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HD-MAC

Selecting quartz

Interfaces



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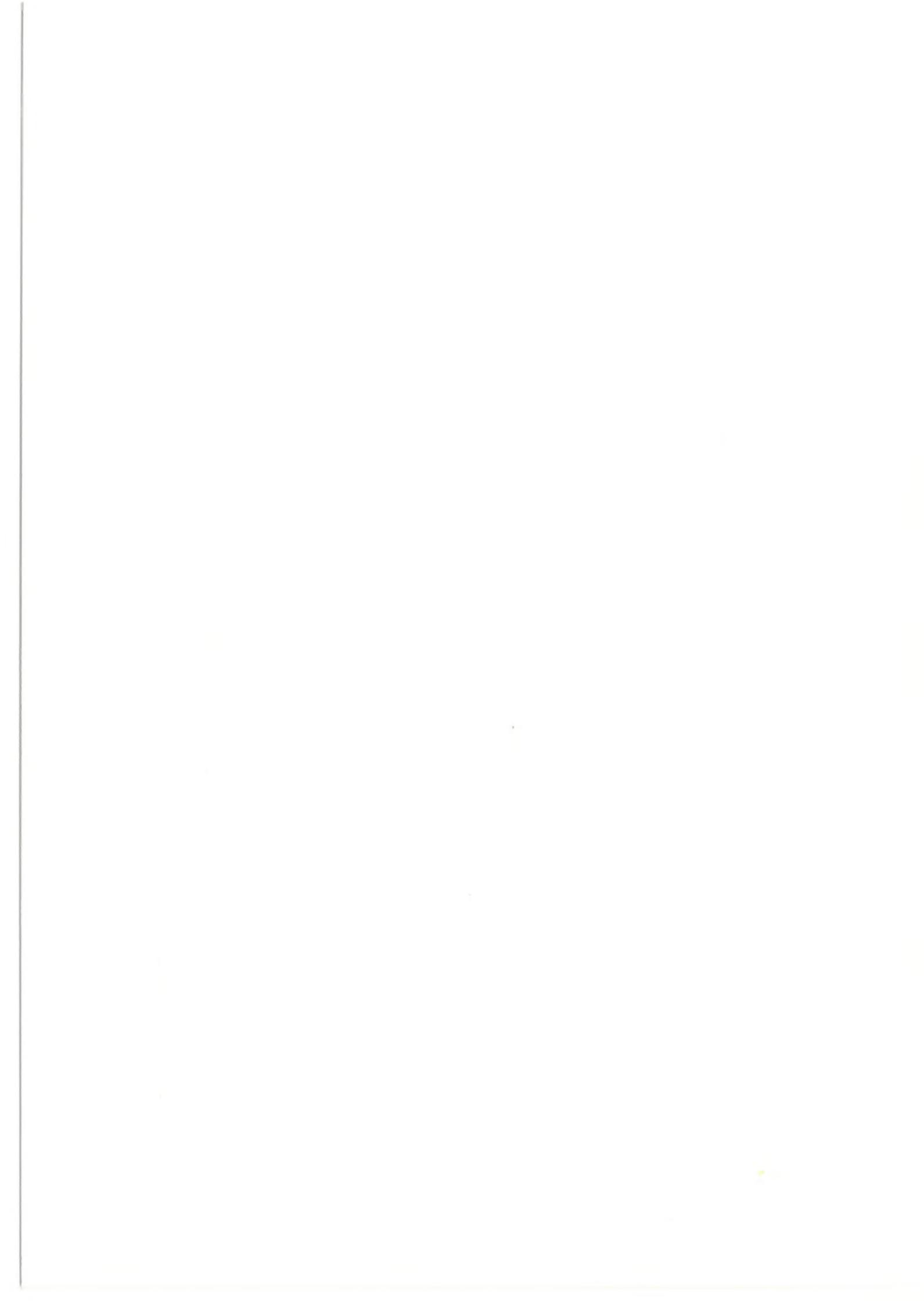
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HD-MAC: a step forward in the evolution of television technology

M. J. J. C. Annegarn, J. P. Arragon, G. de Haan,
J. H. C. van Heuven and R. N. Jackson

The first experiments with television were made about a hundred years ago, and were mainly based on mechanical devices such as the Nipkow disc. Then in the thirties of this century purely electronic solutions became available for all the elementary problems of image transfer. From that time, in its triumphal progress, television has marched on, and on. Now there are some 500 000 000 television receivers throughout the world. Yet the end of the road is still over the horizon: with broadcasting satellites, chips and advanced signal-processing methods, new perspectives have opened before us — literally and figuratively. From a purely technical point of view the possibilities for the future seem to be virtually unbounded. However, for quite other reasons (economic ones especially) it is vitally important that the development should be evolutionary rather than revolutionary. In the article below a new television system of such an evolutionary nature is described.

Introduction

A map of the world showing the television system used in each country looks something like a patchwork quilt. To start with, some systems have 30 pictures (frames) per second, with 525 lines per picture, whereas others have 25 pictures per second, with 625 lines per picture. Then there are three different standards at present for transmitting colour pictures: NTSC, PAL and SECAM. Recently, for use in television broadcasting satellites and cable systems, a 'family' of MAC systems (MAC stands for Multiplexed Analog Components) has been added^[1]. There are also many smaller differences, e.g. in the methods used for including the sound, for encoding the stereo sound information and for handling teletext and videotex. Clearly, in spite of all the international agreements and recommendations, the situation is very varied,

and this is far from ideal. The undesirable consequences of this are becoming more and more noticeable as the exchange of picture information by electronic methods becomes more common. Although conversion of one type of television signal into another is always possible in principle (and is often used in practice), complicated professional equipment is generally required, and loss of quality cannot always be avoided.

But another, and in fact more fundamental, criticism can be made of the situation just described. Television is sometimes called 'the window on the world'. However, it is a very small window giving only a limited experience of reality. It can be shown that larger, sharper pictures greatly improve the viewing experience — with a difference that is of the same order of magnitude as was the addition of colour to monochrome TV. Unfortunately the existing TV systems were not designed for producing adequate pic-

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^[1] H. Mertens and D. Wood, Standards proposed by the EBU for satellite broadcasting and cable distribution, J. IERE 56, 53-61, 1986.

ture quality when used with large-screen displays. What is needed, therefore, is a new and improved television signal that satisfies a 'high-definition' *broadcast* standard and is known as an HDTV broadcast signal.

There is yet another important point: much of the picture material intended for transmission by television is initially recorded ('produced') on photographic film, because the quality on film is superior to that of the present television standards. It will only be possible to change this situation by using a considerably improved and as yet not agreed (electronic) 'high-definition' *production* standard.

There is therefore a clear need for a new television standard that will make HDTV possible, and it is most important to achieve the best possible world-wide consensus here. However, it is at present a matter of debate whether the HDTV broadcast standard should in fact be exactly the same as the HDTV production standard, in spite of the close relationships between the two. For an HDTV broadcast standard it is important that the vast quantities of existing consumer equipment should not suddenly be made obsolete: existing equipment must be capable of processing any improved signals to give the quality now attainable. In other words, this standard should permit a gradual ('evolutionary') progress towards equipment with improved picture quality^{[2][3]}. This could perhaps imply that a single world standard for HDTV broadcasting might not be sufficient: for example in relation to the picture frequency it might be better to consciously retain the existing 25-Hz/30-Hz frontier. The HDTV production standard, on the other hand, should be so universal that it will permit conversion without loss of picture quality to any other existing standard (thus including any accepted HDTV broadcast standard).

In this article we should like to show, as an example, how an HDTV broadcast standard could be based on the standardized MAC family. First, however, we shall pause briefly to look at HDTV in general. Next, we shall give a short description of the existing MAC family, which we shall usually call the 'MAC/packet' system from now on. The remaining — and longest — part of this article will be devoted to the equipment and the special signal-processing operations that are required to obtain the desired high-definition quality with this system.

High-definition television (HDTV)

The term 'high-definition television' is not new; it was used some fifty years ago by a British government committee to refer to all television systems that used more than 240 lines. Today we take it to mean something quite different. HDTV means satisfying the need

for an enhanced viewing experience by providing large, high-quality pictures. To do this we must improve present television quality in the following respects:

- an improvement in the resolution in the vertical and horizontal directions by a factor of about two;
- suppression of the undesirable interaction between chrominance and luminance information ('cross-colour' and 'cross-luminance');
- an increase in the aspect ratio (this is the ratio of picture width to picture height, and is now 4:3) to 16:9 to give greater compatibility with cine images and the characteristics of the human eye;
- stereophonic sound with 'hi-fi' quality.

Experiments have shown that the first two improvements allow a considerably larger picture to be used for the display, and in combination with the change in aspect ratio this gives a greater involvement of the viewer. None of the three older colour-television standards PAL, NTSC and SECAM is suitable for the full attainment of the above improvements. Fortunately, however, this does seem to be possible within the newer MAC television standard. This opens the way for a gradual transition to HDTV, with existing equipment remaining fully serviceable and providing the quality for which it was originally designed^[4].

Multiplexed Analog Components (MAC)

With the prospect of geostationary terrestrial satellites as 'suspended' television transmitters, which transmit the signal directly to the individual television viewers ('direct-broadcasting satellites'), the need arose a few years ago for a new television broadcast standard. As far back as 1977 international agreements were concluded at the World Administrative Radio Conference (WARC) about the available frequency band and the permitted signal level for each television channel. The European countries were each allocated five channels with a bandwidth of 27 MHz in the frequency range around 12 GHz. For these channels, mainly because of the maximum permissible transmitted power, frequency modulation (FM) is the best modulation method. This means, however, that the noise appearing on reception has the characteristic triangular spectral shape associated with FM, so that the noise power increases linearly with the frequency. In the existing PAL/NTSC/SECAM systems, however, it is the higher frequencies that carry the chrominance and sound information, so that these are relatively the most affected by this FM noise (*fig. 1*).

Quite apart from this, the long range of satellite transmitters creates almost automatically a need for more sound channels and more arrangements for sub-

titling than exist in conventional transmitters. Moreover, it is highly desirable to be able to 'encode' television signals in a simple and reliable way so that certain programmes can only be obtained after extra payment (pay TV and subscriber TV). A solution for all these problems and special features has been found in the form of the MAC/packet system. This system has the same scanning structure as conventional TV systems, i.e. 625 lines per picture, 25 pictures per second and 2:1 interlacing^[5]. The most fundamental characteristic of a MAC television signal, however, is that all the types of information — such as luminance, chrominance and sound — occur alternately (in 'time-division multiplex') and only become simultaneously available again on display. To make this possible the conventional luminance signal Y and the conven-

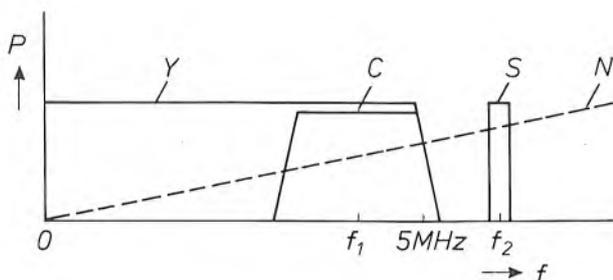


Fig. 1. General diagram of the frequency spectrum P of a colour-television signal in one of the current systems PAL, NTSC and SECAM. Y luminance information. C colour information. S sound information. N triangular noise resulting from frequency modulation. f_1, f_2 subcarrier frequencies for C and S respectively.

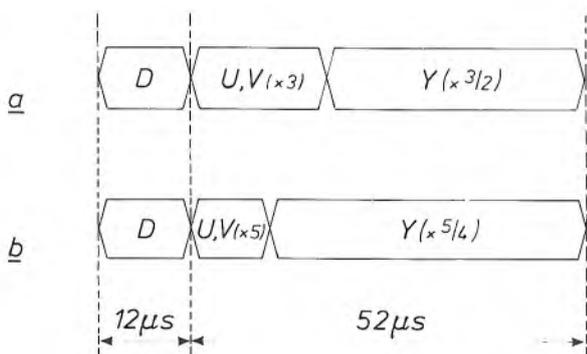


Fig. 2. In the MAC system each line period of $64 \mu s$ contains one of the two colour-difference signals U or V and the luminance signal Y in a compressed form, one after the other. Two combinations of compression factors are possible: *a*) 3 and $3/2$, or *b*) 5 and $5/4$. The rest of the line period (the flyback time D) is used for sound signals, synchronization signals, etc.

