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Multi-track magnetic heads

Innovation in consumer electronics

Sound radiation

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Multi-track magnetic heads in thin-film technology

M. G. J. Heijman, J. H. W. Kuntzel and G. H. J. Somers

Magnetic conductors, electrical conductors and insulators are the principal materials used in magnetic heads for sound recording. These materials can be deposited on a substrate by techniques much like those used in IC technology. This makes it possible to combine a large number of magnetic heads, each with an extremely small gap of length 1 μm or less. The multi-track magnetic heads made in this way for recording 32 signals simultaneously work in the usual way with a coil. The heads that read out all these signals simultaneously do not have a coil, but an element based on the magnetoresistance effect. These multi-track magnetic heads have been developed for Philips CLS equipment (CLS stands for Communication-Logging System).

Introduction

Philips CLS equipment (CLS stands for Communication-Logging System) is designed for recording spoken messages sent by the police, fire-fighting services, banks, health-care services, and in aviation or road-traffic control. A CLS logger has to be highly reliable and capable of simultaneously recording large numbers of different speech signals containing frequencies from 300 to 3400 Hz. Tape utilization should also be very small. The latest generation of logging equipment, the CLS 8000 series, see *fig. 1*, uses magnetic-tape cassettes derived from video cassettes. Tape speed is very low, 6.6 mm/s, so that with automatic reversal the tape will run unattended for 24 hours. If the logger only records during preset times or when a speech signal is actually presented, the period of unattended operation can be very much longer.

In a CLS logger the magnetic heads that record the signals on the magnetic tape — the recording or 'write' heads — and the magnetic heads that read the signals from the tape — the playback or 'read' heads — are different. These recording and playback heads have to meet some difficult requirements. First, they must have a long life, longer than 50 000 hours. Secondly, there should be multiple channels, so that large numbers of signals can be recorded simultaneously on a magnetic tape only 12.65 mm wide. A third requirement is that the gap in the heads should be so small that signals at a frequency of 3400 Hz can be processed at the low tape speed.

The latest equipment in the CLS 8000 series, if designed for automatic reversal of tape travel, has 32 input channels and a running time of 24 hours. Without

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automatic reversal there are a maximum of 64 channels and a running time of 12 hours. The loggers have 32-track recording and playback heads. In the version with 32 channels the 32 tracks recorded in the reverse direction are 'interleaved' with the 32 tracks recorded in the forward direction. In the version with 64 channels, 64 signals are simultaneously recorded on the tape by two 32-track recording heads.

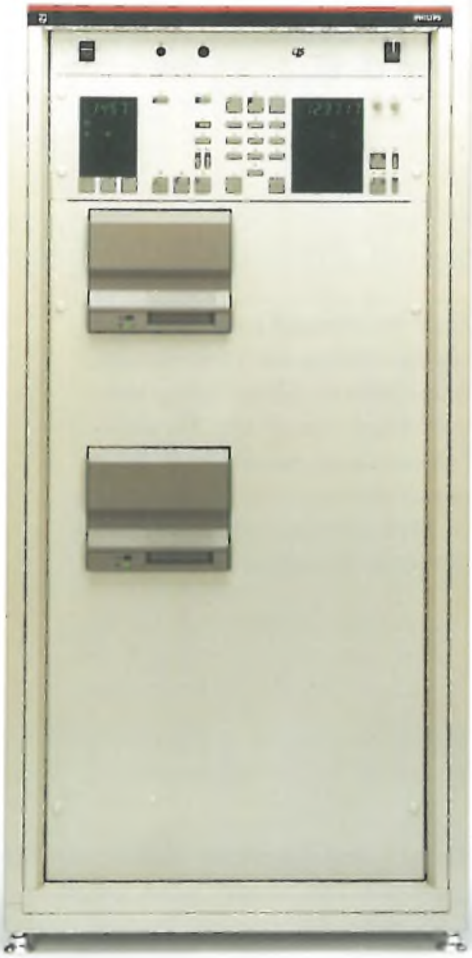

Fig. 1. One of the communication loggers in the Philips CLS 8000 series (type number is LDB 8522/32). The equipment has 32 input channels and will operate continuously, unattended, for 24 hours, or in special cases for even longer. It has a dual transport mechanism, so that two cassettes can be fitted. When one of the cassettes is full, recording is automatically switched to the other one.

The pitch of the tracks on the tape is $12.65/64 \approx 0.19$ mm. The pitch of the individual heads in a 32-track head is 0.38 mm. On automatic reversal a special mechanism moves the recording and playback heads through a distance of 0.19 mm. The effective width of a single recording head is 0.16 mm. This is also the width of a track on the tape. The tracks have to have free space between them because they are not recorded in a perfect straight line on the tape. For the same reason the width of a playback head is slightly less than the track width: it is 0.10 mm.

Just how large is the smallest wavelength in the recorded magnetization pattern (the track)? To answer this question we must first look at *fig. 2*, which shows the principle used in recording and playback of signals by conventional magnetic heads with a coil. The wavelength λ in the magnetization pattern is equal to the ratio of the tape speed v and the frequency f. In our case the wavelength λ of a sinusoidal signal at 3400 Hz, the highest frequency that can occur, is 1.9 µm.

The length l of the 'air gap' or 'head gap' in the magnetic circuit of the playback heads should preferably be no greater than half the wavelength λ [1]. (In magnetic heads the direction of tape travel is usually called the longitudinal direction.) The value of l adopted for CLS playback heads is 0.7 µm, which is a fairly low value for magnetic heads. Until recently the CLS magnetic heads were made by mechanical methods. This meant that only 12 heads could be combined, so that no more than 24 signals could be recorded on a tape. The small gap length and the demand for more tracks on the tape made it necessary to adopt a more sophisticated method of manufacture: thin-film technology.

The manufacture of magnetic heads by thin-film technology usually starts with a substrate of ferrite, since this material can form part of the magnetic circuit. The magnetic 'yoke', the coil and other parts of the heads are 'planar' in the form of thin layers on the substrate. In actual use the substrate is mounted with its upper surface perpendicular to the direction of tape travel.

The first fabrication step consists in depositing a thin film by an electrochemical technique or by 'sputtering'. A photosensitive resist (a photoresist) is then applied to the film and locally illuminated through a mask. With a 'positive' resist the exposed areas are dissolved in a developer, and with a negative resist the unexposed parts are dissolved. The areas where there is no resist are then etched away. After removal of the remaining resist the next layer is deposited and subjected to the same treatment, and so on.

The processes are very like those used in IC technology. A difference is that higher temperatures are used in IC technology, because of the need for thermal diffusions. High temperatures are not required in the fabrication of magnetic heads, and indeed are undesirable since they can adversely affect the magnetic properties. The main materials used for magnetic heads are:

- permalloy (nickel-iron: 80% Ni, 20% Fe), for the magnetic circuit,
- gold, for the electrical circuit and
- silicon dioxide, for electrical insulation and for the 'air gap'.

The magnitude of the magnetic flux in the gap of a recording head, see fig. 2, is proportional to the current I in the coil and the number of turns. For CLS recording heads two turns per coil are sufficient, since the current can be large enough. However, an r.f. biasing field is necessary to prevent nonlinear effects due to the hysteresis of the ferromagnetic material of the tape. This bias field generates additional heat, however. As we shall see later, this problem was solved by using a pulsed high-frequency bias current instead of a sinusoidal current.

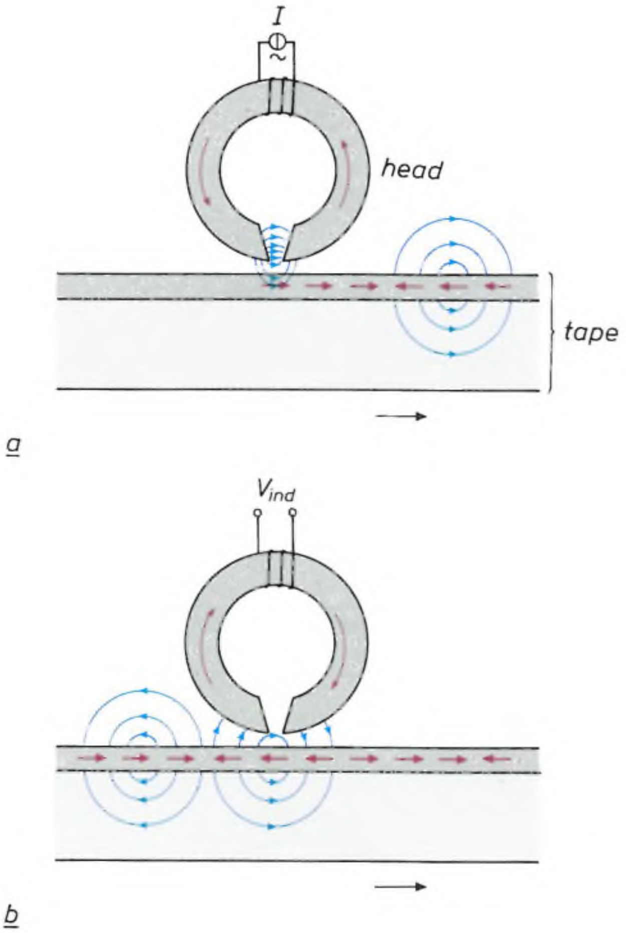

Fig. 2. Principle of recording signals on magnetic tape and playing them back in the conventional way by using magnetic heads with a coil. *a*) During recording the signal current I generates a magnetic fringeing field in the head gap. This field records the signal on the tape as a magnetization parallel to the surface (red arrows). *b*) At playback the varying magnetic flux in the head, due to the fringeing field around the tape (blue arrows), induces a voltage V_{ind} in the coil.

The voltage V_{ind} induced in the coil of the playback head in fig. 2 is equal to the product of the number of turns and the time derivative of the flux. The derivative is fairly small because of the low signal frequencies. To obtain a sufficiently large V_{ind} it would be necessary to have a very large number of turns for the playback head; say a hundred or more. It is not very easy to make coils with so many turns in thin-film technology. The CLS playback heads are therefore made with an element whose operation depends on the magnetoresistance effect. When this effect is used the magnitude of the signal in the playback head is essentially independent of the signal frequency.

In the rest of the article we shall first show how the magnetoresistance effect is applied. Next we shall deal with the excitation of the r.f. bias in the recording heads. Finally, we shall discuss the method of manufacture, touching on the processes, on the methods of testing and the assembly of a 32-track head.

The magnetoresistance effect

When an electric current flows in a ferromagnetic material the magnitude of the electrical resistance depends on the angle between the direction of the current and that of the magnetization [2]. It is rather surprising to find that the magnetoresistance effect was discovered by Lord Kelvin well over a century ago, in about 1856. He wrote: 'I concluded with confidence that the electric conductivity of magnetized iron is greater across than along the lines of magnetization.' *Fig. 3* shows the complicated arrangement of plates of copper and soft iron he used for the experiment he described [3].

The operation of thin-film playback heads depends on the magnetoresistance effect in a permalloy strip. When the external magnetic field is zero, the preferred direction of magnetization will be in the longitudinal direction, in our case the x-axis. When an external magnetic field is applied in the transverse direction, along the y-axis, the resistance encountered by an electric current in the strip changes, since the angle between the current and the magnetization has changed. The curve of the change in resistance as a function of the field-strength in the y-direction, H_y, approximates to a parabola, as can be seen from the dashed curve in *fig. 4a*. Near $H_y = 0$, however, an approximately linear curve is desirable.

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[1] J. P. M. Verbunt, Laboratory-scale manufacture of magnetic heads, Philips Tech. Rev. **44**, 151-160, 1988.

[2] W. J. van Gestel, F. W. Gorter and K. E. Kuijk, Read-out of a magnetic tape by the magnetoresistance effect, Philips Tech. Rev. **37**, 42-50, 1977.

[3] W. Thomson, Mathematical and physical papers, part II, Cambridge University Press, Cambridge 1884, page 307 to 327.

The change in resistance can be made linear by applying a 'barber pole' structure of electrically conducting material to the permalloy strip; see fig. 4*b*. The material used for this structure is gold. Because of the high conductivity of these areas on the strip, the angle between the current and the magnetization is 45° for $H_y = 0$. The continuous curve in fig. 4*a* shows the relation between the change in resistance and the magnitude of H_y.

Fig. 4*c* shows very schematically how the magnetoresistive element, *MRE*, is included in the magnetic circuit of the playback head. The lines of force that come from the 'yoke' in the second air gap supply a component H_y of the magnetization in *MRE*. The change in the resistance of the strip and hence in the magnitude of the signal produced by the playback head is proportional to the magnetic flux in the yoke, and not to its derivative, as in a playback head with a coil. The amplitude of the signal in the playback head in fig. 4*c* is therefore independent of its frequency.

The form of the magnetoresistance element

As we have seen, the magnetoresistance element is built up from a ferromagnetic strip with a conducting structure on top of it; see fig. 4*b*. In general, such a

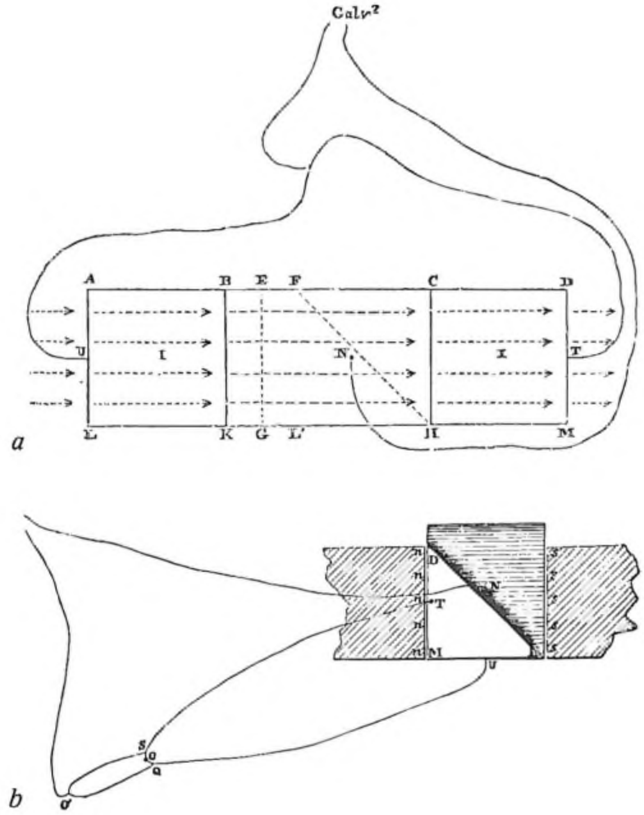

Fig. 3. The experimental arrangement that William Thomson, later Lord Kelvin, used for the first observation of the magnetoresistance effect [3]. *a*) *BCHK* copper plate. *ABKL* and *CDMH* soft-iron plates. The plates are soldered together along the lines *BK* and *CH*. The entire assembly is bent through 180° along *FH*, *CH* and *EG*, and is provided with copper connecting wires. Pieces of cardboard prevent electrical contact between the surfaces folded over one another. *b*) The assembly is now placed between the poles of a 'Ruhmkorff electromagnet'. The poles are denoted by *n* and *s*. The two connecting wires are connected to the poles of a multiple Daniell cell, a precursor of the modern battery. The directions of current flow in the various plates are indicated by arrows in (*a*). When the electromagnet is energized, the direction of the electric current in the soft iron of *CDMH* is parallel with the direction of the magnetization; in *ABKL* they are at right angles to each other. In the bridge circuit shown here the terminals of a galvanometer are connected to the points *N* and *O*. When the electromagnet is not energized, the deflection of the galvanometer can be set exactly to zero by moving the contact point *O'* along the wire loop. Thomson discovered that the galvanometer deflected when the electromagnet was energized. The different directions of the magnetization with respect to the current in *CDMH* and *ABKL* apparently unbalance the bridge, and thus cause a difference in the electrical resistance of the soft iron.

