of the resistance capacitance amplifier is given, no mention is made of the important modifications that have to be made when the higher frequencies are considered.

These criticisms are very minor, the book being well written and well produced. Mr. Renton has succeeded in his task, and has compiled a book which students in the lower technical grades will find a valuable guide long after they have passed their examinations.

BASIC MATHEMATICS FOR RADIO AND ELECTRONICS

by F. M. Colebrook and J. W. Head. Iliffe and Sons, Ltd. Price 17s. 6d.

This book is really based on the assumption that most people, including radio engineers, do not always appreciate what they are doing when applying mathematics to practical problems. The late Mr. Colebrook therefore went to great lengths to vitalize and humanize (to use his own words) an apparently academic subject. In so doing he produced a most stimulating and entertaining book. The style is so individualistic that Mr. Head was wise in revising the book not to attempt to rewrite it but rather to extend its scope.

It is doubtful, however, whether anyone who has reached the status of a radio engineer without gaining a reasonable idea of the physical reality behind his use of the symbols and rules of elementary algebra, will be able to make up for lost time by reading this novel presentation of what is largely schoolboy knowledge. It is true that many people would have got further had they been taught by someone with the genius for anticipating and illuminating their difficulties that is displayed in these pages, but, when all is said and done, mathematics remains an art which some can be taught to understand formally but few to apply with contindence and originality.

The scope of the book is much narrower than the title suggests, as the relatively short chapter on the application of mathematical ideas to radio is concerned solely with alternating current theory with which Mr. Colebrook was primarily concerned, while there is no reference whatever in the book to electronics. The title is therefore somewhat misleading and would be better replaced by "Basic mathematics with applications to alternating current theory."

Apart from two very brief sections on numerical computations and random variations, the two chapters added by Mr. Head are also directed towards circuit analysis. The description of Heaviside's technique is quite different in approach from the original part of the book, as the reader has to accept a set of rules and learn how to apply them without necessarily understanding how they are derived. This is in effect an admission that the science of mathematics is much more difficult than the main theme of the book suggests, and that the radio engineer who has to apply mathematical methods to solve his problems may have to take a good deal for granted, unless he is prepared to master far more basic mathematics than this book even hints at.

The engineer concerned with aerial theory, wave propagation or circuit synthesis would need to know, for instance, something about vector analysis, complex variable theory and partial differential equations. It is a pity that Mr. Head did not take the opportunity to give some guidance in these directions. It would have made no more difficult reading than his treatment of matrices with its introduction without proof of an elegant theorem taken from a recently published paper.

However, although this book, like the many others that have been written with the same aim, will probably not succeed in turning the non-mathematically minded into competent users of mathematics, it nevertheless makes refreshing reading. It is certainly a salutary reminder that it is a good thing to know, if possible, the reason behind the techniques which the engineer applies to his practical problems if he is to avoid misusing them on occasion.

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Beam Aerials for Long Distance Telecommunications

n the mid 1920s significant changes were made in the technique of long istance point to point communication systems. Due to the new beam erial designs, pioneered largely by C. S. Franklin, systems hitherto onfined to long wave working were able to operate successfully in the IF spectrum (or so-called short waves) giving increased reliability and hannel capacity. Any doubts about the improvements brought in by the ew short wave beam systems were soon swamped in the flood of traffic hat followed the change over, and communications in the HF band 0 Mc/s to 30 Mc/s has continued to be a very important and active feature f world wide systems to the present time.

The beam aerials which supplied the impetus for this departure in echnique were designed to concentrate a high proportion of the available ransmitter power into a beam aligned at a fairly low angle to the horizon n the direction of the co-operating station. Receiving aerials were likewise eamed and made capable of discriminating against unwanted signals. These aerials, operating at wavelengths between 3 metres and 100 metres, re in general either the standing wave type such as the dipole curtain rrays and the uniform current arrays, which radiate the beam in a irection approximately normal to the plane of the array (hence they are ometimes called broadside arrays), or the travelling wave type of aerial such as the rhombic or the H.A.D (Horizontal Array of Dipoles) which

equivalent circuit of the resistance capacitance amplifier is given, no mention is made of the important modifications that have to be made when the higher frequencies are considered.

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