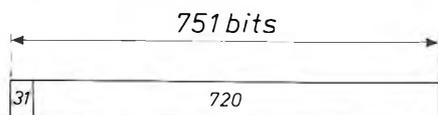


Fig. 3. The sound and other digital information are included in the MAC signal as packets of 751 bits, with 720 bits representing actual information. The bit rate is $10\frac{3}{8}$ or $20\frac{3}{4}$ MHz. One packet is distributed over about 8 or about 4 line-flyback times respectively.

tional chrominance signals U and V are compressed in time, so that they then fit together, one after the other, into the same time interval as before ('the line period'; fig. 2). Each line period, moreover, contains only U or V , in alternate sequence. Because of the time compression the bandwidth increases proportionately. Two possible combinations of compression factors have been selected: a compression factor of $3/2$ for Y combined with a compression factor of 3 for U and V or a factor of $5/4$ for Y and a factor of 5 for U and V . In this latter case, a greater bandwidth for the Y information is available for a given bandwidth of the compressed signal, at the expense of a reduced bandwidth for U and V .

One of the great advantages of a MAC television signal is that in principle there is now no question of cross-colour and cross-luminance, because luminance information and chrominance information are no longer present simultaneously in the signal. Moreover, it is also easier to take advantage of the full bandwidth of the luminance and chrominance signals after reception, so that a MAC signal alone (i.e. without specific HDTV measures) can give a better picture quality than existing systems.

During each line period (in the line-flyback time) there is also room for sound information (4 to 8 mono channels), synchronization and various forms of digital information ('data'). The sound is digitally encoded to 'hi-fi' quality. The sound and the data are divided up into 'packets' (whence the name MAC/packet system) of 751 bits. Of these, 31 bits represent auxiliary information (the opening or 'header') and the remaining 720 bits serve as the actual information (see fig. 3). The header mainly indicates the kind of information transmitted in the packet. Each packet extends over more than one line-flyback time. In the field-flyback times more space is reserved for

[2] H. Mertens, The future evolution of broadcasting standards (The 1984 Shoenberg Memorial Lecture of the Royal Television Society), Television (J.R. Telev. Soc.) 22, 4-12, 1985; C. J. van der Klugt, New television standards: revolution or evolution (The 1985 Shoenberg Memorial Lecture of the Royal Television Society), Television (J.R. Telev. Soc.) 23, 6-12, 1986.
 [3] C. P. Sandbank and I. Childs, The evolution towards high-definition television, Proc. IEEE 73, 638-645, 1985.
 [4] M. J. C. Annegarn, J. P. Arragon and R. N. Jackson, High definition MAC: the compatible route to HDTV, paper presented at the International Broadcasting Convention, Brighton 1986; G. M. X. Fernando and D. W. Parker, Improved display conversion for high definition MAC, paper presented at the International Broadcasting Convention, Brighton 1986; G. de Haan and W. Croymans, Subsampling techniques for high definition MAC, paper presented at the International Broadcasting Convention, Brighton 1986; F. Fonsals and J. Y. Lejard, A method for chrominance contour enhancement applied to HD-MAC television pictures, paper presented at the International Broadcasting Convention, Brighton 1986.
 [5] A similar system also exists for 525 lines per picture and 30 pictures per second.

other extra information (such as teletext and subtitles) and — perhaps at least as important — information about the precise way in which the MAC signal has been built up from various signal components (*fig. 4*). For example, in addition to the conventional aspect ratio of 4:3 an aspect ratio of 16:9 is permitted in the MAC/packet system. Since this is possible with each of the two combinations of time-compression factors mentioned earlier, there are already a total of four different kinds of picture coding in the MAC/packet system. The extra information transmitted creates a large measure of flexibility, which at the same time opens the way for a gradual evolution to HDTV display of suitably encoded MAC/packet signals. This will be explained further in the following section.

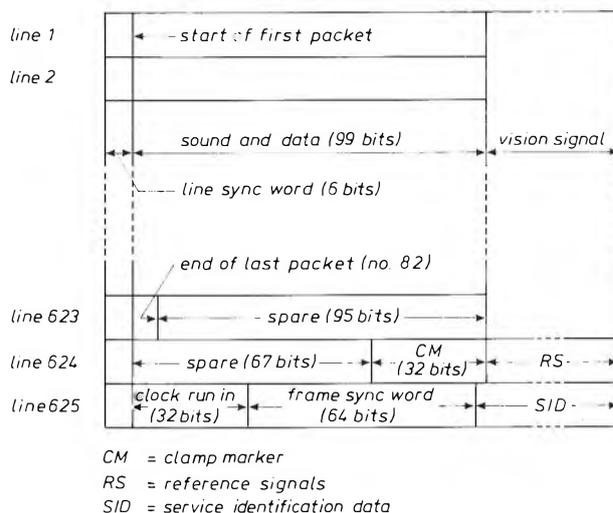


Fig. 4. General arrangement of a complete frame for a member of the MAC/packet family ('D2-MAC'), corresponding to a complete television picture of 625 lines. The intervals that correspond to one line period are shown here one above the other; in fact the picture information occupies about 5/6 of the line period (see *fig. 2*).

High-Definition MAC (HD-MAC)

A schematic, but almost self-explanatory presentation of the possibilities of the MAC signal standard can be found in *fig. 5*. *Fig. 5a* shows a simple MAC television system. A television picture, consisting of 625 lines per picture, with 2:1 interlacing, 50 fields (rasters) per second, a bandwidth of about 5 MHz for the luminance signal and an aspect ratio of 4:3, is generated in a camera. The signals pass through a MAC encoder, a standard MAC channel (e.g. a broadcast satellite) and a MAC decoder, to produce eventually a good picture on a standard receiver. *Fig. 5b* shows an HDTV system in which the same standard MAC channel is used. At the transmitting end, however, an HDTV camera is now used, with 1250 lines per picture, 2:1 interlacing, 50 fields per second, a Y band-

width of 20 MHz and an aspect ratio of 16:9. A signal that can be transmitted via the standard channel is derived from the camera via an HD-MAC encoder. At the receiving end a picture of HDTV quality can be displayed with the aid of a special HD-MAC decoder and a special receiver; the signal that originates from the standard MAC channel can however also be processed to give the conventional quality by standard MAC equipment. *Fig. 5b* shows clearly the 'downward compatibility' of the HD-MAC approach. The key to proper operation is to be found in the special HD-MAC encoder and decoder. In the following sections we shall therefore look more closely at these circuits and the signal-processing theory on which they are based.

Television signal processing

The essence of generating a television signal is the conversion of an image, generally moving, into an electrical signal. For the moment we shall confine ourselves to the luminance information from the picture, which in both monochrome and colour television is represented by a single signal $s(t)$.

The picture is usually considered as an intensity function $I(x, y, t)$, where x is an independent variable in the horizontal direction, y is an independent variable in the vertical direction and t is time. The conversion of $I(x, y, t)$ into $s(t)$ is made by means of a line scan, in much the same way as our eyes scan when we read the successive pages of a book. In the acquisition of the image (and later when it is displayed) this scan corresponds essentially to a discretization of the variables y and t , or in other words, to a double 'sampling' by vertical position and time. This leads to certain peculiarities that are not fully taken into account in existing television systems. The subdivision of a picture into horizontal lines, for example, means that the television camera cannot distinguish between a uniform white surface and a fine pattern of horizontal black and white lines if it so happens that only the white lines are scanned. Also, the subdivision of a moving scene into a series of successive separate images means that changes that occur in the interval between two images are not observed, whereas certain parts of stationary images tend to show a periodically varying intensity on display ('large-area flicker'). By taking better account of the peculiarities of the scanning process a considerable improvement in the picture quality of television can be obtained^[6]. We shall describe this in the section 'Improvement of the resolution in the vertical direction'.

As long as most of the signal processing in television is 'analog', there is no discretization or sampling

in the x -direction. As soon as analog-to-digital conversion comes into play, there is sampling in that direction as well. Then, if the sampling theorem is not satisfied, we run into the danger of certain additional unwanted effects occurring. However, by deliberately applying 'sub-Nyquist sampling', we can again obtain a considerable improvement in picture quality, particularly for stationary images, at practically the same sampling rate. We shall consider this more closely in the section 'Improvement of the resolution in the horizontal direction'.

To describe the various types of signal processing of images and their consequences, we can make good use of the concept of frequency. However, there are now three kinds of frequencies. First of all, there is the vertical frequency f_y , which we express in *cycles per picture height* or c/ph and the horizontal frequency f_x , which we express in *cycles per picture width* or c/pw . In addition to these there is the temporal frequency f_t , expressed in Hz, which indicates how fast the image intensity changes as a function of time. We can illustrate the concepts of horizontal and vertical frequency

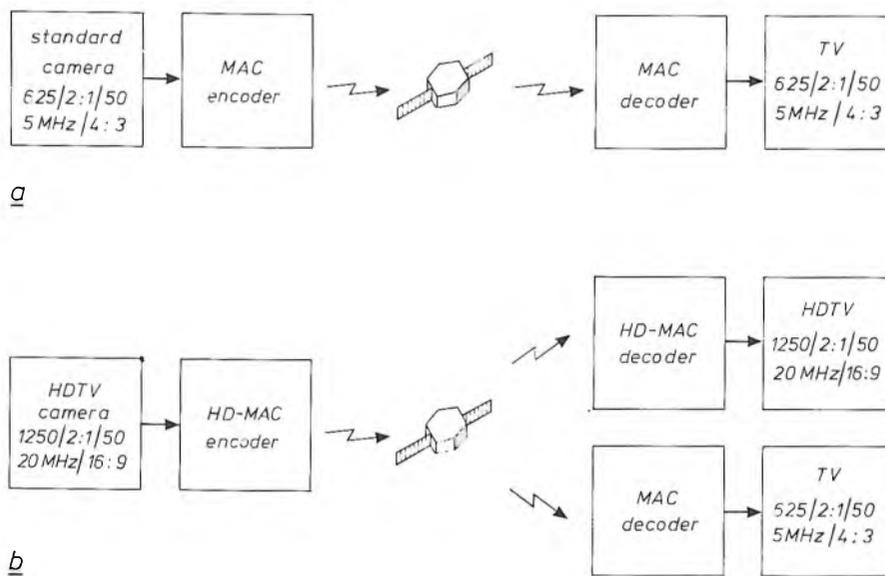


Fig. 5. a) With standard equipment for encoding and decoding MAC signals good television quality can be obtained via broadcasting satellites. b) By using an HDTV camera and an HD-MAC encoder at the transmitting end it is possible — depending on the receiving equipment — to obtain both a standard-quality display and the much better 'high-definition' quality.

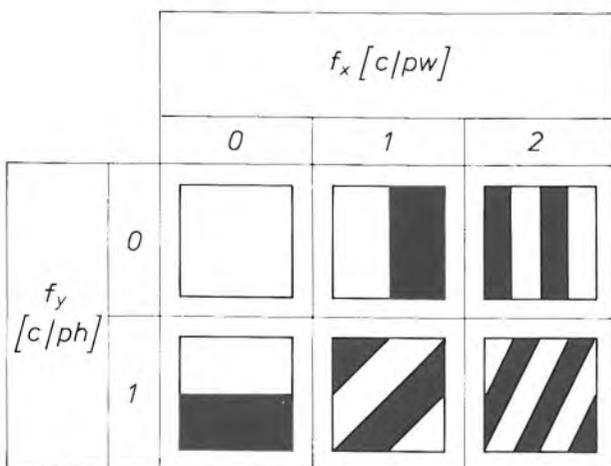


Fig. 6. The concepts of 'horizontal frequency' f_x and 'vertical frequency' f_y , expressed in number of cycles per picture width (c/pw) and number of cycles per picture height (c/ph) can easily be recognized from these simple stationary images. For simplicity the sinusoidal variation in luminance between maximum white and maximum black is replaced here by a stepwise variation.

with the aid of a number of stationary images (so that $f_t = 0$); see fig. 6. Until further notice we shall limit our considerations mainly to stationary and — as we stated earlier — monochrome images.