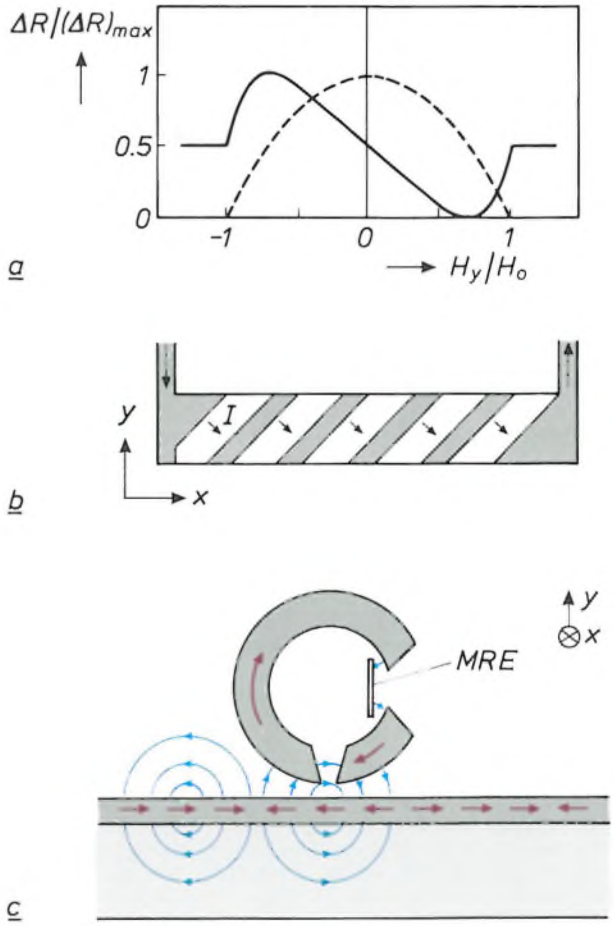

Fig. 4. *a*) The relative change $\Delta R/(\Delta R)_{\max}$ in the resistance of a ferromagnetic strip as a function of the ratio of the magnetic field-strength in the *y*-direction to a reference field-strength H_0 [2]. The dashed curve refers to an untreated strip. The continuous curve, which in a wide range approximates to a straight line, refers to the case where a 'barber pole' structure of conducting material is applied to the strip. *b*) A strip treated in this way. The grey areas correspond to conducting material. For $H_y = 0$ the angle between the current *I* and the magnetization is 45° in the areas in between. *c*) Principle of a playback head with a magnetoresistance element *MRE* in the form of a 'barber pole'. A change in the magnetic flux in the yoke causes a change in the direction of the magnetization in *MRE*, and hence in the electrical resistance. The *x*-direction is perpendicular to the plane of the drawing.

strip does not just contain a single domain in which the magnetization has the same direction everywhere, but has different domains each with a different direction of magnetization. These are often known as Weiss domains and their common boundaries are called Bloch walls[4]. In a rectangular strip the Bloch walls generally start from the corners; see *fig. 5a*. When a magnetic field is applied at right angles to the longitudinal direction, the various domains change in size, so that the Bloch walls have to change their positions. Owing to slight inhomogeneities in the material, there are discontinuities in the movements of the walls — the Barkhausen effect. As a result, 'Barkhausen noise' is superimposed on the output signal of a playback head.

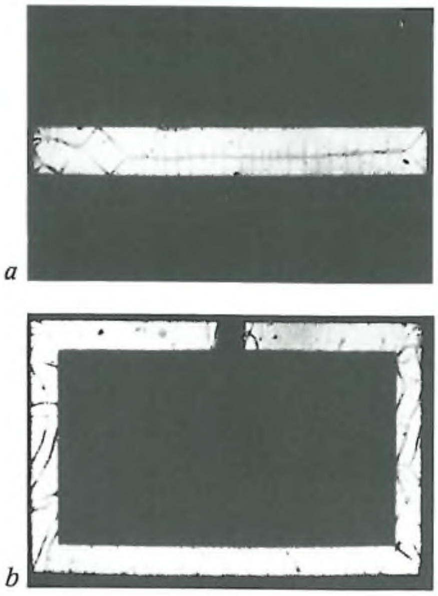

Fig. 5. The magnetic (or Weiss) domains *a*) in a rectangular magnetoresistance element and *b*) in a magnetoresistance element in the form of an interrupted loop.

We solved the problem of the Barkhausen noise by getting the Bloch walls to form outside the active part of the magnetoresistance element. Fig. 5*b* shows that this was done by making the permalloy strip in the shape of an interrupted loop. (The break is necessary to prevent circulating currents.) The corners where the Bloch walls originate thus lie outside the region of the 'barber pole'. Partly because a magnetic field is applied in the appropriate direction (horizontal in the figure) when the layer for the magnetoresistance element is deposited, there is only one domain at the location of the 'barber pole'. In the vertical parts there are more domains, but these do not cause any perceptible Barkhausen noise.

The r.f. bias field in the recording heads

In the magnetic recording of an analog speech signal an r.f. bias signal is superimposed whose frequency is much higher than the maximum frequency occurring in the analog signal. A bias frequency between 60 and 100 kHz is usually used. The bias signal induces an r.f. bias field in the recording head, and the bias ensures that the hysteresis of the tape material does not cause distortion of the recorded signal.

The bias current required for each recording head is about 100 mA. The total bias current for a 32-track CLS recording head is therefore about 3 A. A current as high as this would raise the temperature of the recording heads above the Curie point of ferrite, 130 °C.

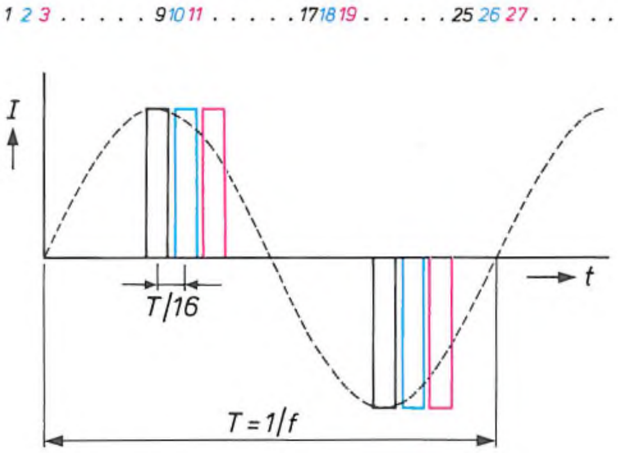

Fig. 6. The pulsed bias current supplied to the individual recording heads, numbered *1* to *32*. *I* current. *t* time. The pulses shown in black are associated with the four heads with the black numbers, and similarly for blue and red, and so on. During any half-period of the original sinusoidal bias current (dashed line) there are eight successive pulses of the same polarity; in the next half-period there are eight more of the opposite polarity. *T* period. *f* frequency.

This problem was solved by using a pulsed current for the bias instead of the usual sinusoidal current and by not applying it to all 32 recording heads simultaneously. The pulse duration is only 10% of half a period of the original sinusoidal signal. Trains of positive pulses alternate with trains of negative pulses in successive half-period intervals; see *fig. 6*.

The analog speech signal is only applied to a recording head while a positive or negative pulse is present. The individual recording heads are divided into groups for pulse supply. If the heads are numbered from *1* to *32*, a current pulse is applied first to heads *1*,

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[4] H. J. de Wit and K. Jager, Magnetic domains in amorphous alloys for tape-recorder heads, Philips Tech. Rev. 44, 101-109, 1988.

9, *17* and *25* (shown black). The heads *2*, *10*, *18* and *26* (blue) receive current pulses next, but with a delay of 1/16 of a period, and so on. Then all the heads receive a succession of negative pulses, and so on. This procedure greatly reduces the amount of heat generated, and the heat is distributed more evenly over the surface.

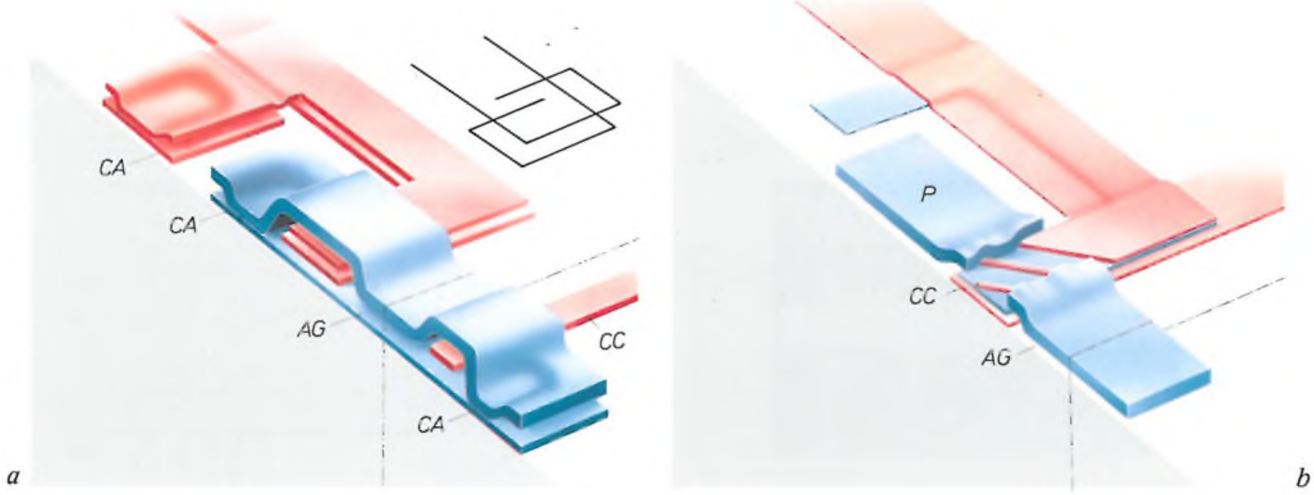

Fig. 7. *a*) A recording head and *b*) a playback head in thin-film technology. The heads have been cut through perpendicular to the surface of the magnetic tape. The chain-dotted line is the line of intersection with the plane of the tape, where the heads are sawn from the wafer. The part in (*a*) on the right below the chain-dotted line is the counter-head. Blue: permalloy; red: gold; grey: ferrite. The silicon dioxide has been omitted for clarity; it is assumed to be 'transparent'. *AG* head gap. *CC* common test conductor. *CA* contact areas of the two turns of the recording head and the flux guides, passing through SiO_2 layers between them. The two turns are shown schematically at the upper right in (*a*). The playback head only has an upper flux guide; the ferrite of the substrate acts as the lower flux guide. In this case the upper flux guide is separated by an SiO_2 layer from the substrate, since the relatively large area at *P* presents a low resistance to the magnetic flux.

The manufacture of thin-film magnetic heads

Thin-film technology

The yokes or flux guides of the heads shown schematically in figs 2*a* and 4*c* can be produced in thin-film technology by depositing thin films of permalloy on a ferrite substrate. The electrical conductors are formed by depositing thin films of gold, and the insulation between permalloy and gold is formed by depositing films of silicon dioxide. The head gap of 0.7 μm therefore corresponds to an SiO_2 film of this thickness between the two flux guides.

A recording head built up in this way is illustrated schematically in *fig. 7a* and a playback head is shown in fig. 7*b*. The two turns of the recording-head coil lie one above the other, separated by SiO_2. They make contact with each other through a hole etched in the SiO_2. Each recording head has a 'counter-head', used for testing the heads while they are still on the wafer. All 32 counter-heads have a common conductor, *CC*, so that each combination of recording head and corresponding counter-head can act as a kind of transformer. In all the good recording heads an r.f. current in the common conductor of the counter-heads should induce an alternating voltage at the same frequency and of amplitude above a certain threshold value. When a 32-track recording head is sawn from the wafer, the counter-heads are destroyed by the saw-cut.

A 32-track playback head also has a common test conductor (*CC*) that runs underneath all the magnetoresistance elements. If this conductor is energized with an alternating current it produces an alternating flux in the flux guides. In a good recording head the resistance of the magnetoresistance elements should then also vary at this frequency. The test conductor can still be used after assembly of a complete 32-track recording head.

The films are deposited on the wafer by sputtering or by an electrochemical process. After application of photoresist, exposure through a mask and removal of the exposed resist, the film is etched away locally as shown in *fig. 8*. As we have said, the techniques are essentially no different from those used in IC technology[5]. In general the manufacture of thin-film heads presents no difficulties in this respect and there is no

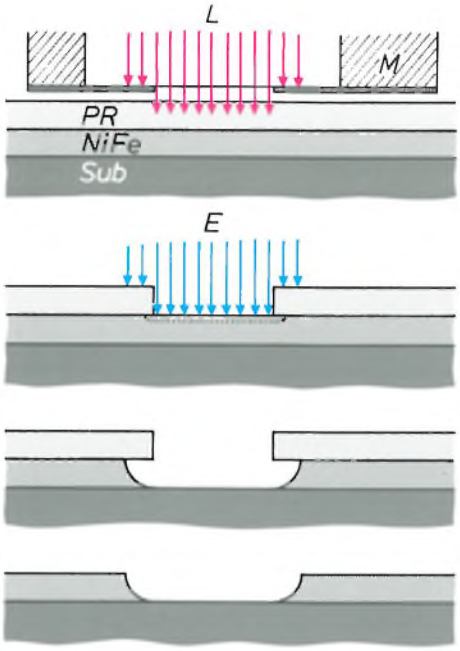

Fig. 8. Local removal of permalloy by means of a 'positive' photoresist, exposure and etching. *L* light. *E* etchant. *M* mask. *PR* photoresist. *Sub* substrate: ferrite or silicon dioxide applied in a previous process step.

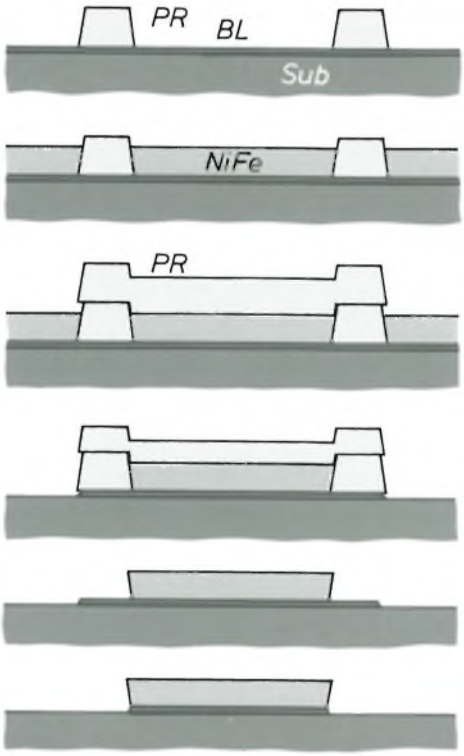

Fig. 9. The box-and-lid process. *BL* base layer. See also the caption of fig. 8. The substrate *Sub* is silicon dioxide from a previous step.

need for a detailed description here. We shall however look at a few techniques that are peculiar to the manufacture of thin-film heads: formation of a flux guide on an uneven surface, making patterns in gold and fabricating the magnetoresistance element.

In the recording heads the magnetic flux is greater than in the playback heads. This is why the recording heads have a lower flux guide of permalloy, which has a higher permeability and saturation flux than the ferrite of the substrate. In the playback heads, on the other hand, the ferrite acts as the lower flux guide. In the recording heads the lower flux guide is sputtered on to the flat base of the substrate. The upper flux guides in both playback and recording heads are applied on top of the SiO_2 and gold films applied previously, and therefore on a relatively uneven surface. The upper flux guide is relatively thick, several microns. Also, a layered structure is produced in the permalloy by periodically varying the ratio of nickel to iron. This 'laminated' structure is used to prevent eddy currents. Because of these various complications the upper flux guides have to be applied in a special electrochemical technique, the 'box and lid' process. This technique gives a much better side wall than an etching process, and the side wall is less affected by corrosion.

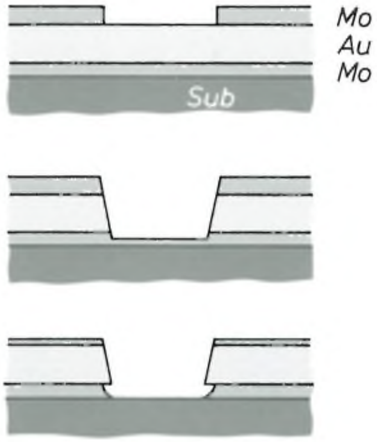

Fig. 10. Removal of gold, using a molybdenum mask, to leave a 'barber pole' structure. *Sub* substrate, in this case silicon dioxide.

Fig. 9 shows the principle of the box-and-lid process. On a thin conducting permalloy base layer *BL* with titanium oxide beneath it for adhesion, walls of photoresist *PR* are built up, forming the side walls of the 'box'. Permalloy with periodically varying composition is then grown on the base layer. At the places where the flux guide is to remain, another layer of

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[5] S. M. Sze (ed.), VLSI technology, McGraw-Hill, New York 1983.

photoresist is deposited (this is the 'lid'). Then the surplus permalloy is etched away, the photoresist is dissolved and finally what is left of the base layer is removed by a brief ion-etching process [6].

The gold for the electrical conductors is deposited by sputtering. Gold does not adhere well to silicon dioxide, however, and so an adhesion layer of molybdenum is applied first, again by sputtering; see *fig. 10.* A second layer of Mo is deposited on the gold. At the places where gold is to be removed an opening is made in the second Mo layer by wet-chemical etching through a mask of photoresist. The second Mo layer then acts as a mask for etching away the gold with a plasma of O_2 and Ar [7].

To protect the permalloy of the magnetoresistance element when making a 'barber pole' the etching process is stopped when about half of the lower Mo layer has been removed. The remainder is then etched away by a CF_4 plasma. The other electrical conductors are made by etching with O_2 and Ar alone, and the process continues until the lower molybdenum has been completely removed.

As mentioned earlier, the magnetoresistance element in a playback head takes the form of an interrupted loop; see fig. 5*b*. The element need be only a few hundredths of a micron thick. The original layer, which will be etched later, can therefore be applied by sputtering. During the sputtering process a highly uni-

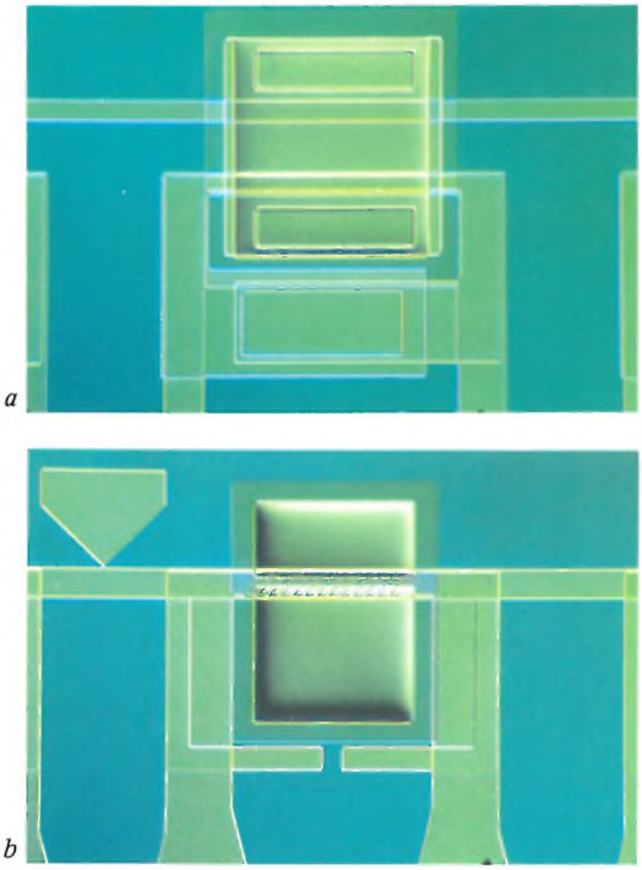
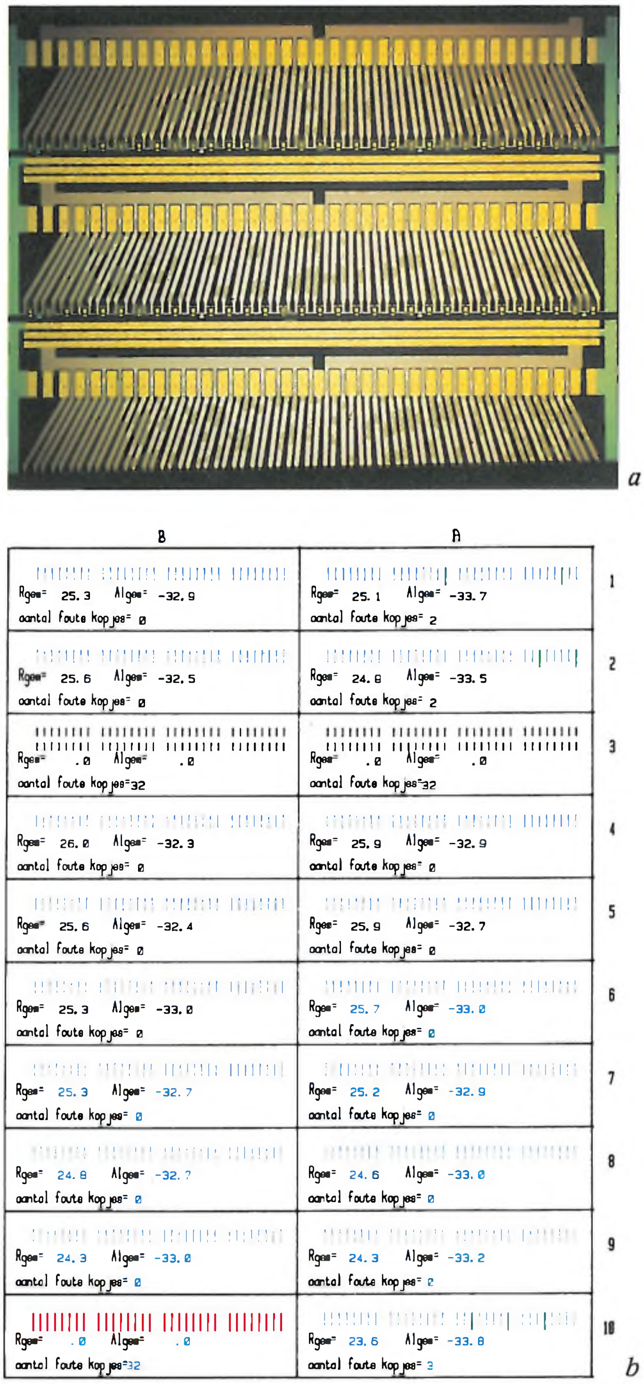


Fig. 11. Photomicrograph of *a*) a single recording head and *b*) a single playback head.



B	A	
Rgem= 25.3 Algem= -32.9 aantal foute kopjes= 0	Rgem= 25.1 Algem= -33.7 aantal foute kopjes= 2	1
Rgem= 25.6 Algem= -32.5 aantal foute kopjes= 0	Rgem= 24.8 Algem= -33.5 aantal foute kopjes= 2	2
Rgem= .0 Algem= .0 aantal foute kopjes=32	Rgem= .0 Algem= .0 aantal foute kopjes=32	3
Rgem= 26.0 Algem= -32.3 aantal foute kopjes= 0	Rgem= 25.9 Algem= -32.9 aantal foute kopjes= 0	4
Rgem= 25.6 Algem= -32.4 aantal foute kopjes= 0	Rgem= 25.9 Algem= -32.7 aantal foute kopjes= 0	5
Rgem= 25.3 Algem= -33.0 aantal foute kopjes= 0	Rgem= 25.7 Algem= -33.0 aantal foute kopjes= 0	6
Rgem= 25.3 Algem= -32.7 aantal foute kopjes= 0	Rgem= 25.2 Algem= -32.9 aantal foute kopjes= 0	7
Rgem= 24.8 Algem= -32.7 aantal foute kopjes= 0	Rgem= 24.6 Algem= -33.0 aantal foute kopjes= 0	8
Rgem= 24.3 Algem= -33.0 aantal foute kopjes= 0	Rgem= 24.3 Algem= -33.2 aantal foute kopjes= 2	9
Rgem= .0 Algem= .0 aantal foute kopjes=32	Rgem= 23.6 Algem= -33.8 aantal foute kopjes= 3	10

Fig. 12. *a*) Photomicrograph of three 32-track read heads still on the ferrite wafer. The indentations on the contact faces were made by test pins. *b*) Summary sheet produced by the computer from the automatic tester. Each frame contains the results of measurements on a 32-track playback head. The colour coding for the heads is: blue stripe — pass; dashed blue stripe — second harmonic of the signal transferred by the test conductor is too high; black stripe — interrupted magnetoresistance element; dashed black stripe — short-circuit in the element; red stripe — resistance of the element is outside the limits; green stripe — the amplitude of the transferred signal is too small.

form magnetic field is applied along the long axis of the magnetoresistance element to be formed in the etching step. In this way an 'easy' axis of magnetization is produced in the permalloy film.

The permalloy film is applied by r.f. sputtering, with high-frequency electric fields. Since the r.f. source and the load are not usually perfectly matched, reactive currents at the same frequency occur in metal near the plasma. We had to develop specially shaped permanent magnets to obtain a uniform magnetic field with the required direction at the ferrite wafers.

After the permalloy has been etched to produce the structure shown in fig. 5*b*, the next step is to deposit the 'barber pole' of gold and molybdenum on the element by the process described above. If the temperatures are too high, or if there are magnetic fields in undesired directions, the preferred direction of magnetization in the magnetoresistance elements may be lost. In this and later process steps the wafers must therefore be handled with extreme care.

After all the process steps have been successfully completed, a recording head and a playback head will look as shown in *fig. 11*.

Testing

Fig. 12a shows part of a ferrite wafer with three 32-track playback heads. Each individual head is tested on the wafer before the multiple head is sawn off and assembled to form a head ready to be mounted in a system. The indentations made by the test pins in an automatic test instrument can be seen in the figure. A row of four test points (vertical in the figure) consists of, from top to bottom: two common connections to the test conductor, a common connection to the magnetoresistance element and an individual connection to this element.

The resistance of the magnetoresistance element and the magnetic transfer of a 2000-Hz test signal are measured for each head. A computer print-out from the automatic test unit lists the following figures for each 32-track playback head:

- the mean and the standard deviation for 32 results of the resistance measurement.
- the mean and the standard deviation for 32 results of the magnetic transfer measurement, and
- the number of heads that have passed the test.

The last figure is obtained by using specified pass values for the resistance and the magnetic transfer.

Fig. 12*b* shows a summary sheet produced by the computer for each measured ferrite wafer. A blue vertical line represents a head that has passed. Fourteen of the twenty multiple heads have passed. In two of the heads all the individual magnetoresistance elements are short-circuited. A summary of the pro-

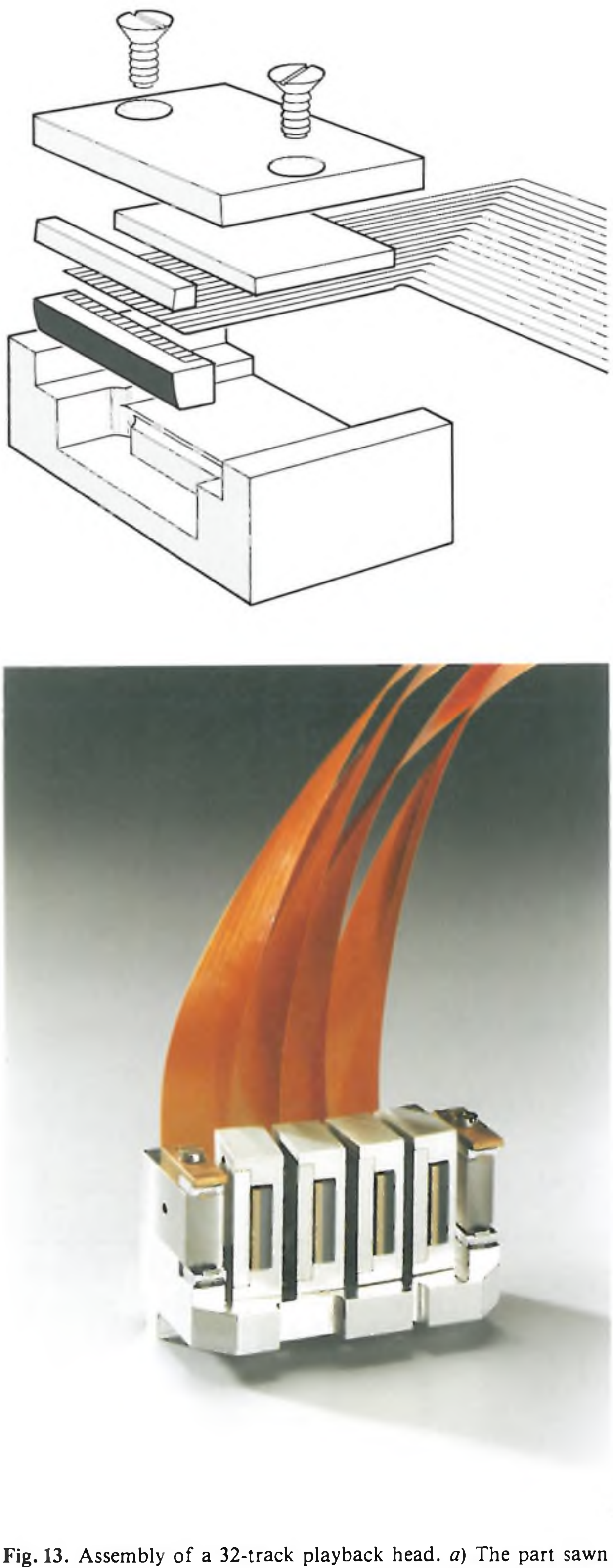


Fig. 13. Assembly of a 32-track playback head. *a*) The part sawn from the ferrite wafer is clamped into an aluminium block with a ceramic 'tile' and a ribbon cable. *b*) The complete assembly of two 32-track recording heads and two 32-track playback heads, ready for mounting in a CLS logger.

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[6] H. Dimigen and H. Lüthje, An investigation of ion etching, Philips Tech. Rev. **35**, 199-208, 1975.

[7] H. Kalter and E. P. G. T. van de Ven, Plasma etching in IC technology, Philips Tech. Rev. **38**, 200-210, 1978/79.

duction results for each wafer can thus be obtained quickly. These results refer to laboratory-scale production, of course.

In the production of the 32-track recording heads the automatic tester is only used for measuring the resistance of the coils in the individual heads. Sample tests are taken of the magnetic-transfer of randomly selected individual heads by applying a 500-kHz signal to the test conductor in the counter-heads.

Assembly

The multiple heads that have passed the test are sawn from the ferrite with a fine diamond saw. The wafer is 2.4 mm thick. A 'tile' of ceramic barium titanate, 1.2 mm thick, is then bonded to the ferrite; see *fig. 13a*. This assembly is then polished to a rounded shape, with the required height of the head gap — the gap dimension perpendicular to the surface of the tape. The small triangles in fig. 11*b* and 12*a* serve as reference marks for measuring gap height. Finally, the surface is lapped with diamond powder of decreasing grain size until the surface that comes into contact with the tape is exceptionally smooth. This means that tape wear is extremely low.

Fig. 13 also shows how the ferrite-and-ceramic assembly with a flexible ribbon cable are clamped in an aluminium housing. The contact faces of the ferrite are pressed against the contact faces of the ribbon cable. After a final test the complete head is ready to be mounted in a Philips CLS logger.

Summary. CLS loggers (CLS stands for Communication-Logging System) used for logging spoken messages have to record or play back a large number of signals simultaneously at a very low tape speed. Multiple magnetic heads have to be used. Thin-film technology is used for fabricating 32-track recording heads that are different from the 32-track playback heads. The recording heads have the conventional coils, the playback heads have a magnetoresistance element. In the magnetoresistance element the resistance of a permalloy strip changes when the field in the magnetic 'yoke' of the playback head changes. The 32-track recording and playback heads are fabricated on a ferrite substrate by process steps like those used in IC technology: sputtering, electrochemical growth, photoresist deposition, exposure, plasma etching, ion etching, and photoresist removal. Test conductors in the heads enable tests to be carried out on the wafer. After all the tests have been carried out the multiple heads that have passed are sawn from the wafer and assembled to form a unit ready to be mounted in a logger.

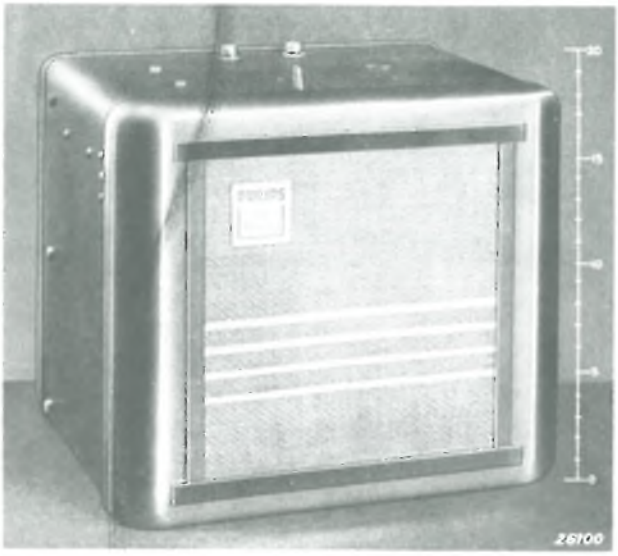
1938 THEN AND NOW 1988

Car radios

The first car radios, designed for long-wave and medium-wave reception, were built in the thirties. The valves and other components then available were far from small and the early sets, which sometimes had built-in loudspeakers, were so large (lower photograph [*]) that they had to be fitted outside the reach of the driver. Remote control was achieved by using Bowden cables and a control unit (photograph right[*]) fitted in the dashboard or underneath it.