Television signal spectra

The concept of 'sampling' is of central importance in a detailed analysis of signal processing in television. The sampling theorem for simple one-dimensional signals (such as a mono audio signal) is well known: no information is lost on sampling provided that the sampling frequency is at least twice that of the highest

[6] B. Wendland, High definition television studies on compatible basis with present standards, in: Television technology in the 80's, SMPTE, New York 1981, pp. 151-165; B. Wendland, Extended definition television with high picture quality, SMPTE J. 92, 1028-1035, 1983; G. J. Tonge, The television scanning process, SMPTE J. 93, 657-666, 1984.

frequency in the sampled signal. The spectrum of the sampled signal then consists of an infinitely extending periodic repetition of the original signal spectrum. The original signal can be reconstructed exactly from this with an ideal lowpass filter *LP*. This is illustrated in *fig. 7a* and *b*. *Fig. 7c* shows a situation in which the sampling theorem is *not* satisfied; now *aliasing* or *folding distortion* occurs and the original signal cannot be reconstructed. It is also interesting to note here that a shift in the sampling times by half the sampling interval (*fig. 7d*) multiplies alternate periodic repetitions by a factor of -1 . By adding $S_1^*(f)$ and $S_2^*(f)$ from *fig. 7c* and *d* we can however recover $S^*(f)$ from *fig. 7b* exactly, without aliasing. This is because

$$s^*(t) = s_1^*(t) + s_2^*(t),$$

and therefore

$$S^*(f) = S_1^*(f) + S_2^*(f).$$

The same principle can be very usefully applied in television. However, things are rather more complicated because we are dealing with *three* frequencies, f_x , f_y and f_i . These frequencies can be plotted along three axes perpendicular to one another. Any moving scene can thus be represented as a three-dimensional body (a 'three-dimensional spectrum') located around the origin (*fig. 8a*). The bounding planes of this body indicate the limiting values which we wish to consider for each of the three frequencies. A stationary image with limited detail, for example, is characterized by a finite part of the (f_x, f_y) -plane, and a moving image that only consists of infinitely long vertical lines is bounded by the (f_x, f_i) -plane. The different stages in the processing of television signals can now be clearly demonstrated within this context:

- Scanning in a horizontal line pattern is sampling in the vertical direction and gives a periodic repetition of the spectrum along the f_y -axis, with a period proportional to the number of lines f_v .
- Breaking a scene down into successive images is sampling in time and gives a periodic repetition of the spectrum along the f_i -axis, with a period proportional to the picture frequency f_p .
- Any analog-to-digital conversion leads to repetition of the spectrum along the f_x -axis, with the period determined by the number of samples on each line.

If more than one of these three types of sampling occur at the same time, then there is periodic repetition of the spectrum in more than one direction, of course; see *fig. 8b*. In each of these spectral repetitions aliasing can arise (especially in the f_x - and f_y -directions) and this degrades the final picture. If there was no kind of aliasing at all on display, and all the periodic spectral repetitions could be completely re-

moved, then we would be able to recover the original scene absolutely faithfully without line structure or flicker, for example. The objective in HDTV is to approach this situation as closely as possible. Here we make extensive use of operations that we can characterize as manipulations of the spectrum — especially

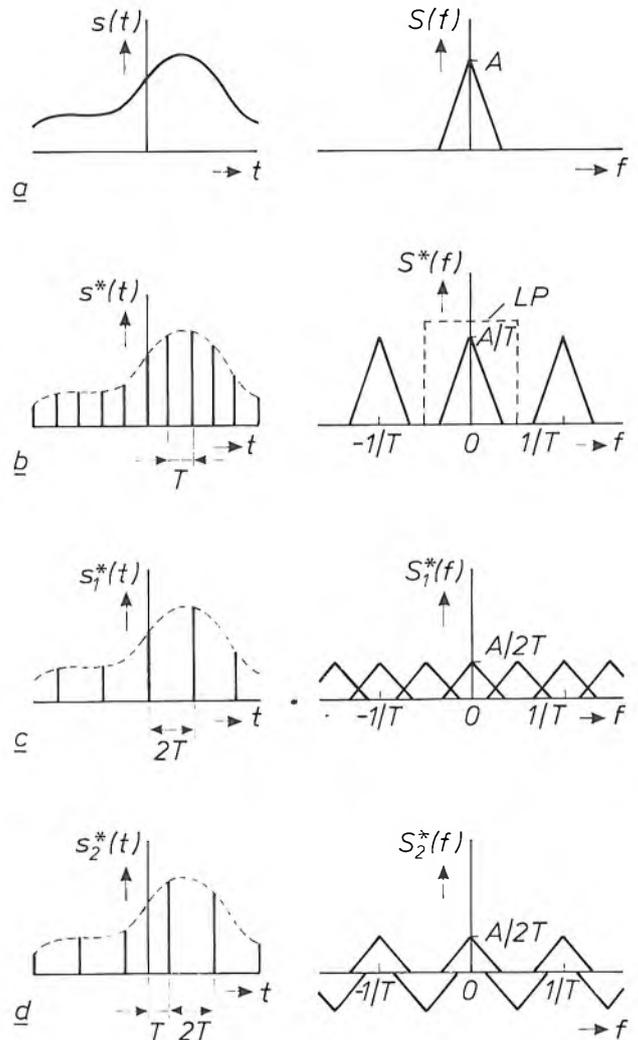


Fig. 7. *a*) Analog signal $s(t)$ and the associated frequency spectrum $S(f)$. *b*) After sampling the signal $s^*(t)$ is obtained with frequency spectrum $S^*(f)$. If the sampling theorem is satisfied, the original signal $s(t)$ can be reconstructed with an ideal lowpass filter *LP*. *c*) and *d*) If the sampling theorem is not satisfied, there is aliasing in the frequency spectrum: parts of the spectrum overlap. By adding $S_1^*(f)$ and $S_2^*(f)$, however, $S^*(f)$ can be recovered accurately.

as filtering. Therefore it is useful to distinguish between a number of types of filtering, and we should remember that filtering (in the classical sense as well) amounts to the combination (e.g. averaging) of the information from a number of different pixels. If we only combine pixels on the same line, we refer to *horizontal filtering*. We can represent this in the (f_x, f_y, f_i) -space by means of planes that are parallel to the

(f_t, f_y) -plane. The effect is shown in *fig. 9a* of an ideal horizontal lowpass filter with a cut-off frequency of f_{x1} on the spectrum $S(f_x, f_y, f_t)$ of *fig. 8a*. In a similar way we refer to *vertical filtering* if the combined pixels

we can obtain various kinds of combined filtering, such as horizontal-temporal or vertical-temporal filtering. The general term *spatio-temporal filtering* is also used in these cases.

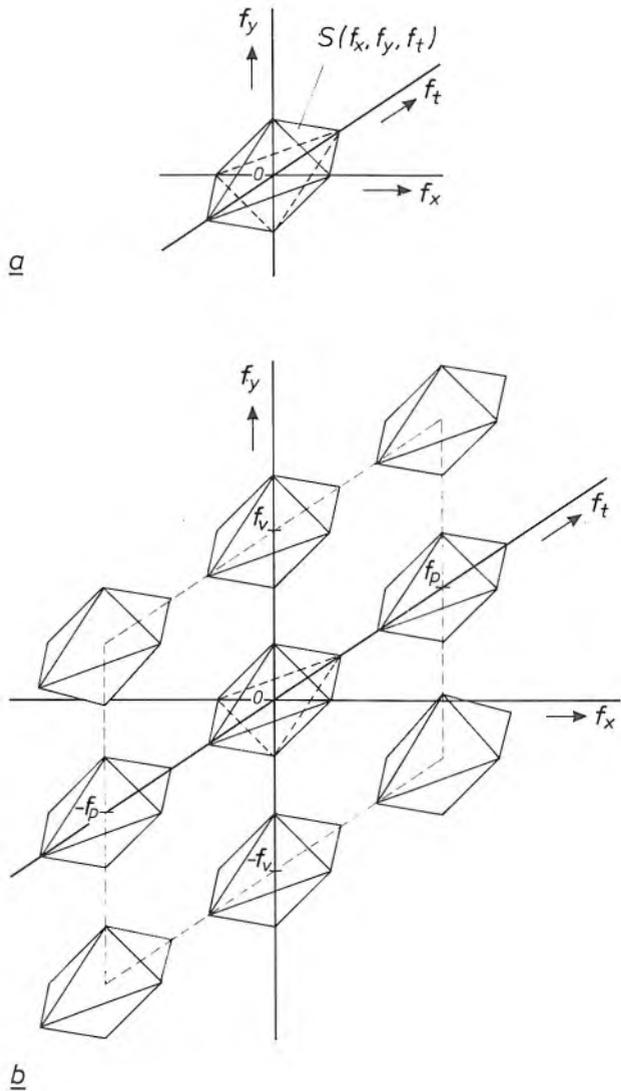


Fig. 8. a) By making use of the horizontal frequency f_x , the vertical frequency f_y , and the temporal frequency f_t we can produce a three-dimensional representation of any scene. The surface $S(f_x, f_y, f_t)$ indicates the limiting values in all directions for the frequencies to be considered. b) On sampling there is periodic repetition of the spectrum along the frequency axis corresponding to the dimension (horizontal position, vertical position or time) in which the discretization occurs. Aliasing can occur here, just as in *fig. 7*. This diagram shows the first spectral repetitions that occur in the discretization of the scene in terms of vertical position and time; it is assumed here that we have f_v lines per picture and f_p pictures per second.

in successive lines lie directly one above or below the other.

The term *temporal filtering* indicates that the only pixels combined in the filtering are those that relate to the same position in successive images. By including more than one kind of pixel in the same filtering pro-

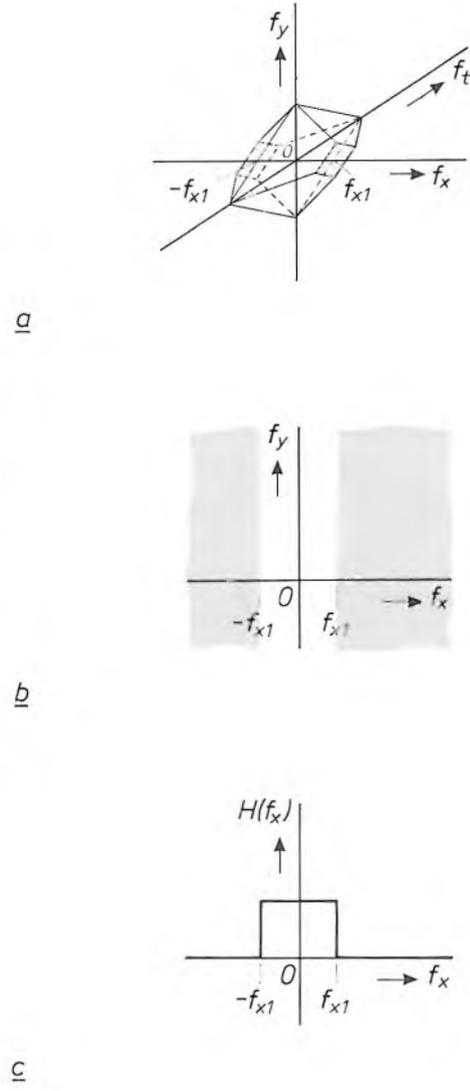


Fig. 9. a) An ideal horizontal lowpass filter with cut-off frequency f_{x1} restricts the spectrum of *fig. 8a* in the x -direction to the interval $(-f_{x1}, f_{x1})$. b) Two-dimensional representation of the ideal horizontal lowpass filter. c) Conventional one-dimensional representation $H(f_x)$ of the same filter characteristic.

Fortunately we do not always have to deal with three-dimensional spectra; we can frequently make do with a two-dimensional cross-section, since all the relevant information can be derived from this. The ideal horizontal lowpass filter is shown in *fig. 9b* as a two-dimensional filter. (In this case, in fact, the conventional one-dimensional representation alone is sufficient; *fig. 9c*.)