In the past fifty years, there have been many radical changes in car radios. Transistors have been followed by integrated circuits. Car radios have become much smaller, they are easier to operate, and the performance is much better. There are so many new facilities — FM, FM-stereo and cassette players — that we speak of 'in-car entertainment'.

The most advanced car radio/cassette combination today is the Philips DC 682 (colour photograph). It makes use of coded digital information added to radio transmissions in the 'radio data system' (RDS) developed by European companies and broadcasting authorities. Philips Research have played a leading part in this development and Philips were the first to put an RDS car radio/cassette combination on the German market. RDS will soon be introduced in other countries as well.



The DC 682 incorporates the primary RDS features: it displays the station selected, switches automatically to the strongest transmitter with the desired programme, and traffic information will override the broadcast signal. It also has many features from other recent Philips car radios which were unthinkable in 1938: preselection from eighteen stations, digital tuning, autostore for automatic tuning to the six strongest FM and MW stations, 2 × 20 W or 4 × 7 W output with fader, line-out, anti-theft security code and retractable unit, and autoreverse cassette deck with Dolby noise reduction, metal/chrome tape selection and Music Sensor System for track repeat and skip. RDS will include many more features in the future, like paging, clock time, radio text and programme type (e.g. sport, jazz).

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[*] From Philips Technical Review, April 1938.

Philips Tech. Rev. 44, No. 6, 180-189, Dec. 1988

Applied research — the source of innovation in consumer electronics

S. van Houten

On 1st June 1988 Dr S. van Houten, a member of the Board of Management of N.V. Philips Gloeilampenfabrieken, gave an invited speech in Nanjing in the People's Republic of China. In his speech Dr van Houten gave a short introduction to the Philips company, then used examples to show how important the role of scientific research is in bringing out a wide variety of electronic consumer products.

China may be distant, but its people are rapidly learning to master the latest technologies, and the speaker was privileged to address a large and attentive audience.

The article below is the text of his speech; we have merely added references and figure captions.

A picture of Philips

The company to which I belong is called Philips Electronic Industries. Our headquarters are located in Eindhoven in the Netherlands, a provincial town situated roughly midway between Amsterdam and Brussels — if that is of any help to you.

Philips Electronic Industries is a major electronics company — in fact number six in the world in terms of sales (*fig. 1*). In 1987 sales totalled 28 billion dollars at current rates. Philips employs over 330 000 people in 60 countries throughout the world. About two-thirds of our activities are concentrated in Western Europe, one quarter in North America. The remainder is divided more or less equally between Latin America and the countries of Eastern Asia.

Among the latter, our activities in the People's Republic of China are growing fast; they are generally carried out by joint ventures in which government agencies participate. Under this scheme we jointly manufacture car radios and radio recorders which are to be sold under the Philips brand name throughout China. Agreement has been reached on the joint manufacture of fluorescent lamps and colour picture tubes. Innovative products such as Compact Discs, CD players and optical cables will in the future be manufactured under joint ownership. Video cassette recorders and integrated circuits will follow.

Philips was started just under a century ago, in 1891, by two brothers named Philips as a light bulb factory. I show a historic picture here: the workers of that first year (*fig. 2*). About 40 years later, the company diversified into gas-discharge lamps, X-ray equipment, radio, gramophones and measuring instruments. Electric shavers and household appliances

			Sales (US$ × 10^9)
1	IBM (International Business Machines)	U.S.A	51.3
2	General Electric	U.S.A	35.2
3	AT&T (American Telephone and Telegraph)	U.S.A	34.1
4	Matsushita	Japan	26.5
5	Hitachi	Japan	22.7
6	Philips	The Netherlands	22.5
7	Siemens	W. Germany	20.3
8	Samsung	Korea	16.5
9	Toshiba	Japan	15.0
10	CGE (Compagnie Générale d'Électricité)	France	11.7

Fig. 1. The ten largest producers of electronic equipment in 1986, in order of sales (source: Fortune).

Dr S. van Houten is a member of the Board of Management and the Group Management Committee of N.V. Philips' Gloeilampenfabrieken.

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Fig. 2. The Philips personnel in the year the company was founded (1891). Today, nearly a century later, there are more than 330000 Philips people in some 60 countries.

were to follow, along with telephone exchanges. Television supported an unprecedented growth in the post-war era. Optical discs carrying sound, picture and data are among our latest inventions.

This means that Philips now covers a wide range of disciplines. For all new fields of activity, the essential components are manufactured in our own plants. We express this by saying that our company is vertically integrated.

Research at Philips

The successful diversification of our company could not have been achieved without a firm base of fundamental knowledge and technical know-how. Our corporate research has played an essential role in the history of our company. Next year it will be 75 years [1] since the first scientist was recruited; he was told to conduct research into the gas-discharge phenomenon. Today our Research Laboratories in the Netherlands employ 2500 people; roughly the same number is employed in seven other laboratories scattered all over the world. All of them are doing fundamental research: product development is done by another 20 000 people. Philips spends a total of more than 8% of its sales on Research and Development — roughly $2.5 billion each year.

As is apparent from the wide variety of Philips products, our research covers a great number of disciplines. Thus we are fortunate in being capable of a multidisciplinary approach to modern systems as modern technology depends increasingly on the combined use of several disciplines. Materials science, fundamental physics, electrotechnology, chemistry and software are combined in products which are to be found everywhere, in hospitals, workshops, banks and — the home.

Modern fluorescent lighting

Fluorescent lamps [2] are a good example. They are an offspring of the gas-discharge lamps which our first research scientist was told to investigate almost seventy-five years ago. The gas discharge generates ultraviolet radiation which causes specially selected phosphors to emit visible light. The first such lamps, which were tubular, came on to the market in the 1930s. From then on, a continuous process of optimization took place. The mercury-vapour discharge was studied in detail, more efficient phosphors were found, the emission spectrum was adjusted to improve colour rendering, the ignition circuit (the 'ballast') was miniaturized by the introduction of electronics. Finally, our PL* and SL* economy lamps were introduced: these are roughly the same size as incandescent lamps but are four times more efficient (*fig. 3*).

a *b*

Fig. 3. In recent years developments in fluorescent lamps have led to compact lamps with more than four times the efficacy and five times the life of comparable incandescent lamps. Examples are the PL* lamp (*a*) and the SL* lamp (*b*). The SL* lamp has a built-in ballast and the same base as conventional incandescent lamps, so that existing fittings can be used.

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[1] A special multiple issue of Philips Technical Review on this 75th Anniversary will appear in 1989.

[2] A. G. Jack and Q. H. F. Vrehen, Progress in fluorescent lamps, Philips Tech. Rev. 42, 342-351, 1986.

TV technology

TV technology always has been an important area of research with Philips [3]. Let us have a look at the video screen; it occupies a key position in consumer electronics. The existing technology, based on electron beams, is still advancing. But new developments are coming on to the market, namely liquid-crystal screens.

The colour picture tube

The electron optics of the conventional colour picture tube have reached a high level of precision, the luminescence of the phosphors has increased over the last few years and new manufacturing techniques have been developed for the electron gun. An important development of the last few years is the 'flat square' tube which has a flatter, more right-angled screen (*fig. 4*). The tube is made of thicker glass; special strength calculations were needed to ensure a safe design. Thanks to perfected electron optics the colour registration right into the corners of the picture is outstanding.

Projection television allows screen sizes of over 1 metre, diagonally (*fig. 5*). These larger sizes give an enhanced viewing experience. Three projection tubes provide the colour picture (*fig. 6a*). Projection cathode-ray tubes have been developed with electron guns which emit an extremely intense electron beam, and phosphors which are subject to 50 times the load of a normal picture tube. 100 watts are continuously applied to the phosphor screen; this necessitates liquid cooling. A special high-grade lens system with aspherical lenses has been developed for the projection optics; this is coupled to the screen via the coolant (fig. 6*b*).

Fig. 5. To obtain a larger picture than with a 'direct-view' picture tube of reasonable dimensions and weight, a projection television set can be used, as shown here. This contains three projection tubes that each produce a subpicture in one of the basic colours red, green or blue. The three subpictures are projected on to the screen exactly in register.

Fig. 4. Modern television picture tube, type 45AX. This is a 'flat square' tube, with the screen as flat and rectangular as possible and the total tube depth as small as possible. The tube shown here also has an extremely thin neck (29.2 mm), so that the deflection of the beam requires less energy.

The projection optics have to meet strict quality requirements. At the same time, however, they have been designed so that they can be produced at a reasonable cost. In projection TV we see once again the many different disciplines involved and the conflicting requirements that are to be met. Once again it is the task of the research department to find the solution [4].

LCD displays for direct-view and projection television

Research also finds completely new ways. Liquid-crystal displays or LCDs will probably be familiar to you from your wrist watch. Their application to colour TV is a recent achievement, which has the advantage that it does away with the bulky and power-consuming picture tube. A pocket-size TV set as shown in *fig. 7* becomes feasible. Larger displays can be hung on the wall like a picture.

Liquid crystals are peculiar liquids. They consist of elongated cigar-shaped molecules. The plane of polarization of the light propagating through the liquid follows the arrangement of the molecules.

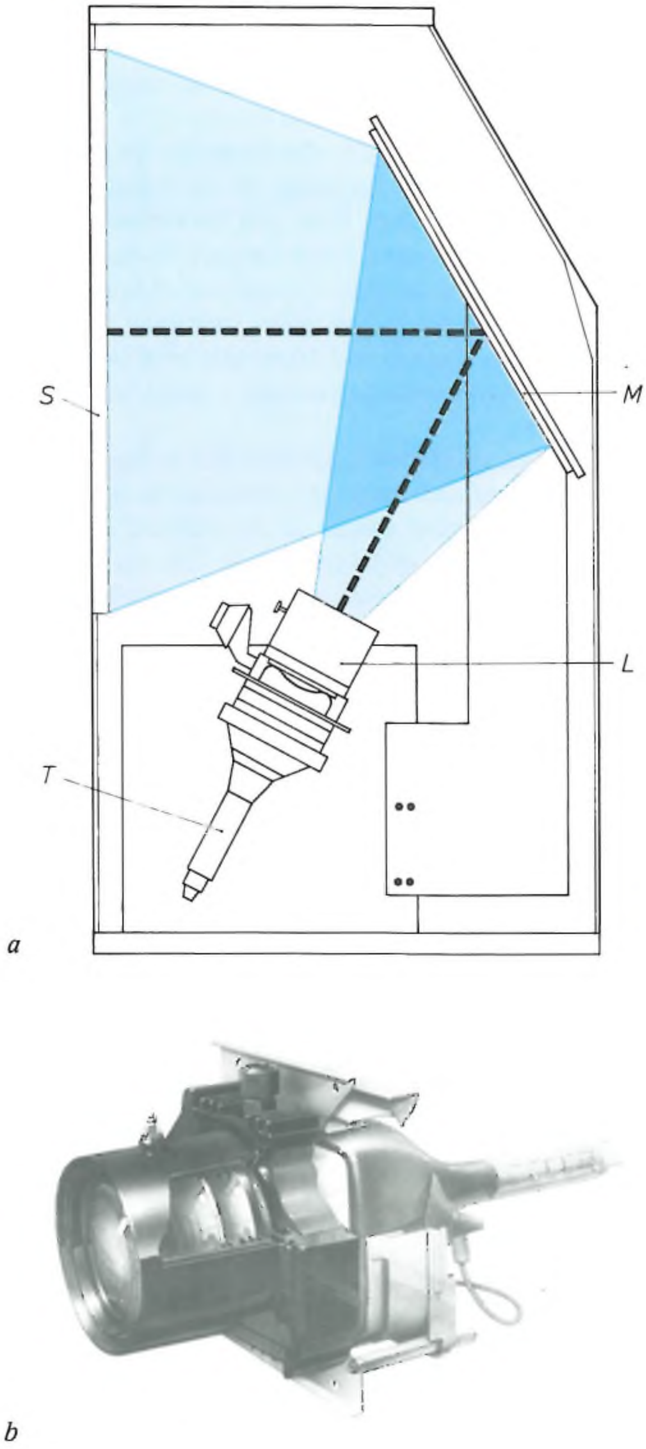

Fig. 6. *a*) Light path (in blue) in one of the three projection tubes in a Philips projection television. The light is not directly incident on the back of the projection screen *S*, but is reflected by a mirror *M*. Each projection tube *T* is connected to a lens system *L* consisting of four lenses, some of them aspheric. The connection is made via a liquid that also cools the front of the tube. *b*) This is called a liquid-cooled, liquid-coupled tube/lens system.

When using liquid crystals for visual display purposes they are inserted between two narrowly spaced parallel glass plates which are covered on the inside with transparent electrodes. In the absence of an electric voltage between the electrodes the molecules assume a twisted configuration, as shown in *fig. 8a*. There is a polarizer on top of the assembly. The plane of polarization of the light falling through the glass plates is twisted in the same way as the molecules. We have designed the unit to give rotation through 90°. A crossed polarizer is present at the output side of the unit and, thanks to the 90° rotation, light will be transmitted. Application of an electric voltage between the electrodes causes the molecules to align axially (see fig. 8*b*); they will no longer influence the plane of polarization of the light and the crossed polarizers will cancel the light.

It is a long way from this principle to a TV display in which a great number of picture elements have to be switched independently. Multiply that number by three for the three different colours. In the Philips display, electrodes are replaced by vapour-deposited

Fig. 7. The use of liquid-crystal displays (LCDs) opens new possibilities for television. The colour television receiver shown here has a screen with a diagonal of 7.5 cm (3 in) and requires only a few watts of power.

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[3] K. Teer, Looking back at distant vision: television technology from 1936 to 1986, Philips Tech. Rev. 42, 297-311, 1986.

[4] Three articles on research into subjects of direct interest for the development of projection television will shortly appear in this journal. These articles deal with interference filters, phosphors and electron guns.

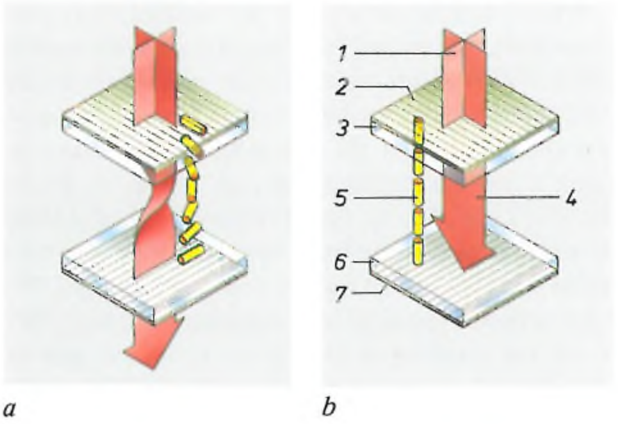

Fig. 8. Basic principle of operation of a liquid-crystal display (LCD). *a*) If no voltage is applied, some of the incident light is transmitted through the LCD. *b*) If a voltage is applied, no light is transmitted. *1* incident light; *2* polarizer; *3* glass; *4* polarized light; *5* liquid-crystal molecules; *6* glass; *7* polarizer.

thin-film transistors. Here too, close cooperation between different disciplines is essential: materials science, cell and circuit design, production under strictly controlled conditions.

Backlighting is required when viewing your LCD colour display. Large-area, energy-efficient light sources are needed; here our lighting expertise is of great value.

Projection TV using LCD light modulation is under investigation. The LCD is flat and thin; it could take the place of the slide in a slide projector.

HDTV

Currently, a debate is going on about television with greater picture resolution: High-Definition TV or HDTV as it is known. There is a call for pictures with more lines, for example 1250 instead of 625 — and thus with more information. Projection on larger screens is then possible, as is the introduction of a broader 'CinemaScope'-type picture. Transmission channels with a larger bandwidth are needed for the broadcasting of these pictures. A number are available thanks to the advent of broadcast satellites having a fixed position high above the earth's equator. The Federal Republic of Germany has launched one. Unfortunately it is not functioning properly: one of the two solar panels failed to unfold in space. It is now a question of waiting for a similar satellite to be launched by France.

For television broadcasts over the earth's surface and for recording on magnetic tape it is necessary to limit the bandwidth. There is ample room for this because, in normal TV signals, the same information is transmitted over and over again. You see, large parts of consecutive TV pictures are often the same, and changes take place relatively slowly. For bandwidth reduction there are sophisticated digital signal processing techniques which use mathematical transformations. This is a typical research matter.

Of course, a standard is also necessary for HDTV broadcasting, so that the owner of the television set can receive broadcasts from any transmitter. We would really like to see a world standard. A complicating factor is that the picture frequency of broadcast television is linked to the mains frequency. In the United States, Canada and Japan that is 60 hertz, in most other areas, including Europe — and China — it is 50 hertz.

In Europe cooperation between Philips and other electronics manufacturers has produced a standard called MAC, which stands for Multiplexed Analog Components. One of its features is that the colour and brightness information are not transmitted simultaneously, but the colour first and then the brightness. *Fig. 9* shows how this works; after decoding there is again a colour picture. In this way, interference, known as cross-colour and cross-luminance, is avoided. The MAC system is compatible with the current standards and can therefore be applied alongside the current system in a transitional period. This prevents all TV receivers becoming suddenly unusable upon the introduction of HDTV [5].

Fig. 9. Picture obtained when a MAC signal is displayed without special decoding, as if it was an ordinary television signal. In every line period a small part is first used for transmitting the chrominance information, and the rest is used for the luminance information. Since there are two chrominance signals (*U* and *V*), *U*-information and *V*-information alternate from line to line. A colour picture of very high quality can be obtained with a MAC decoder, because all the various undesirable interactions between chrominance and luminance information are intrinsically avoided with this system. (The line-flyback periods are used for sound transmission; this is not visible here of course.)

Storage

Consumers are not satisfied by picking up radio and television signals from the air. There also is a great demand for recorded music and television. Storage devices and storage media are an important sector of the consumer market.

Magnetic tape recording

For many years the gramophone record and the magnetic tape have fulfilled the existing need. Magnetic recording on tapes has developed to a high degree of sophistication. Much of the gain in information density on the tape surface is attributable to the ongoing improvement in tape quality and the improved characteristics of the recording heads. This has enabled us to attain a satisfactory recording quality with ever-decreasing tape speeds.

A milestone in sound recording for the consumer public was the introduction in the 1960s of the Philips Compact Cassette, which made use of the low tape speeds that had just become acceptable. Recording video on tape at that time was still the preserve of the professional community. Once again it was Philips who first introduced the video cassette recorder for home use.

Throughout the years magnetic recording has remained one of the key topics of our research. Apart from improving the physical characteristics of the tape and tape heads [6], and developing more accurate mechanics and servocontrol systems, recording density on the tape has been increased by proper signal processing. Most tape recording is done by writing analog signals. It is only recently that digital tape recording of sound has become commercially viable. Digital video recording is available in our laboratories.

In the meantime, optical recording media have been introduced. Compared with these, magnetic tape recording trails far behind in terms of recording density. The audio Compact Disc carries about one million bits per square millimetre, a digitally recorded audio tape four times less. Secondly, magnetic tape does not allow rapid access. However, it has the advantage of bulk storage — it can provide hours of playing time.

Optical recording media

In fact it was IC technology, in which intricate details of optical fineness are repeated flawlessly over and over again, which, in our laboratories, gave rise to the idea that the same means could be used to record information on discs. 1972 saw the introduction of the LaserVision video disc on which video information is recorded in analog form. The LaserVision disc can store up to 40 000 still pictures; in the well-publicized Domesday Book project it has been used to record data about all of Great Britain for educational purposes. Meanwhile, the art of digital signal processing progressed at a rapid pace, and 1982 saw the birth of the Compact Disc — also an invention by Philips. It carries audio information in digital form and has set a new standard of high-quality sound recording.

The Compact Disc is more than just an electronic device. It is part of a system, the Digital Audio Compact Disc System [7]. In consumer electronics too the trend is one of moving away from stand-alone products and more towards systems. The Digital Audio Compact Disc System first of all encompasses many technical disciplines: the laser, the chemical process of the disc manufacture, servomechanisms for focusing, tracking and motor control, sophisticated optical systems, digital signal processing including error correction, etc.

Secondly, a *standard* is also part of it. It must be possible to play a CD from one manufacturer on any other manufacturer's player. And given that today's market for consumer electronics is a *world* market, the standard must be a *world standard*. Throughout

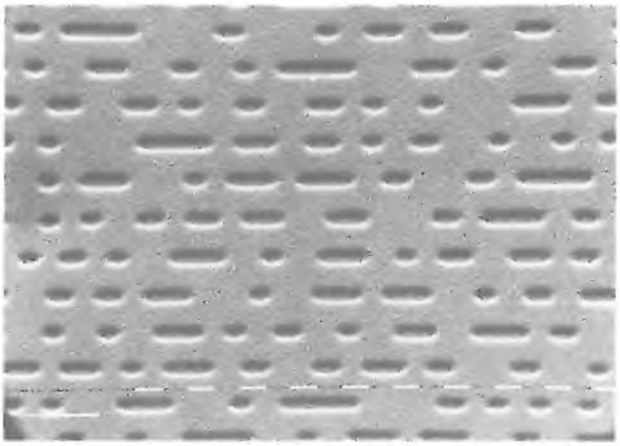

Fig. 10. The sound information on the Compact Disc is recorded as a succession of pits in a spiral pattern. The measurements here are microscopically small: the pits are only 0.6 μm wide, 0.12 μm deep and the length varies between 0.9 and 3.3 μm.

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[5] M. J. J. C. Annegarn, J. P. Arragon, G. de Haan, J. H. C. van Heuven and R. N. Jackson, HD-MAC: a step forward in the evolution of television technology, Philips Tech. Rev. 43, 196-212, 1987.

[6] H. J. de Wit and K. Jager, Magnetic domains in amorphous alloys for tape-recorder heads, Philips Tech. Rev. 44, 101-109, 1988;
J. P. M. Verbunt, Laboratory-scale manufacture of magnetic heads, Philips Tech. Rev. 44, 151-160, 1988;
M. G. J. Heijman, J. H. W. Kuntzel and G. H. J. Somers, Multiple-track magnetic heads in thin-film technology, this issue, pp. 169-178.

[7] See our special issue on the Compact Disc: Philips Tech. Rev. 40, No. 6, 149-180, 1982.

the world the digital information must be recorded in the pattern of small pits (*fig. 10*) on the disc using the same code. We, when developing the Compact Disc, considered the issue of standardization as very important. To establish a world standard it is necessary to work together with others; we chose to cooperate with the well-known Japanese company Sony, which also specializes in consumer electronics. Sony made major contributions to the coding on the disc; the code has an extraordinary capacity to correct errors which arise when the disc is being read.

The capabilities of the Compact Disc system extend far beyond sound reproduction. The Compact Disc Video stores video, which is encoded in the LaserVision format alongside fully digital sound (*fig. 11*). The Compact Disc Read-Only Memory or CD-ROM is a fully digital storage medium for computer read-out; the Compact Disc Interactive or CD-I is derived from CD-ROM for purposes of interactive communication with a personal computer (*fig. 12*); one existing CD-I contains an entire encyclopaedia.

Fig. 11. The well-known 'silver' Compact Disc (second one down in the drawing) is slowly acquiring a tribe of audio and video relatives. From top to bottom: the CD Single, the CD, the CD Video Long-play and the LaserVision video disc. All of these discs can be played on a single universal combination player.

So far, I have mentioned pre-recorded discs only. The user may wish to record his own data. Research shows different techniques to make this possible [8]. All of them rely on local heating of the disc surface by a laser. In one technique, the laser melts small holes into a thin metallic layer applied on to the disc. The process is irreversible; we call this process 'Write Once, Read Many times'; it is very useful in many computer applications.

In a second technique, the laser produces amorphous spots in a crystalline layer; just as the holes of the first example, the amorphous spots can be detected by scanning the disc with a laser beam. This process is reversible; by giving the disc an overall thermal treatment, crystallinity is restored. A third technique is based on a magnetized layer in which the direction of the magnetization is locally inverted by the heat of the laser beam. The state of magnetization is read out optically. This last technique also is reversible; it is the one which generally is referred to when one speaks about 'erasable Compact Disc'.

Fig. 12. Two highly promising versions of the Compact Disc are the CD-ROM and the CD-I, which each contain some 600 megabytes of information on a disc with a cross-section of about 12 cm. This photograph gives an impression of the use of a CD-ROM. For both CD-I and CD-ROM screens have an important part to play in displaying the information.

Obviously, exploring these different techniques requires very fundamental materials research. The life expectancy of the recording is an important issue.

Another aspect is the intricate digital processing to which the signals are subjected in order to exploit the recording media optimally. This is valid for magnetic as well as for optical recording. For both the challenge will be to record High-Definition Television, which generates a bit stream not of 140 megabits per second, as standard television does, but of 560 megabits per second. Intricate bandwidth-reduction techniques are necessary to meet this new challenge. They will be feasible only if Very Large-Scale Integrated circuits will be available to reduce the signal processing hardware to reasonable proportions.

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[8] G. E. Thomas, Future trends in optical recording, Philips Tech. Rev. 44, 51-57, 1988.

ICs

And thus we arrive at what is perhaps the mainstream of research in today's electronic industries — integrated circuits. Hardly any technology has shown a faster development than that of circuit integration. It is only 20 years ago that Philips produced its first commercial integrated circuit; it was a three-transistor amplifier circuit for a hearing aid, realized on 0.6 square millimetres of silicon.

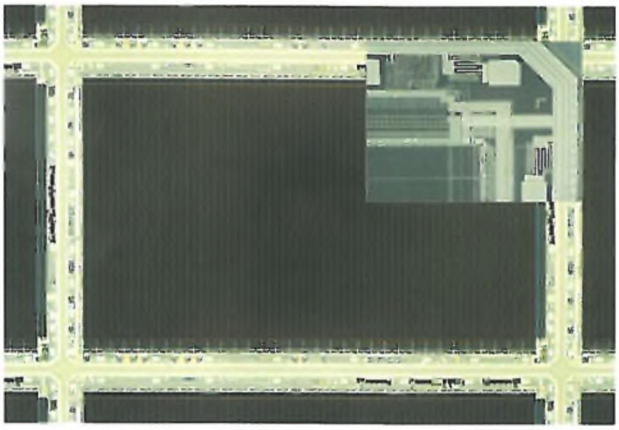

Fig. 13. In the present state of technology millions of transistors can be integrated on a single chip. The photograph shows a static random-access memory with a capacity of more than a million bits (the 1-megabit SRAM). The smallest details measure only 0.7 µm, while the entire chip has an area of about 94 mm^2; an enlarged view of a portion of the IC is given at the upper right-hand corner to show the details more clearly.

Today, for contrast, we are happy to have just produced in our laboratory first samples of an integrated circuit having about ten million transistors on an area of no less than 90 square millimetres. To accomodate so many transistors on the surface of one chip it is necessary to reduce the dimensions of the individual transistor. We aim at structural details as small as 0.7 micron, smaller than anything that is on the market today. The small dimensions have another advantage: small transistors are faster than large ones.

Our first goal is a one-megabit Static Random-Access Memory or SRAM incorporating one million six-transistor memory cells (*fig. 13*). Fabricating error-free ICs of this size in the sub-micron technology puts extreme requirements on processing conditions; as an example, its requires highest-class clean rooms. We have had to build special laboratories for this project. One of the buildings (*fig. 14*) is the pilot plant. As you will notice it looks like the well-known dual-in-line IC package. The clean rooms occupy

Fig. 14. An entirely new centre for studying and manufacturing ICs with details smaller than a thousandth of a millimetre — 'submicron details' — has appeared on the Philips Research Laboratories site in Eindhoven in recent years. The large building in the foreground is the pilot-production plant. The building behind it by the lake houses the research and design department.

about 15% of the floor area, the remainder being required for air conditioning and dust filtering. The building next to it houses hundreds of IC designers [9].

The costs of a research project like this are tremendous; in fact, they are expressed in billions of dollars rather than millions. These vast sums are beyond the means of an individual company; we are happy to cooperate with Siemens of West Germany. The project is of great significance for all of Western Europe, as it will give Western Europe a position in the forefront of modern IC technology. For this reason the project receives support from the West-German and Dutch governments.

Nor will this be the end of IC developments. In our laboratories, we have created transistors of even smaller dimensions, with 0.4 and 0.2-micron details. They have been configured by direct electron-beam writing on the silicon surface (*fig. 15*). They will be components of the future, even larger ICs storing tens of millions of bits or doing an equivalent amount of signal processing.

Fig. 15. The precursor of the next generation of ICs with detail dimensions from 0.2 to 0.4 µm. In this photograph two MOS transistors can be seen with common source (connection top left), common gate (connection lower left) and separate drains (connection top right and lower right). The thin 'needle' at the centre is the actual gate and has a width of 0.5 µm in one transistor and only 0.4 µm in the other. These small dimensions are achieved by using an electron-beam pattern generator. The relatively thick connections for the two transistors are of aluminium and are made by photolithography.

Philips is the largest European manufacturer of ICs in current technology. In bipolar ICs for analog signals it is even one of the biggest in the world. Analog ICs have been a speciality of Philips since many years; they are used in consumer products like TV sets and hi-fi audio, as well as in domestic appliances. In electric shavers they check the charge level of the batteries.

Fig. 16. The computer is becoming more and more vital to the automation of the design process for integrated circuits. There is no other reliable way of managing the enormous complexity of the latest semiconductor circuits in an acceptable time.

But let me return to the ever-larger digital ICs that are being developed for signal processing and for mass storage. As an application, I have mentioned the digital signal format of the CD. It would have been impossible only a few years before. I have mentioned high-definition TV and digital recording. They ask for many megabits of storage capacity, to store entire TV frames. This requires several square centimetres of silicon realized in the most advanced processes.

It is, however, not enough to have the newest technology available. One needs system concepts and designs to use it. It is a tremendous task to translate one's ideas into an electrical circuit on a chip. Standard design methods fail with the growing complexity. Too many designers are needed. It becomes impossible to survey a total design, and this will cause so many errors that the process will fail — or the design process will simply take too much time. In order to overcome these difficulties the total design process must be upgraded — a task comparable in size to the upgrading of the technology.

Of course, computers are extensively used in circuit design. Large-scale drawings are plotted of IC layout. But these methods no longer work. With the increasing scale of the circuits the size of the drawings will exceed the floor area of our buildings. What we need is a higher level of design automation. We are working towards silicon compilation — upon specification of the desired functions the computer produces the IC layout (*fig. 16*).

Concluding remarks

Let me conclude by three remarks.

- Modern consumer products are research-intensive. The time is gone that they were simple products and derived their technology from elsewhere, i.e. from professional fields.
- The distinction between the consumer and the professional field disappears or is even reversed. Modern silicon technology and design methods make it possible to integrate highly sophisticated functions into consumer goods. There are only two fields of industry which are of a sufficiently large economic scale to support the high costs of the new technologies — the computer industry and consumer electronics. Small-scale professional production will not be able to bear the high expense. As a result, we encounter a degree of sophistication in today's consumer goods which earlier was found only in professional products. As examples I mentioned the error-correcting code of Compact Disc or the bandwidth-reducing algorithms on behalf of transmission and recording of high-definition television.
- These consumer goods are to be handled by non-specialists. In spite of their sophistication, they should be easy to use. Many consumers nowadays are baffled by the multitude of push-buttons and switches that are available on their equipment, and very rarely touch more than one or two of the controls. Human-friendly design becomes more and more mandatory. This is what true sophistication stands for: to please the customer and make him feel at ease.

Summary. Text of a speech given in Nanjing in the People's Republic of China on 1st June 1988 by Dr S. van Houten, member of the Philips Board of Management. After a short introduction to the Philips company the speaker shows how important the role of scientific research is in bringing out electronic consumer products. He gives examples for a number of important fields such as lighting (economical lamps), television technology (various kinds of displays, high-definition television), magnetic and optical recording (Compact Cassette, Compact Disc) and integrated circuits (submicron technology). The speaker makes various points in conclusion, emphasizing that the traditional distinction between professional products and consumer products has changed its character completely and that the user-friendliness of consumer products will be a factor of growing significance.

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[9] W. G. Gelling and F. Valster, The new centre for submicron IC Technology, Philips Tech. Rev. 42, 266-273, 1986.

Philips Tech. Rev. 44, No. 6, 190-199, Dec. 1988

Sound radiation from a vibrating membrane

J. H. Streng

'Mr. Watson, come here, I want you' are reputed to be the first intelligible words that Alexander Graham Bell spoke via his telephone connection. On 14th February 1876 he filed the first application for a patent on a telephone. Whether he should really be seen as the inventor seems to be a matter of some doubt[*]. *There is however no doubt that the development of electro-acoustic transducers, essential components in telephony, has flourished since that first patent application. There are various mechanisms for the conversion of electrical energy into acoustic energy in such transducers, such as the vibration of an electrically charged membrane in a varying electric field. This article deals with the radiation of sound from such a membrane. It is shown that the combination of classical analytical mathematics and modern computer techniques has led to a better understanding of this sound radiation and that there is an interesting application.*

Introduction

In electroacoustic transducers such as telephones and loudspeakers electrical energy is converted into acoustic energy. Electrical quantities give rise to forces that in turn set up air vibrations. The conversion of electrical quantities into mechanical quantities is based on the interaction of magnetic fields and electric currents — Lorentz forces — or on the interaction of electric fields and charges — electrostatic forces. Electroacoustic transducers are therefore mainly classified as either electrodynamic or electrostatic versions. If we now just consider loudspeakers, we find that electrodynamic loudspeakers are by far the most widely used. In the most common type a coil energized by alternating current moves in a magnetic field produced by a permanent magnet. The forces acting on the coil cause a membrane — usually conical — to vibrate. The vibrating membrane produces sound waves in the surrounding air.