Improvement of the resolution in the vertical direction

It has been known since 1934^[7] that a television picture built up from horizontal lines has a much worse resolution in the vertical direction than might at first sight be expected. For example, it has been found from subjective tests that with 100 scanning lines a scene consisting of a maximum of 32 black horizontal lines and 32 white horizontal lines (and not the expected 2×50 lines) can be displayed successfully. This loss of 'sharpness' in the vertical direction we call the 'Kell effect'. It can be expressed by the 'Kell factor', which can vary from 0.5 to 0.7 depending on various circumstances. If the Kell factor could be made equal to 1, it would be possible to achieve a considerable improvement in the quality of the existing television pictures and hence make a significant step in the direction of HDTV. What exactly causes the Kell effect? Let us look at the spectrum in the (f_x, f_y) -plane of a television image consisting of $f_v = 625$ lines, which are scanned sequentially at a picture frequency of 50 Hz. This spectrum looks like the diagram of *fig. 10a*.

It can happen that in considering vertical frequencies account is only taken of the number of *active* lines instead of the *total number* of lines in the picture, as we shall usually do in this article. In a system with 625 lines, for example, the number of active lines is 575; the change to this other approach means that all vertical frequencies should be multiplied by a constant factor of $575/625 = 0.92$.

In yet another approach reference is made to the number of pixels N_v that can be distinguished in the vertical direction; this number corresponds to twice the highest possible vertical frequency $f_{y,\max}$ that can be displayed with the given number of active lines N_{act} . In the most favourable case (Kell factor = 1):

$$f_{y,\max} = N_{\text{act}}/2$$

and therefore

$$N_v = N_{\text{act}}.$$

In general, however, N_v will have a smaller value.

In scanning, interlacing is generally used, to limit the bandwidth of the final television signal. This gives a spectrum like the one shown in *fig. 10b*. In both cases the frequencies that can be observed with the human eye fall within the dashed circle drawn around the origin O . We therefore 'see' not only the desired spectrum (centred on O), but also parts of the spectral repetitions around the points A , B and C . The spectra around A give rise to large-area flicker; the spectra around B are responsible for the visibility of the (static) line structure and the spectra around C lead to line flicker and an apparent vertical movement of the line structure (line crawl). And in fact the situation is worse than it appears from *fig. 10*. In the television pictures now generally used the original spectrum

extends beyond $312\frac{1}{2}$ c/ph in the vertical direction. This means that the 'repeat spectra' also overlap and therefore give rise to aliasing. It is in fact these spectral repetitions and aliasing in the vertical direction that cause the Kell effect. (In passing, we should mention that for very rapidly changing images comparable

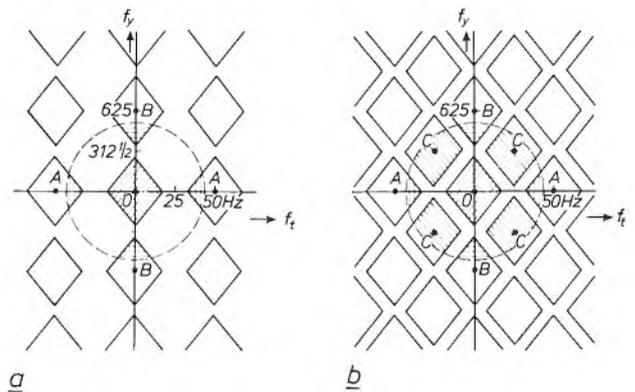


Fig. 10. *a)* Cross-section at $f_x = 0$ of the three-dimensional spectrum of a television signal that has been built up from 625 lines per picture and 50 pictures per second (without interlacing). *b)* As in *(a)* but now with 2:1 interlacing; there are now 50 fields and 25 complete pictures per second. The spectrum of the original scene is concentrated around the origin O ; the spectral repetitions at A cause large-area flicker, the ones at B are responsible for the visibility of the (static) line structure and those at C lead to line flicker and an apparent movement of the line pattern. The dashed circles give a rough indication of the limits of perception of the human eye under normal viewing conditions.

effects arise in the f_t -direction; however, these are much less of a nuisance.)

By starting with a camera with $2f_v$ lines instead of the usual number f_v , but still with 2:1 interlacing and using a number of processing operations, we can obtain a very interesting television signal with f_v lines and 2:1 interlacing. This signal has *no* vertical aliasing and can be transmitted and displayed with standard equipment for f_v lines. Yet the quality of the displayed picture is improved, because some of the Kell effect has been eliminated. However, the same signal can also be used, after a number of additional processing operations in the receiver, for display with $2f_v$ lines, and then the Kell effect can be completely eliminated.

The successive stages in this process are shown in the block diagram of *fig. 11* and the spectra of *fig. 12* for a system starting with a camera signal with 1250 lines, 2:1 interlacing and a field frequency of 50 Hz (designated as 1250/2:1/50 for brevity). With the aid of a number of memories a non-interlaced (i.e. 'sequential') signal with 1250 lines is first generated from this in a 'scan converter'. In this conversion

^[7] R. D. Kell, A. V. Bedford and M. A. Trainer, An experimental television system, *Proc. I.R.E.* 22, 1246-1265, 1934.

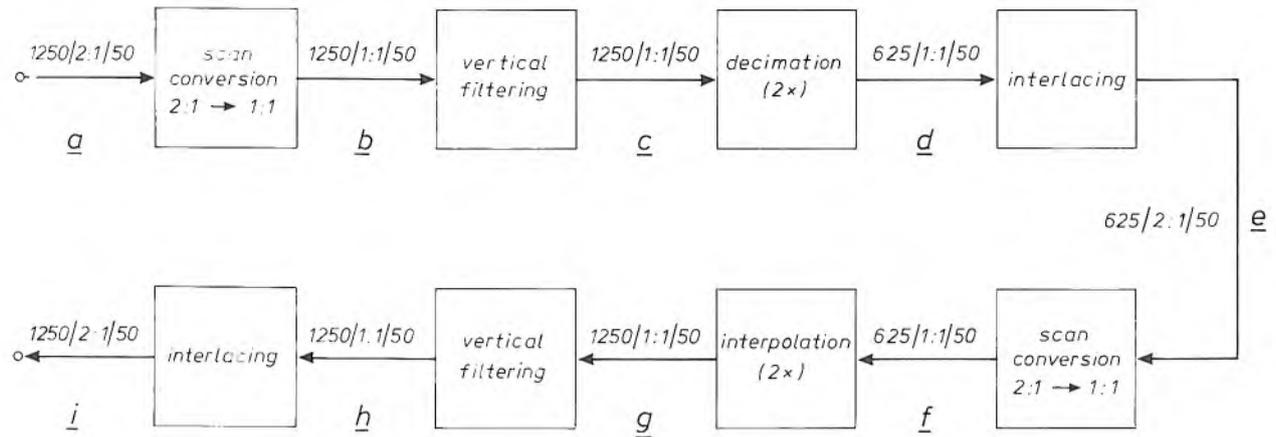


Fig. 11. By starting from a television signal of type 1250/2:1/50, followed by scan conversion (changing from an interlaced picture to a sequential one), vertical filtering, decimation (halving the number of lines) and then interlacing again a signal of type 625/2:1/50 can be obtained in which there is no aliasing in the vertical direction. This signal can be displayed on a standard television set. However, by carrying out a number of operations complementary to the ones we have just mentioned, it is possible to obtain another signal of type 1250/2:1/50 that is completely free from Kell effects and therefore represents a considerable improvement in quality. The spectra of the signals *a*, *b*, ... are shown in fig. 12.

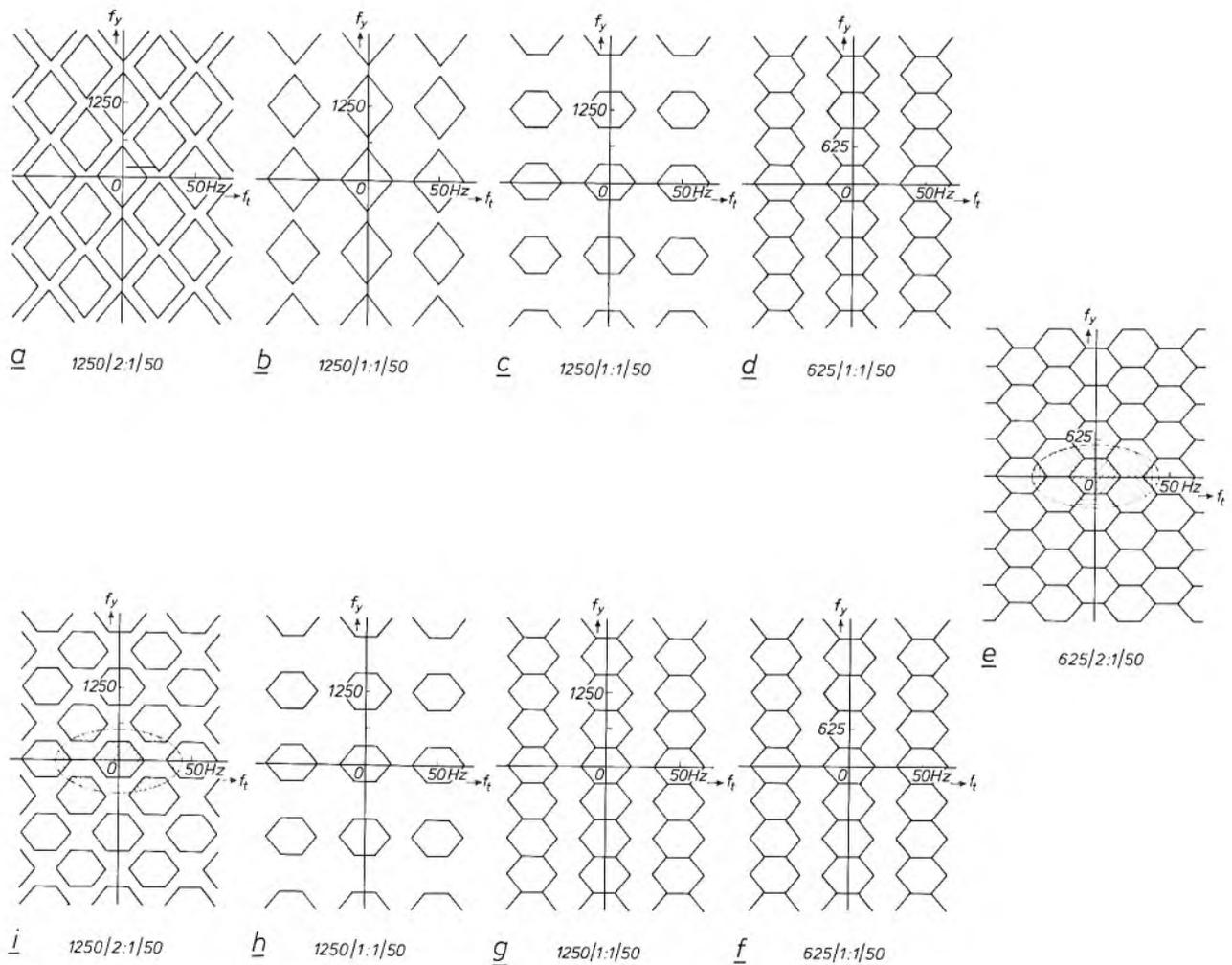


Fig. 12. Two-dimensional spectra in the (f_t, f_y) -plane at various points in the block diagram of fig. 11. The letters *a*, *b*, ... correspond in these two figures. (In this figure the limits of human visual perception appear as an ellipse instead of a circle as a result of the altered scale division in the vertical direction.)

something similar takes place to what we saw for one-dimensional spectra in fig. 7: by combining two discrete signals — representing odd fields and even fields respectively — that contain essentially the same information, certain spectral repetitions (at least for stationary images) can completely compensate one another. Next, the original spectrum is limited to frequencies below $312\frac{1}{2}$ c/ph by purely vertical filtering. After this the number of lines can be reduced to 625 by simply omitting every other line (625/1:1/50). From this sequential signal an interlaced signal can be obtained (625/2:1/50) that is compatible with conventional television signals. Because of the vertical filtering there is no longer any aliasing in this signal in the f_y -direction, but there are still vertical spectral repetitions within the perceptual range of the eye (dashed ellipse).

In the form now reached the signal can be transmitted or stored by all the conventional methods. For optimum display we carry out the following extra operations. First we go from an interlaced signal (625/2:1/50) to a sequential signal (625/1:1/50). Then, with the aid of a vertical 'interpolating' filter [8], we produce in two steps a sequential signal with twice the number of lines (1250/1:1/50) and from which half of the total of spectral repetitions are removed. Finally, we derive an interlaced signal again from this (1250/2:1/50). Because of the interlacing new spectral repetitions appear, but these contain no purely vertical frequencies. There are now no spectral repetitions or overlaps in the vertical direction within the perceptual range of the eye: the Kell effect has therefore been eliminated.

Improvement of the resolution in the horizontal direction

In the standard MAC/packet system the complete television signal after time compression (and hence before the FM processing) can have a bandwidth of about 8.4 MHz. We should now like to concentrate our attention on systems with a time-compression factor of 5/4 for the luminance signal; this means that before time compression a bandwidth of $4/5 \times 8.4$ MHz \approx 6.75 MHz is available. How can we obtain from this the best possible resolution in the horizontal direction? Let us consider a television signal of the type 625/2:1/50. To permit the time compression to be carried out this signal is sampled; a possibility for this is indicated in fig. 13a (crosses for the even fields and squares for the odd fields); if (as here) the pixels to be sampled are in a rectangular pattern in each field, this is called 'orthogonal sampling'. For stationary images we can combine the samples from dif-

ferent fields with one another in the receiver and hence halve the actual vertical distance between the samples.

We can now use the (f_x, f_y) -plane to express the maximum resolution in both horizontal and vertical direction: this is exactly equal to the maximum frequency range to which we have to limit the spectrum of the television signal if we wish to avoid aliasing as a result of spectral repetitions. (Strictly speaking, we are of course dealing with a three-dimensional spectrum [9] again; but now we are confining ourselves to the plane $f_t = 0$.) We consider a picture of height h and width w . At a line spacing (within one field) of Δy and a horizontal spacing of Δx between the samples we find that the maximum resolution for stationary images is given by a rectangle of height $2h/\Delta y$ and width $w/\Delta x$ around the origin (fig. 13b). In the display of moving images, we cannot simply combine samples from different fields with one another, since we then get movement blur. This means that without special measures the maximum resolution in the vertical direction for moving images is only half that for stationary images. (See also the section 'Moving images'.)

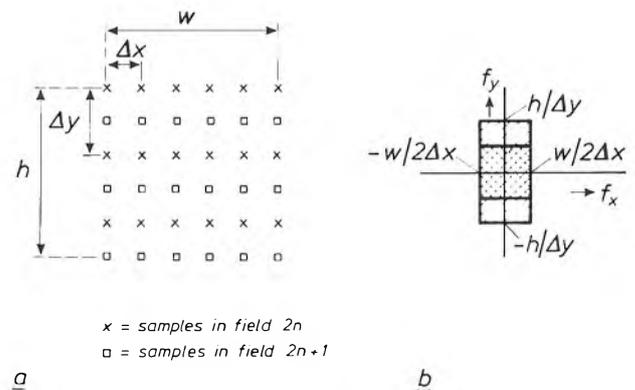


Fig. 13. a) Orthogonal sampling of a television picture. The crosses represent the samples taken in an even field and the squares represent the samples taken from the odd fields. The relative line spacing within one field is $\Delta y/h$ and the relative horizontal spacing is $\Delta x/w$, where h and w represent the height and width of the picture respectively. b) The maximum attainable resolution can be indicated in the (f_x, f_y) -plane. It corresponds to the maximum dimensions of the region in which we can prevent aliasing by performing the appropriate operations. Since image signals from successive fields can be combined for stationary images, the resolution in the vertical direction in this case (////) is twice as large as for moving images (\\\\).

There is of course a very direct relation between the horizontal sampling distance and the sampling rate $1/\tau$ (in Hz) used in taking the samples. This is

$$\frac{w}{\Delta x} [\text{c/pw}] \triangleq \frac{1}{\tau} [\text{Hz}].$$

We can therefore think of the f_x -axis as having a scale in hertz. This

can sometimes be extremely useful: for example a horizontal low-pass filter with a passband up to K/τ (in Hz) has — expressed in another way — a passband up to $Kw/\Delta x$ (in c/pw).

In some treatments the starting point is not the total picture height h and total picture width w , but only the active portion of the picture is considered (i.e. excluding the flyback times). We have already come across this for the vertical direction in the small print of p. 8. By analogy with the concept of active lines we can also refer to the active picture width w_{act} and relate the horizontal frequency to this. Such an approach is particularly useful if we want to refer to the number of pixels N_H in the horizontal direction, since this has a maximum value of

$$N_H = \frac{w_{act}}{\Delta x}$$

In general, however, N_H will have a smaller value, e.g. as a result of horizontal filtering.

A much more interesting situation arises when a sampling pattern like the number 5 on a dice is used in sampling each field; fig. 14a. This is called ‘quincunx

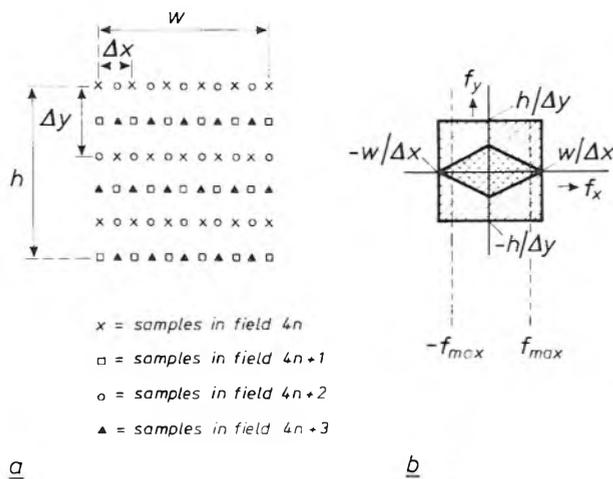


Fig. 14. a) In quincunx sampling the samples in two successive lines in the same field are displaced by half a sampling period with respect to one another. The sampling rate is little different from that in the previous figure (half the line frequency, to be precise), but now four fields must elapse, not two, before the same pixels are sampled again. b) The maximum resolution is quite different, however: for stationary images it is increased by a factor of two in the horizontal direction (////) and for moving images it has a diamond shape (\\\\). For moving images with $f_y = 0$ the maximum horizontal resolution is also increased by a factor of two. If the television picture is limited to a bandwidth of $f_{max} < w/\Delta x$ before sampling, this gives a loss in horizontal resolution as indicated by the dashed lines.

sampling’. Now four field periods elapse before the sampling cycles repeat, i.e. before exactly the same pixels are sampled again. The associated maximum resolution for stationary and moving images^[10] is shown in fig. 14b. In the horizontal direction the resolution for stationary images has been increased by a

factor of two and also for moving images containing no vertical frequencies. We have to remember, however, that to avoid all aliasing at moving parts of the picture we should use two-dimensional filtering, as indicated by the cross-hatched (‘diamond shaped’) area. By using quincunx sampling at a sampling rate of $1/\tau$ we can thus transmit a maximum horizontal frequency corresponding to $1/\tau$. Since (seemingly) we are not satisfying the sampling theorem here, but are really creating a situation like that of fig. 7c and d, we call this *sub-Nyquist sampling* or *subsampling*.

With the bandwidth of 6.75 MHz available to us (before time compression) in the MAC system we can accept a maximum sampling rate of 13.5 MHz. We further ensure that the television signal is limited to 10 MHz before sampling^[11]. After sampling and bandwidth-limiting to 6.75 MHz we then have a one-dimensional spectrum as shown in fig. 15a; in the range between about 3.5 and 6.75 MHz a special kind of

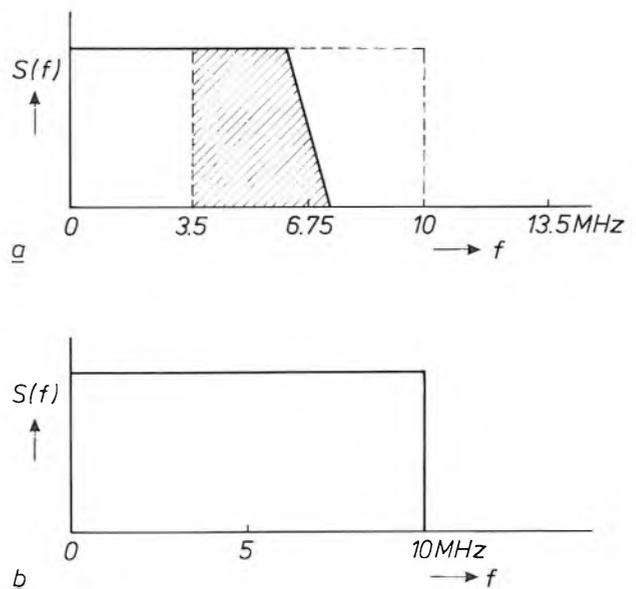


Fig. 15. a) If sub-Nyquist sampling (‘subsampling’) is used, a ‘constructive’ form of aliasing is obtained. Here this takes place in the frequency range between about 3.5 and 6.75 MHz. b) By applying the correct ‘interpolating’ filter operations we can reconstruct the original frequency components from this. The original frequency band from 0 to 10 MHz thus becomes available again without distortion.

[8] A. W. M. van den Eenden and N. A. M. Verhoeckx, Digital signal processing: theoretical background, pp. 110-144 in the special issue ‘Digital Signal Processing I, background’, Philips Tech. Rev. 42, 101-148, 1985.
 [9] G. J. Tonge, The sampling of television images, IBA report 112/81, Independent Broadcasting Authority, Winchester, Hants, England, 1981 (34 pp.).
 [10] The diamond-shaped figure that corresponds to moving images can be derived directly from the theory described in [9].
 [11] Because of this restriction the movement detection is simplified, since there is no aliasing in the frequency range below 3.5 MHz; see fig. 15a.

aliasing occurs. Because of the quincunx sampling and the two-dimensional filtering of moving parts of the image before sampling, we can remove this aliasing and at the same time reconstitute the frequency spectrum in the range between 6.75 and 10 MHz. At the receiving end we need the same two-dimensional filtering operation for this (again at moving parts of the image) as before sampling. This requires a sampling rate of at least $2 \times 1/\tau = 27$ MHz. We then obtain the one-dimensional spectrum of fig. 15b as the result [12]. In this way we can obtain the maximum horizontal resolution corresponding to fig. 14b. Because of the bandwidth limitation of the television signal to 10 MHz before sampling, as mentioned earlier, however, we remain within the strip $(-f_{\max}, f_{\max})$ in the horizontal direction. This means that in the horizontal direction we can resolve a maximum of about a thousand pixels per line.

So far in this section we have been dealing with the luminance signal of a television picture consisting of 625 lines. If we use the techniques of the previous section to display this as a signal of type 1250/2:1/50, we in fact double the total equivalent bandwidth to 20 MHz. This is a great improvement in comparison with the bandwidths of the luminance signal in the existing PAL and MAC systems, which are about 4 and 6 MHz respectively (for 625 lines per picture).

Moving images

In the foregoing we have seen how by applying the appropriate signal processing with a MAC/packet signal of type 625/2:1/50 we can transmit HDTV information that is suitable for display as a 1250/2:1/50 picture with an equivalent bandwidth of 20 MHz.

Strictly speaking, the maximum improvement that we can achieve in this way only applies to *stationary* images. This is because the information from different fields of stationary images can be combined without disadvantage ('inter-field processing'); this is one of the prerequisites in converting from an interlaced (2:1) picture to a sequential (1:1) picture and in reconstituting a subsampled signal. When we have to deal with moving images, however, we have to make sure that the inter-field processing does not cause movement blur. Since we subdivide the television image into pixels at both transmitting and receiving ends, we can in principle decide for each pixel whether there is any movement (this is done in a 'movement detector') and adapt the signal processing accordingly.

Various kinds of adaptation are possible, and at the present it is not yet clear which is the best (and most economic) solution or combination of solutions. We

should like to mention a few possibilities here in connection with scan conversion.