An *electrostatic* loudspeaker consists in its simplest form of a capacitor with air as the dielectric. One of the two electrodes takes the form of a tightly stretched flat membrane, and the other is a stationary plate. When the electrodes are connected to the two poles of a high-voltage direct-current source, the electrodes receive charges of opposite sign. Each electrode is then subjected to a constant force equal to the product of field-strength and charge. If an alternating voltage is superimposed on the constant voltage, the constant forces acquire an alternating component. The result is that the membrane will vibrate at a frequency that as a first approximation is equal to the frequency of the alternating voltage. The vibrations of the membrane set up sound waves in the surrounding air. Later in this article it will be shown that the nonlinear behav-

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iour of this simplest electrostatic loudspeaker can be improved if two stationary electrodes are used, instead of one, with the membrane between them.

In the conversion of electrical power into sound power a loudspeaker behaves as a highpass filter with a transfer characteristic that rises by a constant number of decibels per octave in the low-frequency range. The cut-off frequency of this 'filter' is inversely proportional to the diameter of the loudspeaker, whether electrodynamic or electrostatic. The loudspeaker behaves like a highpass filter because it cannot build up static pressure in the surrounding air. It follows from the shape of the filter response that a loudspeaker should have a large diameter and hence a large area if it is to produce sound at high power at low frequencies.

All loudspeakers tend to some extent to focus the sound in the direction of the principal axis [1]. This focusing effect — which is usually undesirable — is due to interference between sound waves emitted by different parts of the vibrating membrane [2]. Interference becomes perceptible when the dimensions of the membrane are of the same order of magnitude as the wavelength of the sound — about 30 cm at 1000 Hz. The effect increases as the dimensions become larger than the wavelength. To prevent the focusing of high-frequency sound the dimensions of the vibrating membrane should be small. This is one of the reasons why electrodynamic loudspeakers generally have separate loudspeakers for different frequency ranges, with filter circuits to divide the output signal from the amplifier into different signals for each range. Electrodynamic loudspeakers have the disadvantage, however, that the mechanical properties of the membrane have a considerable effect on the shape of the transfer characteristic.

Electrostatic loudspeakers have not been as widely used as electrodynamic loudspeakers, mainly because of mechanical and electrical limitations:

- High voltages have to be used (up to 5 kV or so, a.c. and d.c.).
- The membrane of an electrostatic loudspeaker cannot be deflected as much as that of an electrodynamic loudspeaker, because there is nonlinear distortion if the membrane is stretched too far.
- If the force acting on the membrane of an electrostatic loudspeaker is increased, the field-strength in the air gap between the electrodes may become so high — 2 kV/mm or more — that there is electrical breakdown.

To keep both the deflection and the field-strength within reasonable limits, protection circuits are necessary. These circuits can now be produced more cheaply by integrating them on silicon. The effect of limiting the deflection of the membrane is that the area of an electrostatic loudspeaker that can reproduce the lower audio frequencies must be large, 0.5 m^2 or more. This is why electrostatic loudspeakers have so far only been used for the higher audio frequencies.

An investigation into the acoustic radiation from vibrating membranes has been in progress for some years at Philips Research Laboratories in Eindhoven. Earlier calculations of the sound field were based on the model of a rigid piston moving in air [2] [3]. This model differs from that of a vibrating membrane, however, because a rigid piston has the same deflection at all points of its surface. Also, the edge effects are essentially different: the displacement of a membrane at its circumference is zero, unlike that of a piston. This means that there are turbulences at the edge of a piston that are not found at the edge of a vibrating membrane.

We have devised a method of solving the set of differential equations consisting of:

- an equilibrium equation for the vibrating membrane,
- Helmholtz's equation for the propagation of sound in the surrounding air, and
- an equation that takes into account an 'interface' condition.

The computer program developed for solving this set of equations calculates the membrane movement and the sound pressure on the membrane for arbitrary values of the mechanical and electrical parameters. It is therefore possible to determine the magnitude and direction of the sound intensity (i.e. the energy flux density in W/m^2) at every point of a rectangular network in air; see *fig. 1*.

The investigation has resulted in a laboratory design for an electrostatic loudspeaker. The problem of high-frequency focusing due to the large area necessary for reproducing the low frequencies has been solved by subdividing the surface of the membrane. Signal components at higher frequencies are reproduced by a smaller part of the membrane. The signal is passed through a number of lowpass filters with decreasing cut-off frequencies. The output signal from each filter is applied to a separate output amplifier. The amplifier for the unfiltered signal is connected to the smallest part of the membrane. As the signal

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[*] F. V. Hunt, Electroacoustics, Harvard University Press, Cambridge, Mass., 1954.

[1] The principal axis is defined as the centre-line of the conical membrane of an electrodynamic loudspeaker, or as the line through the centre and perpendicular to the flat membrane of an electrostatic loudspeaker.

[2] L. L. Beranek, Acoustics, McGraw-Hill, New York 1954.

[3] C. J. Bouwkamp, Theoretische en numerieke behandeling van de buiging door een ronde opening, (Theoretical and numerical treatment of the diffraction of a scalar plane wave through a circular aperture), Thesis, Groningen 1941.

passes through the chain of filters, the high-frequency components disappear, and the membrane areas connected to the filter outputs become larger.

This approach has given a loudspeaker with a useful frequency range from 50 to 20 000 Hz. A particular feature is that the output amplifiers in the loudspeaker have optoelectronic couplers between the high-voltage and low-voltage sections. Another feature is that there is feedback to keep the non-driven part of the membrane at rest at frequencies above the filter cut-off frequencies. The optoelectronic couplers in the output amplifiers have the great advantage that the output current of the audio power amplifier can be lower than in conventional designs with isolating transformers. The output current is reduced by a factor equal to the turns ratio of the transformers. Another disadvantage of isolating transformers is that they are expensive.

In the rest of the article we shall first look at the set of three differential equations and consider ways of solving them. Some of the results of calculations made with our programs will then be presented. Finally, the electrostatic loudspeaker and its electronic drive will be described.

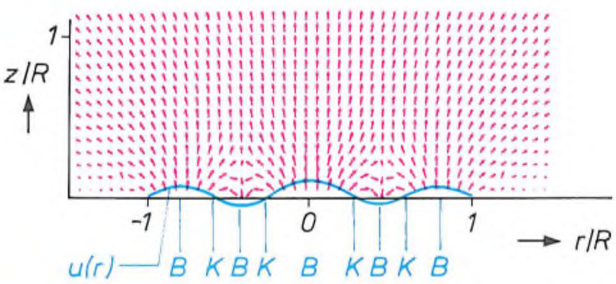

Fig. 1. Results of the calculation of the sound radiation from a vibrating circular membrane of maximum radius R. The arrows indicate the relative magnitude and direction of the sound intensity in the surrounding air as a function of the coordinates r and z, which have been normalized with respect to R. The derivatives with respect to the third coordinate θ are equal to zero. The blue line relates to the instantaneous deflection u of the membrane as a function of the radius r. There are two circular 'nodal lines' K where the membrane is approximately at rest. The nodal lines separate areas B where the membrane is vibrating.

Theoretical background

It should be sufficient here to state the three differential equations and briefly describe their solution. The method used has been described in detail elsewhere[4].

The complex amplitude η of the deflection as a function of the radius r of a circular membrane, see *fig. 2*, is one of the two unknowns in the differential equation that describes the equilibrium of the perpendicular forces acting on the membrane per unit area:

$$T\nabla_2^2\,\eta(r) + \omega^2\varrho_{\mathrm{m}}\,\eta(r) - \mathrm{j}\omega\, Z_{\mathrm{s}}\,\eta(r) + $$
$$+ F(r) - \{p_+(r) - p_-(r)\} = 0, \quad \text{for } r \leqslant R, \qquad (1)$$

with the boundary condition $\eta(R) = 0$. For reasons of symmetry it is assumed that the various quantities are independent of the (tangential) angular coordinate θ. All terms in the equation are harmonic functions. The time-dependent factors $\mathrm{e}^{\mathrm{j}\omega t}$ have been omitted, leaving the complex amplitudes. First of all, the significance of the various terms will be explained.

The first term in eq. (1) represents the resultant force per unit area due to the forces acting on the edges of a circular surface element as a result of the tension in the membrane. T is the membrane tension in N/m, which has the same magnitude in all directions since we are dealing with a uniformly stretched membrane. The factor $\nabla_2^2\,\eta(r)$ is the curvature of the membrane at the position r in cylindrical coordinates, written as:

$$\nabla_2^2\,\eta(r) = \frac{\partial^2}{\partial r^2}\,\eta(r) + \frac{\partial}{r\,\partial r}\,\eta(r).$$

The second term in eq. (1) represents the force per unit area required to accelerate the membrane. In this term ϱ_{m} is the density and ω is the angular velocity of the membrane vibrations.

The third term in eq. (1) takes account of acoustic damping that may be added by fabric or gauze. This extra damping, which is superimposed on the 'ordinary' damping caused by the surrounding air, is characterized by the specific acoustic impedance Z_{s} (i.e. the acoustic impedance for unit area). This impedance is defined as the complex ratio of pressure to air velocity.

The fourth term in equation (1) represents the force per unit area acting externally on the membrane.

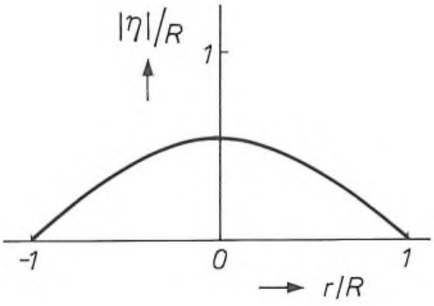

Fig. 2. The absolute value of the complex amplitude η of the membrane deflection as a function of the radius r, both normalized with respect to the maximum radius R.

The last two terms account for the pressure difference resulting from the displacement of air by the vibrating membrane. $p_+(r)$ is the sound pressure acting on the membrane from the positive z-direction, $p_-(r)$ is the sound pressure acting from the negative z-direction; see fig. 1. (The sound pressure is the difference between the instantaneous pressure and the mean pressure.) Because there is antisymmetry, we have: $p_-(r) = -p_+(r)$. The pressure $p_+(r) = -p_-(r)$ is the other of the two unknowns in differential equation (1).

The next differential equation is Helmholtz's equation [2], which follows from the wave equation in three dimensions for a continuous medium, in this case air:

$$\nabla_3^2 p(r,z) + k^2 p(r,z) = 0, \qquad (2)$$

with the boundary conditions: $p(r,0^+) = p_+(r)$ and $p(r,0^-) = p_-(r)$, both for $r \leqslant R$. The pressure p in free space is considered for reasons of symmetry to be a function of the coordinates r and z alone, and not of the third coordinate θ. The symbol 0^+ means that $z \rightarrow 0$ from the positive z-direction; similarly 0^- means that $z \rightarrow 0$ from the negative z-direction. The squared three-dimensional nabla operator in cylindrical coordinates can be written (since partial derivatives with respect to θ are zero, of course) as:

$$\nabla_3^2 p(r,z) = \frac{\partial^2}{\partial r^2} p(r,z) + \frac{\partial}{r\,\partial r} p(r,z) + \frac{\partial^2}{\partial z^2} p(r,z).$$

The wave number k is equal to ω/c_0, where c_0 is the velocity of sound, and also equal to $2\pi/\lambda$, where λ is the wavelength.

In solving the differential equations (1) and (2) an interface condition must also be taken into account. This equates the acceleration of the air at the surface of the membrane to the acceleration of the membrane:

$$\left.\frac{\partial p(r,z)}{\partial z}\right|_{z=0^+} = \left.\frac{\partial p(r,z)}{\partial z}\right|_{z=0^-} = \omega^2 \varrho_0\, \eta(r), \qquad \text{for } r \leqslant R. \quad (3)$$

In this third differential equation ϱ_0 is the density of air.

Now a solution has to be found for the set of three differential equations (1), (2) and (3). The method we have adopted makes use of Green's functions [5]. Let us first consider the complex amplitude η of the deflection of the membrane at the radius r. The deflection is partly due to pressures of complex amplitude $p_+(r)$ and $p_-(r)$, acting on opposite sides of the membrane. Now we consider the pressures at different radii r_0 as 'sources', each contributing to the deflection at r. Then the effect of all these sources from $r_0 = 0$ to $r_0 = R$ can be summed in such a way that the result gives the total deflection at r. It is a property of the Green's function $G_1(r\,|\,r_0)$, which is a function of the two variables r and r_0, that a factor is added to the separate sources such that the summation gives exactly the deflection:

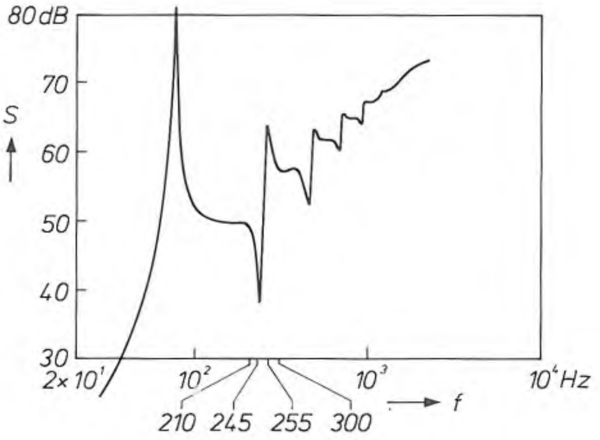

Fig. 3. The calculated sound pressure level S in dB[6] at the principal axis as a function of the frequency f on a logarithmic scale. The sound pressure level is calculated for a distance of 1 m from the surface of a circular membrane. The values of the parameters are: membrane tension T = 100 N/m, density of the membrane ϱ_m = 0.02 kg/m^2, maximum radius R = 0.125 m, acoustic impedance Z_s = 0, force per unit area F = 1 N/m^2.

$$\eta(r) = \int_0^R p_+(r_0)\, G_1(r\,|\,r_0)\, r_0\, \mathrm{d}r_0. \qquad (4)$$

In much the same way the pressures $p_+(r)$ and $p_-(r)$ on opposite sides of the membrane at r_0 can be regarded as sources that contribute to the sound pressure $p(r,z)$ in free space. The Green's function $G_2(r,z\,|\,r_0,z_0)$ adds a factor to the individual sources such that the total sound pressure at r and z is obtained. The result is the integral equation:

$$p(r,z) = \int_0^R p_+(r_0) \left\{ \frac{\partial}{\partial z_0} G_2(r,z\,|\,r_0,z_0) \right\} \bigg|_{z_0=0} r_0\, \mathrm{d}r_0. \qquad (5)$$

If we substitute (5) in equation (3) we obtain a second

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[4] J. H. Streng, Calculation of the surface pressure on a vibrating circular stretched membrane in free space, J. Acoust. Soc. Am. 82, 679-686, 1987;
J. H. Streng, Calculation of integrals which occur in circular stretched membrane sound radiation, J. Acoust. Soc. Am. 83, 1183-1185, 1988;
J. H. Streng, Sound radiation from circular stretched membranes in free space, Proc. 84th AES Conv., preprint 2573 (C-2), 1-41, 1988.

[5] P. M. Morse and K. U. Ingard, Theoretical acoustics, McGraw-Hill, New York 1968.

integral equation for $\eta(r)$:

$$\eta(r) = \frac{1}{\omega^2 \varrho_0} \int_0^R p_+(r_0) \left\{ \frac{\partial}{\partial z}\left(\frac{\partial}{\partial z_0} G_2(r,z\,|\,r_0,z_0)\right)\bigg|_{z_0=0} \right\}\bigg|_{z=0^+,0^-} r_0\,\mathrm{d}r_0. \qquad (6)$$

If we now equate $\eta(r)$ as given by eq. (4) with $\eta(r)$ as given by eq. (6), we obtain an integral equation in which the only unknown is the pressure p_+ on the surface of the membrane. From this we can solve for p_+, by expressing p_+ in terms of a power series whose n coefficients can be determined by solving n equations in n unknowns. Once p_+ is known, we can calculate the complex amplitudes $\eta(r)$ for the membrane displacement and $p(r,z)$ for the sound pressure using equations (4) and (5).