In this conversion we want to calculate missing picture lines. This can be done by combining information from a higher and a lower line from the same field (intra-field processing) or by combining a preceding line and a following line, seen in the time direction (inter-field processing); see fig. 16. The first solution works better for moving images, the second one gives the best result for stationary images. We can base our choice between the two on movement detection. An alternative possibility is to take the same combination of all four adjacent lines in both situations (movement

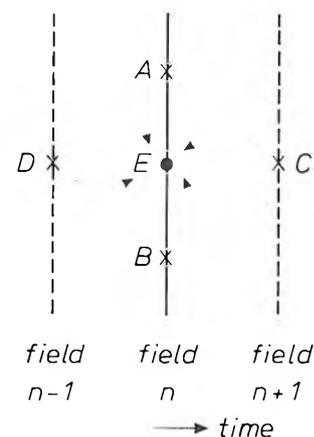


Fig. 16. Calculation of the missing line *E* in scan conversion (the picture lines are perpendicular to the plane of the diagram). If *E* is calculated from *A* and *B* we have intra-field processing. If *E* is calculated from *C* and *D* we have inter-field processing. If all four of *A*, *B*, *C* and *D* are used, we are performing spatio-temporal processing.

or not). In that case we perform a permanent vertical-temporal filtering operation of a lowpass nature in the f_y - and f_t -directions. An advantage of this is that we never have to switch from one kind of processing to the other.

Yet another method of minimizing movement blur is to introduce a movement vector; for example, if a television camera performs a movement, it effects all pixels in the same way. In principle it is possible to pass this information to the receiver in a very efficient way (especially in the MAC/packet system) where it can be accounted for in the display.

The colour signals in HD-MAC

So far we have confined ourselves to a discussion of various processing operations that are carried out on the luminance signal *Y* in the HD-MAC system. To display a colour picture, however, we also require two

colour-difference signals U and V . In general terms these signals are comparable in their characteristics with the signal Y . There is however one important difference: colour information can be displayed in much less detail than the associated luminance information. This feature is put to use in various ways, as we shall explain later. Otherwise the processing of the signals U and V in HD-MAC is much the same as for Y , to obtain the best possible resolution in the vertical and horizontal directions for the colour as well. We shall not go into further detail about this here.

It is however important that in the HD-MAC system on which we shall now mainly concentrate our attention the bandwidth of the signals U and V in the horizontal direction is limited to a quarter of the bandwidth of the signal Y . In the time compression the signals U and V can be compressed four times more than the signal Y (i.e. 5 times instead of 5/4 times). Because of the smaller bandwidth the signals U and V each represent 1/4 of the number of pixels of the signal Y in the horizontal direction.

In addition, in the standard MAC/packet system the Y signal is transmitted during each line period, but only one of the colour-difference signal is transmitted. The missing colour-difference signal is then reconstituted as well as possible by combining colour information from adjacent lines. This gives a smaller resolution for the colour than for the luminance in the

vertical direction. In HD-MAC as well, because of the compatibility, only one colour-difference signal can be transmitted during each line period. To obtain improved vertical resolution as compared with standard MAC, nevertheless, for display as an HDTV picture of type 1250/2:1/50, a number of signal manipulations are required at the transmitting end in the conversion from the 1250/2:1/50 camera signal to the 625/2:1/50 transmitter signal and in the reverse conversion at the receiving end; this is shown in *fig. 17*. The picture lines of the camera signal are designated from top to bottom by the numbers 1, 2, 3, The continuous lines refer to the odd fields, the dashed lines to the even fields. The colour-difference signals with one asterisk are not directly available at the transmitting end, but are calculated^[13] there from signals that are available. For example:

$$U_5^* = \frac{U_4 + U_6}{2} \quad \text{and} \quad V_9^* = \frac{V_8 + V_{10}}{2} .$$

In a similar way the signals with two asterisks are calculated at the receiving end from the received HD-MAC signals. For example:

$$U_2^{**} = \frac{3U_1 + U_5^*}{4}, \quad V_2^{**} = \frac{3V_1^* + V_5}{4} ,$$

$$U_3^{**} = \frac{U_1 + U_5^*}{2}, \quad V_3^{**} = \frac{V_1^* + V_5}{2} ,$$

$$U_4^{**} = \frac{U_1 + 3U_5^*}{4}, \quad V_4^{**} = \frac{V_1^* + 3V_5}{4} .$$

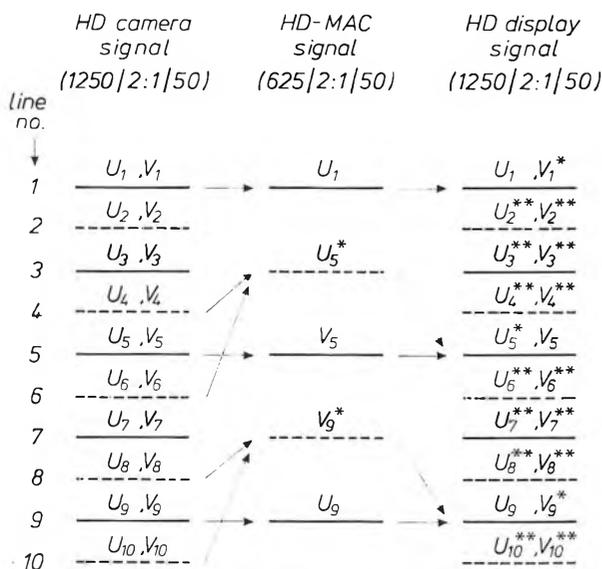


Fig. 17. Diagram illustrating the conversion of the colour-difference signals U and V of an HD camera signal of type 1250/2:1/50 into an HD-MAC signal of type 625/2:1/50 and of the conversion of this signal into an HD display signal. The colour-difference signals with one asterisk are calculated in the first conversion, the colour-difference signals with two asterisks are calculated in the second conversion. The lines from the odd fields are continuous, those from the even fields are dashed.

Since in signal processing in the HD-MAC system it is



Fig. 18. Quincunx sampling is also used for each of the two colour-difference signals in HD-MAC. Because only one of the two difference signals is transmitted in each line, the sampling pattern shown here is obtained. (The symbols have the same significance as in *fig. 14* and *fig. 17*.)

^[12] It is very important here that the overall frequency characteristic $H(f)$ of the MAC channel, including any transmitter or receiver filters has 'Nyquist shaping' around $f_0 = 6.75$ MHz, i.e. $H(f_0 + f) = 1 - H(f_0 - f)$.

^[13] The calculations given here as an example ('linear interpolation') are about the simplest that can be devised for this purpose; those used in practice are more complicated.

required that the U and the V signals should both be sampled in the quincunx pattern described earlier, a cycle of sampling patterns like that shown in *fig. 18* occurs during the transmission; the same symbols are used to designate the different fields as in *fig. 14*.

In HD display, as a result of all the measures described above, a maximum vertical frequency of $156\frac{1}{4}$ c/ph is possible for both colour-information sig-

The final result can be displayed on both a special HDTV set and a standard television set. The HDTV set is suitable for display of the same type of signal as that originally provided by the HDTV camera. The sampling rate f_s used is indicated at various places in the block diagram of *fig. 19*.

The most noticeable difference from the foregoing is the position where the horizontal processing takes

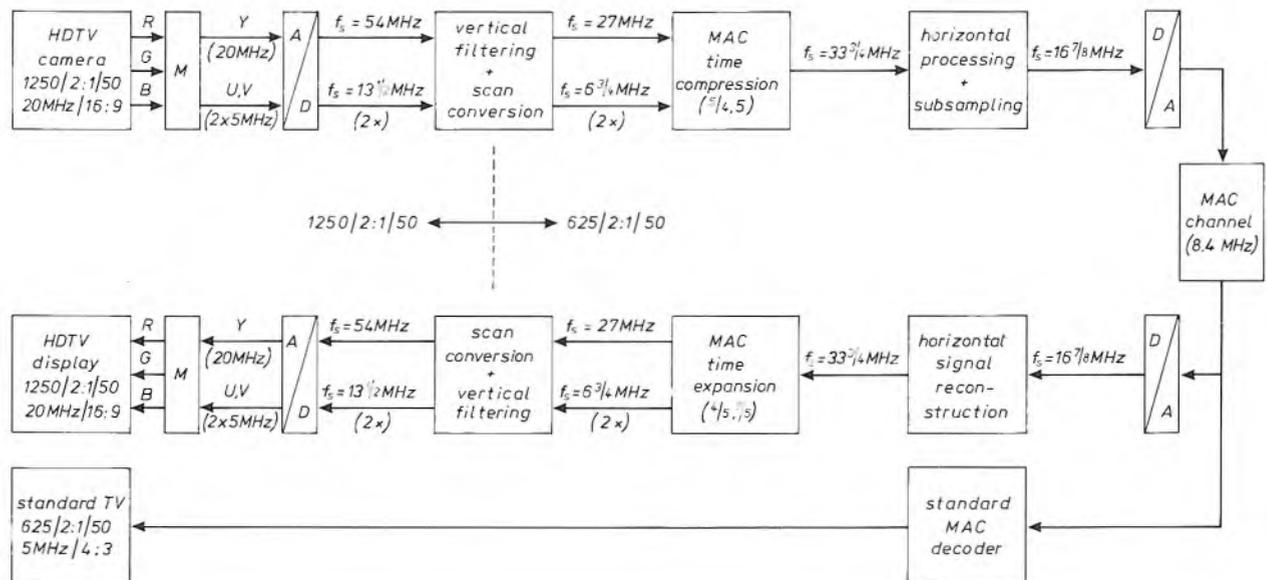


Fig. 19. A complete HD-MAC system corresponding to the simplified diagram of *fig. 5b*. Most of the signal-processing operations we have discussed can be found in this diagram. It is interesting to note that all the horizontal operations take place between time compression and time expansion. Since most of the operations are performed digitally, the system contains A/D and D/A converters. The sampling rate used f_s is indicated at various points. M is a matrix circuit for the conversion of the three original colour signals R , G and B into the signals Y , U and V (or vice versa).

nals with stationary images. This is half the maximum vertical frequency for the luminance signal, but twice the value permitted by the standard MAC/packet system (see also p. 211).

A complete HD-MAC television system

To demonstrate the practicability of HDTV based on the MAC/packet system and the compatibility between HD-MAC and standard MAC we have constructed a complete television system in which most of the signal processing described earlier is applied; see *fig. 19*. The starting point is an HDTV camera that provides a signal of type 1250/2:1/50 with an aspect ratio of 16:9 and a Y bandwidth of 20 MHz. After the appropriate processing the signal is transmitted on a MAC channel with an effective bandwidth of 8.4 MHz.

place: after time compression at the transmitting end, and before time expansion at the receiving end. The reason for this is that the compression gives the signals Y , U and V the same bandwidth, separates them in time and enables them to be processed in a similar way.

At the receiving end the signals U and V , after time expansion, are further processed in a number of special circuits (further detail will be omitted here) to give extra noise reduction with stationary images and to improve the colour transients^[4]. This gives an additional improvement in the quality of the displayed picture.

We should mention that all of the television signals referred to in *fig. 19* are interlaced. The non-interlaced signals that we encountered in the theoretical treatment earlier were only introduced to simplify the des-

cription. In practical signal processing there is no explicit need for non-interlaced signals.

Compatibility of HD-MAC with standard MAC

As we can see from the block diagram of fig. 19, an HD-MAC signal can be presented directly to a standard MAC receiver on reception. Because of the vertical filtering that has been performed on the HD-MAC signal at the transmitting end, the picture quality in the vertical direction will be better than for reception of an 'ordinary' MAC signal, for there can now be no aliasing in the vertical direction. On the other hand, there are a few slight degradations in quality. First, there is an increase in line flicker. This is caused by the fact that in HD-MAC there is less attenuation at the high vertical frequencies (up to $312\frac{1}{2}$ c/ph). Because of this, however, the corresponding frequency components in the periodic repetitions that are responsible for line flicker (see the points *C* in fig. 10*b*) are stronger. Also, because of the subsampling of the HD-MAC signal in the horizontal direction, aliasing is introduced into the luminance signal *Y*

play. This can be explained with the aid of fig. 17. If the HD camera signal shown there were to be converted in accordance with the specifications that apply for the *standard* MAC system into a signal of type 625/2:1/50, then we would require the following sequence of successive lines:

$$U_1, U_3^*, V_6, V_7^*, U_9, U_{11}^*, V_{13}, V_{15}^*, \dots,$$

instead of the present HD-MAC sequence

$$U_1, U_5^*, V_6, V_9^*, U_9, U_{13}^*, V_{13}, V_{17}^*, \dots$$

Half of the colour information is therefore slightly displaced (by two lines) in the vertical direction. The degradation this introduces when an HD-MAC signal is displayed on a standard MAC receiver is very slight, however.

Quality comparisons

To permit a general comparison to be made between various television signal standards, we have collected the leading parameters of a number of existing and proposed television system in *Table I*. Besides the

Table I. A comparison of the leading parameters of a number of television systems.

TV system	Time-compression factor		Aspect ratio	Equivalent bandwidth (MHz)		Number of pixels			
	<i>Y</i>	<i>U, V</i>		<i>Y</i>	<i>U, V</i>	Horizontal		Vertical	
						<i>Y</i>	<i>U, V</i>	<i>Y</i>	<i>U, V</i>
PAL	1	1	4:3	3.7	1.0	370	100	290	230
MAC	3/2	3	4:3 and 16:9	5.6	2.8	560	280	290	144
	5/4	5	4:3 and 16:9	6.7	1.6	670	160	290	144
HD-MAC	3/2	3	4:3 and 16:9	16	8	800	400	520	260
	5/4	5	4:3 and 16:9	20	5 [*]	1000	250	520	260
MUSE	c_1 [***]	c_2 [***]	16:9	22	7	1000	330	520	260

[*] Because of the nonlinear operations carried out in the 'Colour-Transient Improvement' this value is in fact larger.

[**] $c_2/c_1 = 4$.

in the frequency range above 3.5 MHz (see fig. 15). Since this distortion is not compensated in the standard MAC receiver, it introduces — as close observation reveals — a barely noticeable, rapidly moving dot pattern comparable with the 'dot crawl' found in the existing NTSC television system, but it is less annoying, because its structure is almost twice as fine. Moreover, it is not present in unpatterned areas but only in 'textured' areas.

The processing of the colour-difference signals *U* and *V* in the HD-MAC system also introduces what is really a very small error in a standard MAC dis-

time-compression factors and the aspect ratio, we have shown the equivalent bandwidths of the signals *Y*, *U* and *V* (for stationary images). We have also shown the number of pixels for the same signals in the horizontal and vertical directions (N_H and N_V). These numbers relate to the active part of each line period and the active fraction of all the lines (see also the small print on p. 204 and p. 207). The Table mentions the MUSE signal [14], which we have not mentioned

[14] Y. Ninomiya, Y. Ohtsuka and Y. Izumi, A single channel HDTV broadcast system — the MUSE, NHK Laboratories Note No. 304, 1984 (12 pp.).

previously, of the type 1125/2:1/60. This has been zealously promulgated by the Japanese broadcasting organization NHK. At first sight the figures for MUSE and HD-MAC are comparable. However, the fact that the MUSE signal is compatible with no other signal (and so is *not* evolutionary in nature), swings the balance irrefutably in favour of HD-MAC.

The introduction of the HD-MAC system at the transmitting end makes it possible to change over gradually to better receivers at the receiving end, without existing equipment becoming unusable. Four gradations in quality can be distinguished here:

- reception with a standard MAC receiver;
- improvement of reception by the addition of (for example) a horizontal comb filter to eliminate the dot crawl resulting from subsampling;
- reception with a fairly simple HDTV receiver, in which use is made of movement detection and switching between inter-field signal processing and intra-field signal processing;
- reception with an advanced HDTV receiver, in which for example a movement vector is used and information about this is transmitted via the MAC/packet multiplex.

After all that we have said it should be abundantly clear that the HD-MAC system opens the way to a compatible and therefore smooth and attractive evolution towards HDTV.

Summary. As the dimensions and the light intensity of television receivers increase, the limitations of the existing television systems (NTSC, PAL and SECAM) become more obvious, and the need grows for a new system, known as high-definition television (HDTV). This must offer an increase in the resolution, a reduction in the interaction between colour and luminance information, an increase in the aspect ratio and stereophonic sound with 'hi-fi' quality. It is ultimately of vital importance here that a compatible system is chosen, so that existing equipment can still be used and the viewer can experience a gradual ('evolutionary') progress of television quality through the gradual acquisition of new equipment. The MAC system (MAC means Multiplexed Analog Components) recently standardized for use in satellites and cable systems will permit such an evolution. This article describes — by way of example — how various advanced signal-processing operations at the transmitting end will provide an 'HD-MAC' signal. This signal is suitable both for reception with standard MAC equipment, and for reception with a special HD-MAC set that can display a picture of HDTV quality. The signal processing required is described with the aid of one-, two- and three-dimensional spectra. Separate attention is paid to the transmission of moving images and colour information. The article concludes with the description of a complete HD-MAC television system, a discussion of the compatibility of HD-MAC and standard MAC and a quality comparison for various television systems.

1937

THEN AND NOW

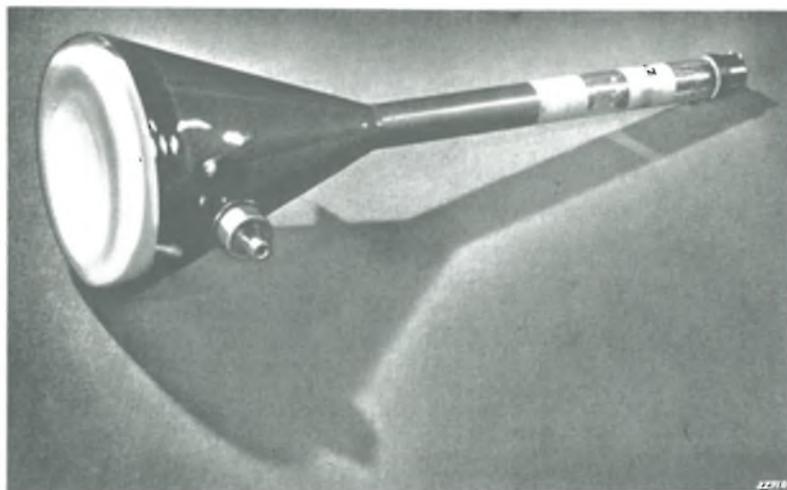
1987

Television projection tubes



Even before World War II, when television was still in its infancy, Philips Research Laboratories were working on projection television to give larger pictures (e.g. 40cm × 50cm) than the screen of the largest cathode-ray tube. To obtain the sharpest pictures the electron beam in the projection tube was focused magnetically instead of electrostatically; also, so that existing optical lenses could be used, the front of the projection tube was curved to match the image-field curvature of the optical lens (black-and-white photo) [*].

In 1987 the technical requirements demanded of television projection tubes are much more onerous. Colour pictures are produced by three separate tubes — one for each primary colour — which have to work in close cooperation; the diagonal dimension of the projected picture should be about 1 m or even larger; to keep the complete receiver compact the projection tube should have a rectangular front face and a large internal de-



flexion angle. For high-definition television (HDTV) — soon to be with us — the requirements will be even more onerous.

Recent research has led to the projection tube as shown on the colour photo. The electron beam is again focused electrostatically through the application of a new electron-optical principle. This includes the use of a special type of pre-focus lens in the electron gun, to give the very high resolution required. The screen is almost rectangular, about 8.5cm × 11cm, and the total length is 25cm.

[*] from Philips Technical Review, August 1937.

Selecting quartz for resonators

J. C. Brice and W. Koelewijn

A chain is only as strong as its weakest link. In an electronic device or system that 'weakest link' is the worst component, of course, and we therefore have to give due attention to the manufacture of even the humblest component. Our care and concern must go right back to the selection of the raw material. This will often determine the performance of the component — so our choice must be soundly based. The article below discusses the criteria for selecting quartz for resonators.

Devices which require accurate timing or well-defined frequency features contain quartz resonators to meet these requirements. Without these resonators the use of colour television, mobile radio, telephone systems etc. would not be as widespread as it is now. In order to achieve satisfactory yields of devices meeting high technical specifications, it is necessary to select the best available raw material. The reasons for selecting a particular type of quartz and the method by which selection can take place are described in this article. Three simple tests appear to be sufficient for an accurate selection. First we shall briefly go into the physical background of the quartz resonators.

Materials with the crystal symmetry of quartz (threefold symmetry axis) or a lower degree of symmetry show piezoelectric behaviour. As a result of a mechanical distortion of a quartz crystal in a specific direction, electrons and nuclei are moved by different amounts. Thus a positive charge appears on one face of the crystal and a negative charge on the opposite face. The inverse effect — an applied voltage resulting in a mechanical distortion — also occurs. An alternating voltage produces cyclic deformation. At resonant frequencies this exchange of electrical and mechanical energy can be significant. A quartz resonator is a plate

of piezoelectric quartz cut in appropriate directions so that its natural resonance occurs at a particular well-defined frequency. Piezoelectricity in quartz only occurs if the mechanical distortion is in a direction that is not parallel to the threefold symmetry axis of the crystal. This implies that plates that are to be used as resonators must be cut according to this condition. Research into the possible orientations of the crystals revealed that some specific orientations resulted in resonators with frequencies that are independent of temperature^[1], a desirable feature in view of the widespread use of these devices. Specifications usually call for errors in the cutting direction of less than 0.01° .

Resonators are characterized by the electrical quality factor Q_e , the fundamental frequency of the mechanical distortion in response to an applied alternating voltage divided by the half-width of this response (see *fig. 1*). The great advantage of the quartz resonator is that it is nearly lossless so that it can have a very large electrical quality factor Q_e . This means that the resonance is very sharp. Typical coil-and-capacitor circuits have $Q_e \leq 200$, while quartz crystals can have a Q_e up to several million but typically in the range 10000 to 100000. The resonant frequencies f of a quartz plate are determined by its thickness: $f = nc/t$, where n is an odd integer, c is the velocity of sound in quartz and t is the thickness of the plate. Since maximum frequency deviations of no more than 1 ppm are

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commonly requested, it must be possible to obtain crystals with well-defined thicknesses. The actual shape of the plate and the strain in the material also have an influence on the resonant frequencies.

Plates with the correct orientation and thickness are made in the following manner. Quartz is obtained from suppliers in batches consisting of a number of bars grown in one process. The crystal bar is oriented using an X-ray technique and then sawn in parallel-sided plates which are lapped to a thickness slightly greater than required. By way of an etching process damaged material is removed from the surface and the required thickness is attained. The electrodes necessary for applying the voltage are added by evaporating electrode material on the faces of the plate. These electrodes have an influence on the resonant frequency eventually reached. During the evaporation of the electrode material on the crystal the resonant frequency is monitored. Evaporation is stopped when the desired frequency is attained. Fig. 2 shows a diagram of a plate and the electrodes together with the shear motion as a result of the applied voltage.

The features of the crystal that, apart from the shape and the thickness, determine its frequency and its electrical quality factor Q_e are related to the crystal structure. It is therefore reasonable to expect that purer material gives better devices. Until 1955 only natural quartz was used, giving a yield of 10 to 30%. Since that date synthetic quartz has been available giving considerably higher yields. This is mainly due to the fact that synthetic quartz, as a result of its controlled growth, is easier to cut in the correct orientations, thus giving less waste material.

Our approach to the problem of establishing selection criteria has been to a large extent statistical. With the help of the results of experiments done by many colleagues we have assessed the performance of devices made from quartz with known characteristics, and so identified the material parameters (purity and perfection) which affect device performance and the interrelations between these parameters in the quartz available^[2]. Since suppliers use different growth processes and different sources of raw material, we also considered the data for each supplier separately besides the overall trend. The necessity for this approach will become evident later (see fig. 9). Obviously data for a particular supplier show less spread than an overall distribution. However, overall trends are useful: they tell us what happens if we choose our supplier at random and change our choice from time to time.