Results of calculations

Our program can provide the following results:

- the frequency spectrum of the sound pressure level S in dB[6] at any distance from a vibrating circular membrane;
- the direction and magnitude of the sound intensity in the air, represented as vectors at the nodes of a rectangular network;
- the absolute value of the complex amplitude p_+ of the sound pressure on the membrane surface as a function of the radius r for a given frequency, with the corresponding phase angle ϕ with respect to the driving force (F in eq. 1);
- the absolute value of the complex amplitude η of the membrane deflection, also as a function of r and with the corresponding phase angle ϕ.

The parameters that can be set as required for each calculation cycle are the membrane tension T, the density ϱ_m and the maximum radius R of the membrane, the specific acoustic impedance Z_s, which characterizes the additional damping of the membrane, and the amplitude F of the force driving the membrane.

Fig. 3 shows a frequency spectrum for the sound pressure level on the axis at a distance of 1 m from a membrane with a diameter of 25 cm. The spectrum extends from 30 to 2000 Hz and applies in the case in which the movement of the membrane does not have extra damping ($Z_\mathrm{s} = 0$, the values for the other parameters are given in the caption). At low frequencies the sound pressure level S increases by 18 dB per octave. It can be shown that this means that the real part of the acoustic impedance of the air is proportional to ω^4, which in turn shows that the vibrational behaviour of the membrane is very like that of a rigid piston, with the entire membrane vibrating in phase[2]. At 75 Hz there is a sharp resonance peak, which shows that at this frequency the mass of the air load and the membrane tension form a mass-spring system.

At frequencies above 1000 Hz S increases by 6 dB per octave on average. In this frequency range the membrane behaves in such a way that a succession of annular areas, which theoretically should vibrate in opposite phase, move radially across the membrane[4]. These 'antinodes' are separated by circular 'nodal lines'; see fig. 1. The average increase of S by 6 dB per octave indicates an acoustic impedance of the air independent of ω. For a plane-wave source this impedance is the product of the sound velocity and the density of air, so that it is indeed independent of ω[2].

Because of the damping action of the air the membrane is not exactly stationary at the nodal lines, so that the nodal lines are only apparent. As the frequency increases, the actual behaviour of the membrane in air departs more and more from the theoretical behaviour of the membrane 'in vacuo'. At high frequencies the membrane therefore becomes very like a plane-wave source. This is less so at low frequencies because the vibration of the individual areas in opposite phase produces 'acoustic short-circuiting'.

The behaviour of the membrane in the low-frequency and high-frequency ranges is not surprising. The increase in S at high frequencies mentioned earlier is due to the focusing of the sound along the axis. What is more interesting, however, is the behaviour of S in the range from 100 to 1000 Hz, where a succession of similar resonance effects appears.

We have investigated this frequency range in more detail by studying the membrane deflection, the sound pressure at the surface and the sound-intensity distribution at the frequencies 210, 245, 255 and 300 Hz; see *fig. 4*. We see that at 210 Hz the surface pressure and the membrane deflection show an apparent nodal line in their amplitude, and that the pressure in the area inside the nodal line is in phase with the driving force, while the deflection in this area is out of phase with it. As the frequency increases to 245 Hz, both the nodal lines move radially inwards. The nodal pressure

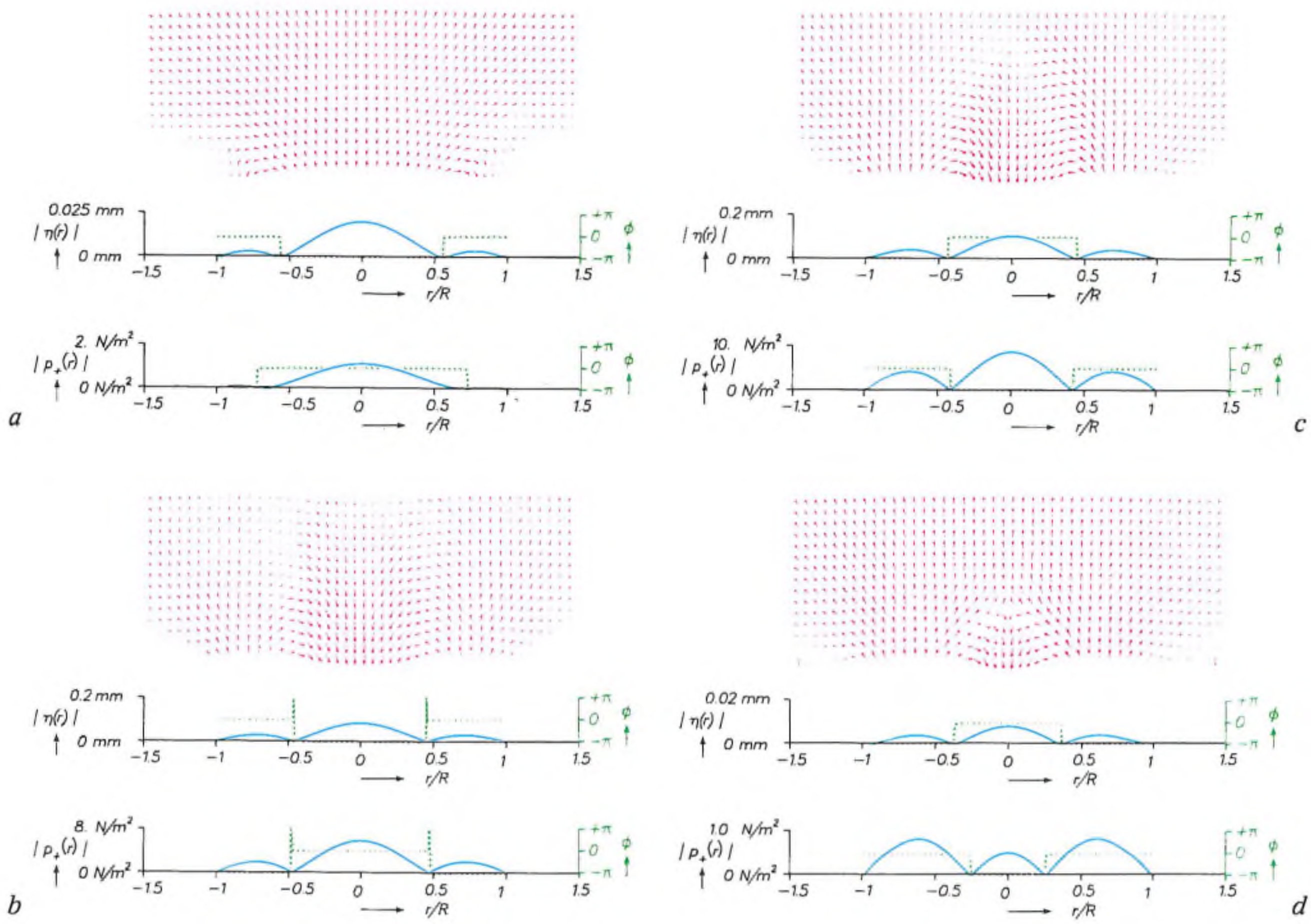

Fig. 4. Results of calculations for the frequencies *a*) 210, *b*) 245, *c*) 255 and *d*) 300 Hz. The absolute values of the complex amplitudes p_+ of the sound pressure at the surface and η of the membrane deflection are plotted as a function of the radius r (blue lines). The sound intensity distribution (red arrows) and the phase angle ϕ relative to the force F (green dashed lines) are also shown. The results apply for the same parameters as in fig. 3. See also the caption to fig. 1.

line moves inwards faster than the nodal deflection line and eventually passes it. The membrane behaves like a combination of two mass-spring systems: the frequency spectrum (fig. 3) has a deep 'antiresonance' dip that is followed by a sharp resonance peak. At 255 Hz the peak in the spectrum has been passed, as can be seen from the 180° phase jump in both pressure and deflection, both inside the nodal line and outside it. It must be concluded that the frequency at which the nodal line for the pressure passes that for the deflection corresponds to the succession of an antiresonance and resonance in the frequency spectrum.

At 300 Hz the situation is again comparable with that at 210 Hz. As the frequency increases, a new set of nodal lines for pressure and deflection will appear at the position $r = R$. These nodal lines also pass each other and again produce a dip and a peak in the spectrum; see fig. 3. In this way more and more nodal lines appear, which separate areas vibrating in opposite phase. At higher frequencies the nodal lines become less pronounced owing to the greater damping effect of the air. Above 1000 Hz the acoustic impedance becomes independent of frequency, as we saw earlier. At the higher frequencies the acoustic impedance is no longer reactive or capacitive but purely resistive.

It can also be seen from *fig. 5* that the sound is focused along the principal axis at high frequencies. This figure shows the sound spectrum obtained when

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[6] The SPL ('sound pressure level') in dB is defined as 20 times the logarithm to the base 10 of the ratio of the r.m.s. value of the sound pressure to a standardized reference pressure of 2×10^{-5} N/m², which corresponds approximately to the threshold of human hearing.

the sound pressure level is calculated on a line at 45° to the axis, again at a distance of 1 m from the source. It is evident that the sound-pressure level decreases with frequency above 1000 Hz.

In most applications strong resonances of the membrane, like those in figs 3 and 4, are undesirable. We have therefore calculated the frequency spectrum for the case in which the specific acoustic impedance Z_s for the additional damping of the membrane differs from zero. *Fig. 6* shows three frequency spectra, for $Z_s = 0$, 20 and 40 Ns/m^3. At the highest damping the peaks and dips in the spectrum are almost completely suppressed. Additional damping can be introduced by fitting an 'acoustically transparent' piece of fabric parallel and fairly close to the membrane. A damping of 40 Ns/m^3 corresponds to the damping caused by a piece of thin cotton fabric.

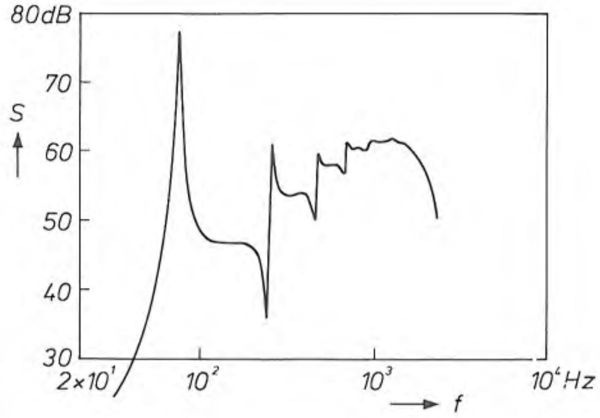

Fig. 5. Sound pressure level S as a function of frequency f for the same parameters as in fig. 3, but now at an angle of 45° to the principal axis.

We varied other parameters as well, such as the mass and the tension of the membrane. As expected, increasing the mass and reducing the tension moves the resonance peaks and dips to lower frequencies. We also examined the effect of a negative compliance, i.e. the effect of a force on the membrane with the same sign as the deflection, and increasing with the deflection. The voltage applied to the electrodes of an electrostatic loudspeaker produces a negative compliance, for example. It has been found that there is instability when the effect of this compliance is greater than that of the membrane tension. If we increase the voltage on the electrodes, we must also increase the tension of the membrane, otherwise the membrane will 'break out' and attach itself electrostatically to one of the electrodes. More sound radiation therefore implies a higher membrane tension in an electrostatic loudspeaker. We shall leave these effects here, and in the next section it will be shown how the better understanding we had obtained led to a practical application.

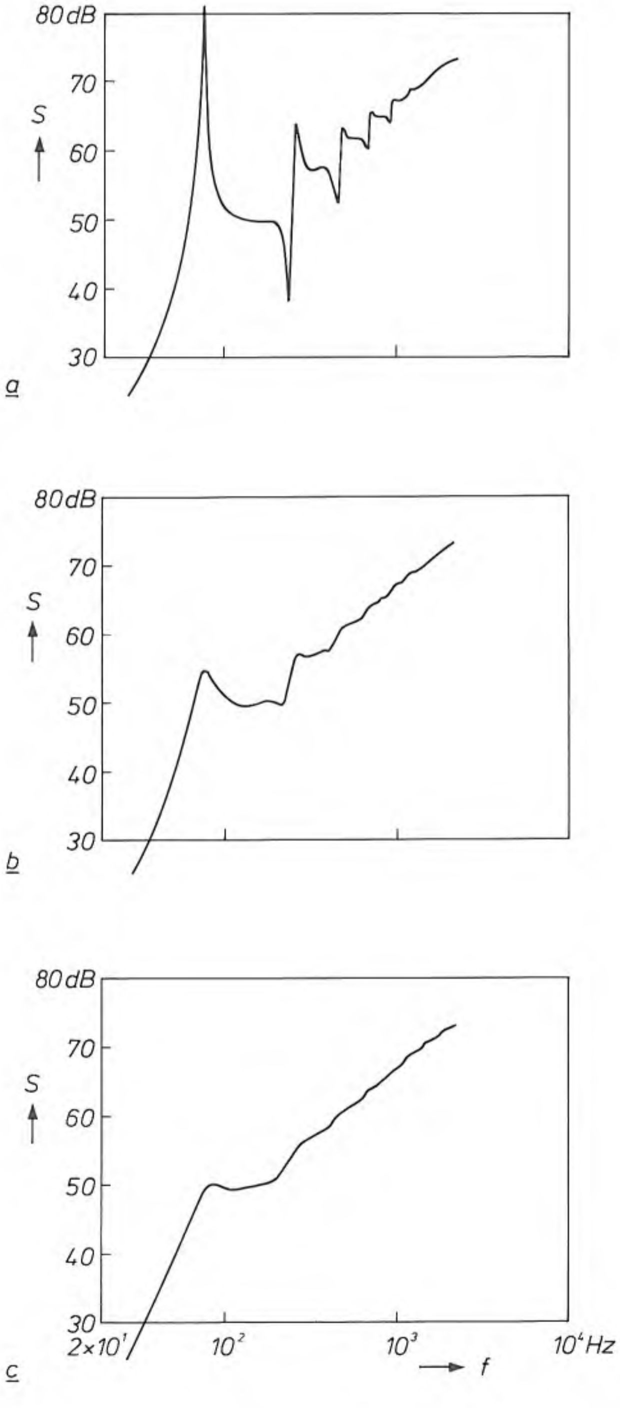

Fig. 6. Sound pressure level as a function of frequency, *a*) for the parameters in fig. 3, *b*) for the same parameters but with acoustic impedance Z_s of 20 Ns/m^3 and *c*) as before but with Z_s = 40 Ns/m^3.

An electrostatic loudspeaker

In the introduction the principle of a single electrostatic loudspeaker was described very broadly: the loudspeaker is a stretched membrane acting as one of the electrodes of a capacitor. Most electrostatic loudspeakers, however, are designed to operate on the 'push-pull' principle; see *fig. 7*. The membrane is located between two stationary electrodes, which are perforated with a number of small holes to allow the passage of sound waves.

The push-pull electrostatic loudspeaker operates as follows. A d.c. source supplies a high voltage V_0. One terminal of this source is connected to the membrane through a high resistance R_0 and the other is connected to the two stationary electrodes. The source provides the charge for both capacitors. The audio signal is represented by the two a.c. sources V_1. The alternating voltages give rise to alternating forces F per unit area on the charges[7]:

$$F = 2\varepsilon \frac{V_0 V_1}{d_0^2}, \qquad (7)$$

where d_0 is the spacing of the plates and ε is the permittivity of air. The alternating force F makes the membrane vibrate.

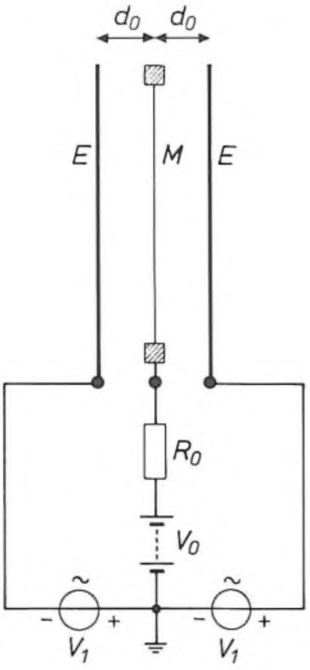

Fig. 7. Schematic illustration of a push-pull electrostatic loudspeaker. M stretched membrane. E stationary electrodes. R_0 high resistance. V_0 high-voltage source. V_1 a.c. voltage sources. d_0 electrode spacing.

In one of our laboratory designs for an electrostatic speaker the area of the stretched membrane is about 0.5 m^2 and the maximum deflection is 3 mm. To produce this deflection it is necessary to give V_0 a constant value of 4000 V and V_1 a maximum amplitude of 4000 V. Obviously, this places some rather special requirements on the material of the electrodes. The membrane consists of an extremely thin polyimide film, coated on one side with graphite. The graphite has a fairly high resistance. The charge cannot therefore move over the surface of the capacitor easily, which might make the field-strength rise locally to the breakdown value. The stationary electrodes are perforated, as we saw just now, and consist of epoxy resin reinforced with glass fibre and coated with copper on the outside. The material is also used for printed circuits. The epoxy resin thus acts as insulation for the actual electrodes. An electrostatic loudspeaker, unlike an electrodynamic loudspeaker in a cabinet, also radiates sound backwards.

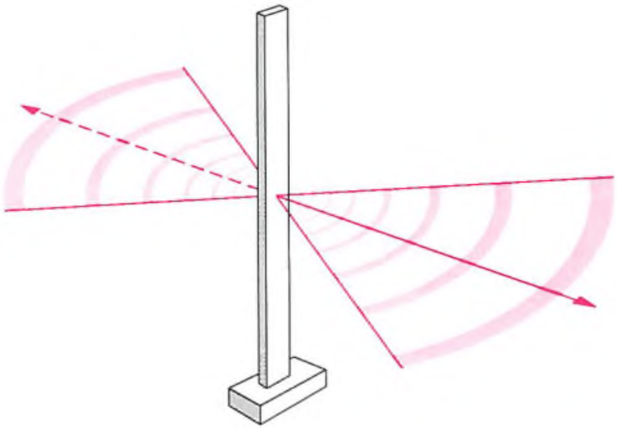

Fig. 8. Electrostatic column loudspeaker. The sound is focused in the vertical plane and there are difficulties because of the 'comb' effect.

To give good reproduction at lower frequencies the electrostatic loudspeaker has a large radiating area. However, to suppress the focusing effect at higher frequencies the dimensions should be small — much smaller than the wavelength of the sound. There are loudspeaker manufacturers who have solved this problem by designing the loudspeaker as a narrow but very high column, again with a radiating area of about 0.5 m^2. In these loudspeakers the higher-frequency sound is only focused in the vertical plane, and fans out in a horizontal plane; see *fig. 8*. The objections to the column shape are that the loudspeaker

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[7] F. V. Hunt, Electroacoustics, Harvard University Press, Cambridge, Mass., 1954.

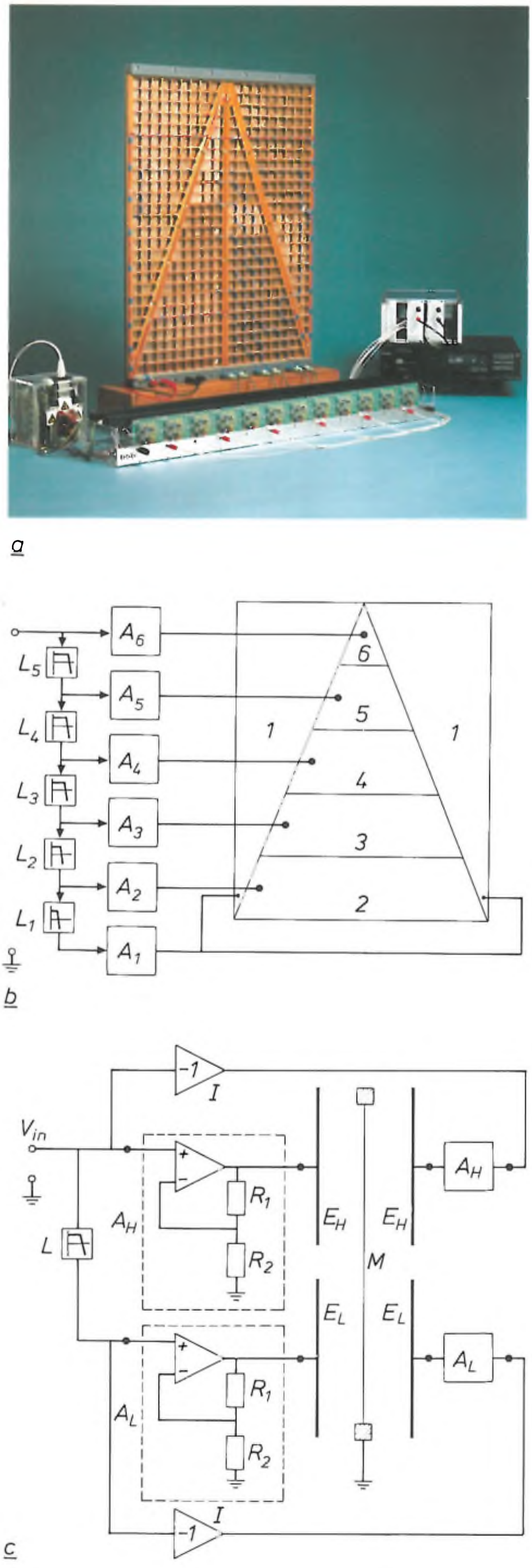

Fig. 9. *a*) Laboratory design for an electrostatic loudspeaker with a total radiating area of 0.5 m^2. *b*) Subdivision of the surface into areas *1* to *6*. A_1 to A_6 electronic circuits. L_1 to L_5 lowpass filters with increasing cut-off frequency. *c*) Circuit for the simplified case in which the loudspeaker area is subdivided into two parts, denoted by subscripts H and L. V_{in} input voltage, the output voltage of an audio power amplifier. *L* lowpass filter. A_H and A_L circuits each consisting of an amplifier, an optoelectronic coupler (not shown) and a voltage divider, resistances R_1 and R_2. The voltage dividers give high feedback of the output voltage from the amplifiers. E_H and E_L stationary electrodes. *M* membrane. *I* amplifiers of gain -1, which drive the stationary electrodes in opposite phase on opposite sides.

◁

is impractically high, 2.5 m perhaps, and the higher frequencies are only perceived in a horizontal region of extremely limited height. Also, this horizontal region contains zones in which the sound is cancelled out — the comb effect — because of destructive interference between sound originating from the centre of the loudspeaker and sound from the extremities.

Our answer to these problems is to reduce the effective radiating area of the loudspeaker as the frequency increases. We subdivided the area of the loudspeaker as shown in *fig. 9*. At the low frequencies all the areas *1* to *6* are operative. The lowpass filters L_1 to L_5, whose cut-off frequencies increase with increasing subscript number, ensure that the circuits A_1 to A_6 receive signals with an increasing frequency range. The two areas *1* are driven by the lowest-frequency components of the audio signal; area *6* is driven by the complete audio signal. Area *6* is so small that there is no undesirable focusing even at the high frequencies.

A problem in subdividing the membrane area as shown in fig. 9*b* is to prevent the high-frequency vibrations from *6*, say, from causing the surrounding areas of the membrane to vibrate. Fig. 9*c* shows how we solved this problem. (The figure is based on a simplified subdivision of the membrane into two parts; the corresponding components are given the subscripts H and L.) Each part of the loudspeaker is driven by two circuits that each include a high-voltage amplifier with high feedback. The two parts of the stationary electrodes on either side are driven by these two circuits in opposite phase with the aid of an amplifier of gain -1.

The special feature here is that the high feedback in the high-voltage amplifiers effectively switches off the parts of the loudspeaker that do not receive any signal. This is because each part of the loudspeaker is a reciprocal element in which a deflection of the membrane induces a signal even though no input signal is present. The feedback then causes a negative output

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[8] The electronic couplers were developed by P. A. Dessens and K. Oostveen of Philips Research Laboratories, Eindhoven.

voltage to appear at the output of the amplifier, which suppresses the original deflection.

Another feature is that we do not use high-voltage transformers as in the electrostatic loudspeakers now on the market. High-voltage transformers are expensive, because they must be highly linear and handle high powers. In our circuits we use a particular kind of optoelectronic coupler (not shown in fig. 9c) [8]. The output stage of the amplifier in this arrangement supplies the high-voltage signal and consists of a circuit containing photosensitive transistors. The output of the power amplifier stage is formed by light-emitting diodes (LEDs). The light emitted by the LEDs drives the transistors of the output stage. This means that there is no electrical connection between the output stage and the input of the amplifier, except for the feedback via the voltage divider (fig. 9c). Finally, *fig. 10* shows the characteristics of the first laboratory version of the new electrostatic loudspeaker.

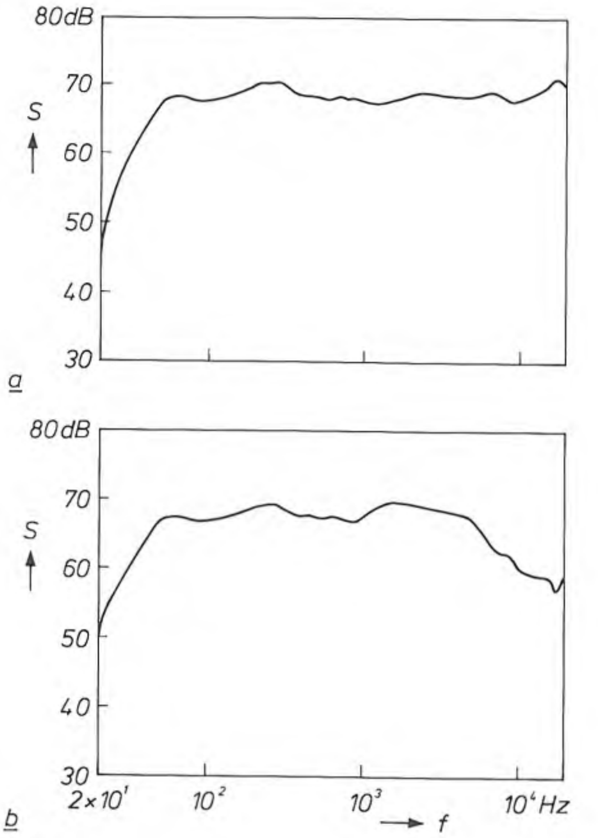

Fig. 10. Characteristics of the first laboratory version of the electrostatic loudspeaker of fig. 9. *a*) Sound pressure level S in dB[6] at a distance of 2 m on the principal axis as a function of frequency f. *b*) Similar characteristic, but at an angle of 20° to the axis. The curves (*a*) and (*b*) are almost identical. Only at frequencies above 7 kHz is curve (*b*) perceptibly below curve (*a*). This indicates that the focusing effect in the electrostatic loudspeaker at high frequencies has been greatly suppressed. Later versions will have even better characteristics.

Summary. The sound radiation from a vibrating membrane can be described by three differential equations: the equation of motion, Helmholtz's equation and an interface condition. This set of equations can be solved with the aid of Green's functions. The results, presented by means of a computer program, show that annular nodes and antinodes occur on a circular stretched membrane, which increase in number with rising frequency. The improved theoretical understanding obtained has led to a laboratory design for an electrostatic loudspeaker. The problem of axial focusing of the higher frequencies has been solved by subdividing the surface of the membrane into separate active areas, each driven by a separate amplifier with a corresponding lowpass filter. Optoelectronic couplers are used in the amplifiers to avoid the need for high-voltage transformers.

Scientific publications

These publications are contributed by staff from the laboratories and other establishments that form part of or are associated with the Philips group of companies. Many of the articles originate from the research laboratories named below. The publications are listed alphabetically by journal title.

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M. P. J. G. Versleijen, P. I. Kuindersma, G.-D. Khoe & L. J. Meuleman *E*	Accurate analysis of dc electrical characteristics of 1.3 μm DCPBH laser diodes	IEEE J. **QE-23**	925-935	1987
J. H. Streng *E*	Calculation of integrals which occur in the analysis of circular stretched membrane sound radiation	J. Acoust. Soc. Am. **83**	1183-1185	1988
C. Colinet*, A. Pasturel* (**Lab. Thermodyn. & Physico-Chimie Métallurgiques, St. Martin d'Hères*) & K. H. J. Buschow *E*	Short-range order and stability in Gd-Ni and Y-Ni systems	J. Appl. Phys. **62**	3712-3717	1987
J. Haisma, A. M. W. Cox, B. H. Koek, D. Mateika, J. A. Pastorius & E. T. J. M. Smeets *E, H*	Heteroepitaxial growth of InP on garnet	J. Cryst. Growth **87**	180-184	1988
R. Grössinger*, R. Krewenka*, H. R. Kirchmayr* (**Univ. of Technol., Vienna*), S. Sinnema⁺, Y. Fu-Ming⁺, H. Ying-Kai⁺, F. R. de Boer⁺ (⁺*Univ. Amsterdam*) & K. H. J. Buschow *E*	Magnetic anisotropy in $Pr_2(Fe_{1-x}Co_x)_{14}B$ compounds	J. Less-Common Met. **132**	265-272	1987
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K. H. J. Buschow, P. Schobinger-Papamantellos (*Inst. für Kristallogr. & Petrogr., Zürich*) & P. Fischer (*Lab. für Neutronenstreuung, Würenlingen*) *E*	Magnetic structure and properties of equiatomic rare earth germanides	J. Less-Common Met. **139**	221-231	1988
C. J. M. Denissen, B. D. de Mooij & K. H. J. Buschow *E*	Structure and ^{57}Fe Mössbauer effect in $R_2Fe_{14}C$ compounds	*ibid.*	291-298	1988
C. J. van der Poel *E*	Rapid crystallization of thin solid films	J. Mater. Res. **3**	126-132	1988
J. C. M. Henning, J. P. M. Ansems & P. J. Roksnoer *E*	A photoluminescence study of the donor structure in $Al_xGa_{1-x}As$	Semicond. Sci. Technol. **3**	361-364	1988
M. M. Abd-Elmeguid*, B. Schleede*, H. Micklitz* (**Univ. Bochum*), T. T. Palstra⁺, G. J. Nieuwenhuys⁺ (⁺*Univ. Leiden*) & K. H. J. Buschow *E*	The stability of the ferromagnetic state in $La(Fe_{0.86}Al_{0.14})_{13}$ under high pressure	Solid State Commun. **63**	177-180	1987
H. Verweij *E*	Defect chemistry of $YBa_2Cu_3O_x$: strong evidence for the presence of Cu^+	Solid State Commun. **64**	1213-1216	1987
P. Deppe*, M. Rosenberg* (**Univ. Bochum*) & K. H. J. Buschow *E*	A Mössbauer spectroscopy study of $Nd_5Fe_2B_6$	*ibid.*	1247-1251	1987

Volume 44, No. 6 pages 169-200 Published 21th December 1988

M. G. J. Heijman, J. H. W. Kuntzel and G. H. J. Somers, Multi-track magnetic heads in thin-film technology,

PhilipsTech.Rev.**44**,No.6,169-178,Dec.1988.

CLS loggers (CLS stands for Communication-Logging System) used for logging spoken messages have to record or play back a large number of signals simultaneously at a very low tape speed. Multiple magnetic heads have to be used. Thin-film technology is used for fabricating 32-track recording heads that are different from the 32-track playback heads. The recording heads have the conventional coils, the playback heads have a magnetoresistance element. In the magnetoresistance element the resistance of a permalloy strip changes when the field in the magnetic 'yoke' of the playback head changes. The 32-track recording and playback heads are fabricated on a ferrite substrate by process steps like those used in IC technology: sputtering, electrochemical growth, photoresist deposition, exposure, plasma etching, ion etching, and photoresist removal. Test conductors in the heads enable tests to be carried out on the wafer. After all the tests have been carried out the multiple heads that have passed are sawn from the wafer and assembled to form a unit ready to be mounted in a logger.

S. van Houten, Applied research — the source of innovation in consumer electronics,

PhilipsTech.Rev.**44**,No.6,180-189,Dec.1988.

Text of a speech given in Nanjing in the People's Republic of China on 1st June 1988 by Dr S. van Houten, member of the Philips Board of Management. After a short introduction to the Philips company the speaker shows how important the role of scientific research is in bringing out electronic consumer products. He gives examples for a number of important fields such as lighting (economical lamps), television technology (various kinds of displays, high-definition television), magnetic and optical recording (Compact Cassette, Compact Disc) and integrated circuits (submicron technology). The speaker makes various points in conclusion, emphasizing that the traditional distinction between professional products and consumer products has changed its character completely and that the user-friendliness of consumer products will be a factor of growing significance.

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J. H. Streng, Sound radiation from a vibrating membrane,
PhilipsTech.Rev.**44**,No.6,190-199,Dec.1988.

The sound radiation from a vibrating membrane can be described by three differential equations: the equation of motion, Helmholtz's equation and an interface condition. This set of equations can be solved with the aid of Green's functions. The results, presented by means of a computer program, show that annular nodes and antinodes occur on a circular stretched membrane, which increase in number with rising frequency. The improved theoretical understanding obtained has led to a laboratory design for an electrostatic loudspeaker. The problem of axial focusing of the higher frequencies has been solved by subdividing the surface of the membrane into separate active areas, each driven by a separate amplifier with a corresponding lowpass filter. Optoelectronic couplers are used in the amplifiers to avoid the need for high-voltage transformers.

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