Synthetic quartz is almost universally specified by an infrared quality factor Q_{IR} . This quality factor is inversely related to the extinction coefficient α^* due to hydrogen absorption. The latter is determined by

measuring the transmission in a quartz sample with parallel polished surfaces at wavelengths where hydrogen absorbs energy from the infrared beam. We really determine the total extinction coefficient in this way

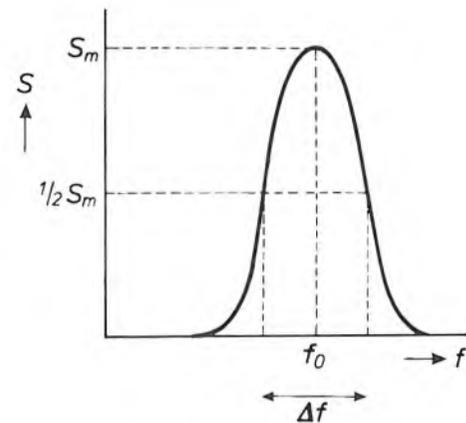


Fig. 1. Plot of the mechanical distortion S of a quartz plate in response to an applied alternating voltage of frequency f . The fundamental frequency of this plate is f_0 and Δf is the width of the response at half the maximum value of the response. These quantities determine the electrical quality factor $Q_e (= f_0/\Delta f)$.

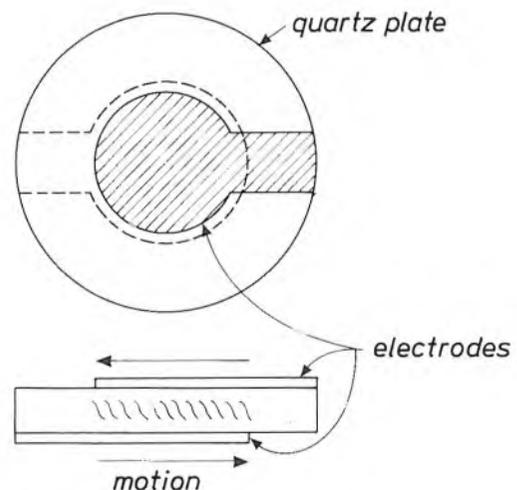


Fig. 2. A schematic representation of a simple device structure. The shaded area indicates the upper electrode; the lower electrode is indicated by a dashed line. In the lower part of the figure, the shear motion as a result of an applied voltage on the electrodes is indicated.

^[1] J. C. Brice and W. S. Metcalf, Quartz-crystal resonators using an unconventional cut, Philips Tech. Rev. 40, 1-11, 1982.

^[2] We received much help from our suppliers who provided us with many samples of material which is not normally commercially available. For some of our experiments, we needed particularly good and particularly imperfect samples. Data from these non-representative samples are, of course, excluded from statistics which show what is usually available. In total we investigated samples from 15 suppliers.

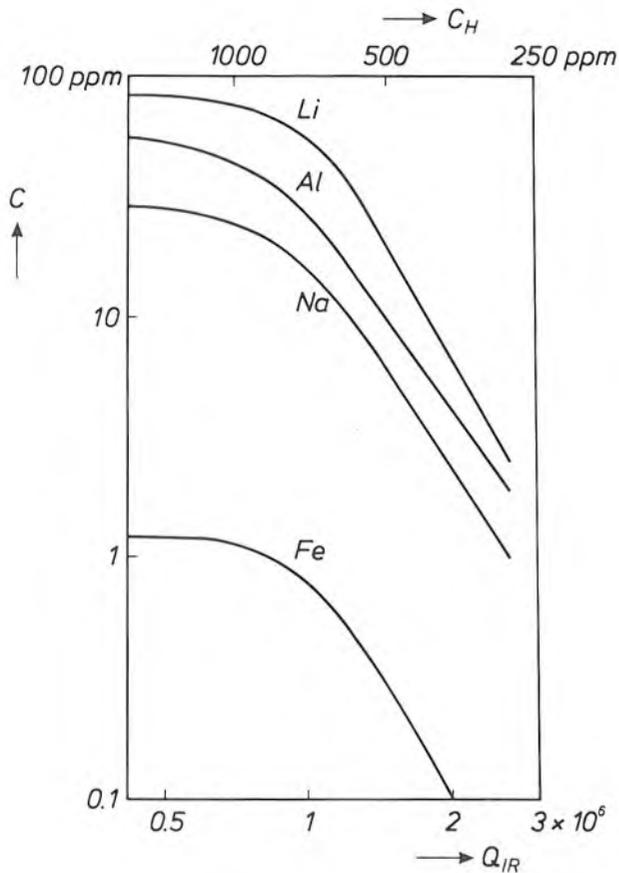


Fig. 3. Overall median impurity concentrations C as a function of Q_{IR} . The data are for the z-zone of crystals. Material grown on other faces is much less pure. For any supplier the distribution of $\log C$ at a given Q_{IR} -value is approximately Gaussian.

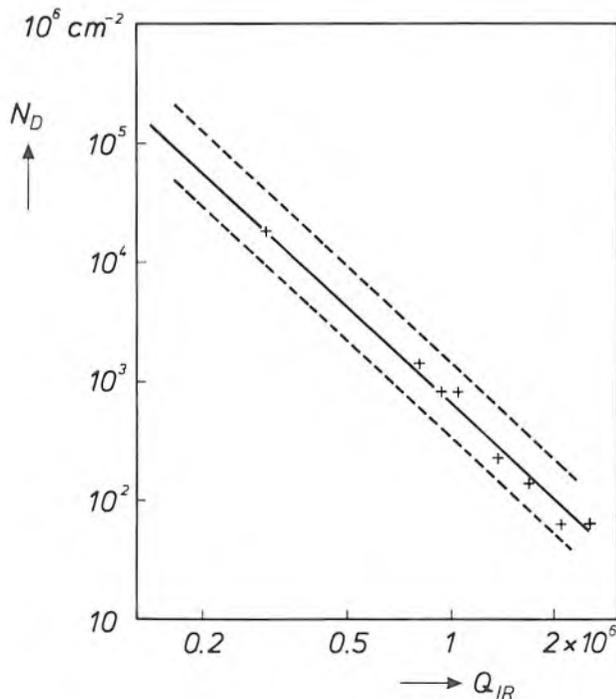


Fig. 4. Overall median dislocation density N_D as a function of the infrared quality factor Q_{IR} (continuous line and crosses). For any supplier the logarithm of the dislocation density has a Gaussian distribution. Results for the two most extreme suppliers are indicated by dashed lines.

but by doing reference measurements at nearby wavelengths the contribution due to hydrogen absorption can be established separately^[3]. The parameters we have investigated (purity, dislocation density, strain, homogeneity) will be shown as a function of Q_{IR} .

Fig. 3 is a plot of the median^[4] purity of the samples as a function of Q_{IR} (lower axis) or the equivalent hydrogen content (upper axis). Data from all the suppliers in the investigation have been used. High Q_{IR} corresponds to fairly pure material. The figure shows the major impurities (lithium, aluminium and sodium), which together with iron, are the only impurities known to be harmful. Other impurities show the same form of variation. Different suppliers have distributions of purity which differ from these data by factors of two or three, and different batches from one supplier at different Q_{IR} -values also show similar differences. However, the worst results differ by less than a factor of five from the median. By experience we learnt that impurities at levels less than 10 atomic ppm usually have negligible effects on devices. At higher levels, aluminium together with sodium can adversely affect yields of very-high-frequency devices: they change the etching characteristics so that very thin plates become porous. Lithium in high concentrations affects device stability^[1] and iron decreases the radiation resistance of devices used in high-radiation environments.

Fig. 4 shows the variation of overall median dislocation densities as a function of Q_{IR} . Different suppliers' results can differ appreciably from this average behaviour. Data from all the suppliers in the investigation have been used. High dislocation concentrations are disastrous in three ways. First, high densities of dislocations reduce the yield of high-frequency devices^[5]. Second, they make the material brittle, as discussed below, and third they reduce the performance of low-frequency devices. (Dislocations affect device performance by scattering the acoustic waves. Scattering is significant when the wavelength exceeds the distance between dislocations. Low-frequency-devices are therefore particularly affected.) This is shown in fig. 5, where the median equivalent series resistance of devices is given as a function of the dislocation density.

The correlation between dislocation density and Q_{IR} is not easily explained. What is found is that the density varies with the hydrogen content to the power of 2.5. The factor of proportionality varies with the supplier. Dislocations involve breaking bonds in the lattice and broken bonds can be terminated by hydrogen, so we might expect a linear relation ($N_D \propto C_H$). Some dislocations come from the seed crystals but most originate at inclusions^[3]. Thus apparently

either the number of inclusions rises rapidly or, more probably, one inclusion results in a number of dislocations. Of course several mechanisms may operate simultaneously and the relation may be more complex than $N_D \propto (C_H)^{2.5}$.

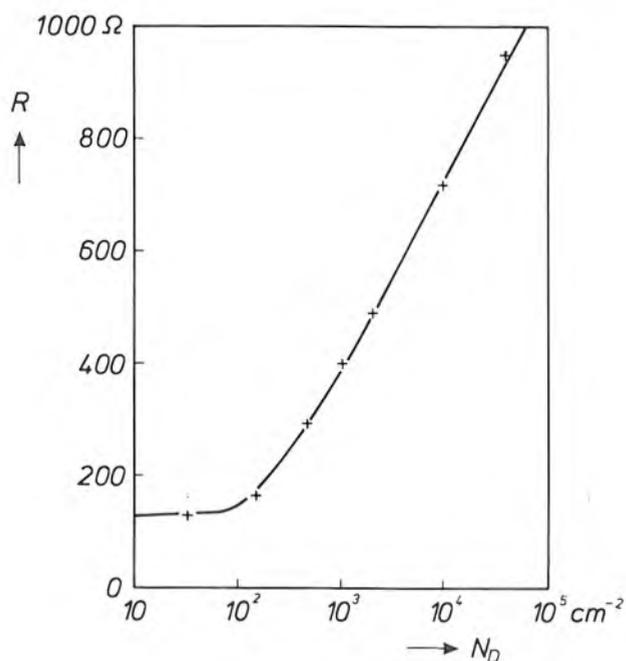


Fig. 5. A plot of the median equivalent series resistance R of devices as a function of dislocation density for 1.3 Mhz devices. An oscillator can be represented as an LC -circuit with a resistance in series. The quality factor Q_e of the device decreases with increasing equivalent resistance R . High dislocation densities imply a high R and thus a low Q_e .

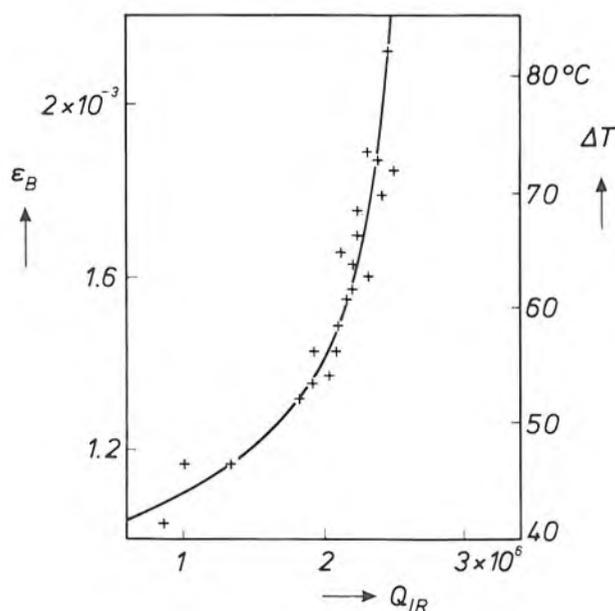


Fig. 6. Breaking strain ϵ_B (left-hand axis) and the temperature shock ΔT (right-hand axis) as a function of Q_{IR} . Samples were placed in a hot bath at a temperature T_B for 30 minutes and then transferred quickly to a cold bath at T_C . The samples of one batch were tested with increasing temperature difference $\Delta T = T_B - T_C$. The infrared quality factor Q_{IR} was measured for each sample.

In the course of fabrication devices are subjected to various stresses. It is therefore useful to know something about the strength of the material used. Strength in a brittle material like quartz is a fairly complex concept. The stress (force per unit area) required to break a plate depends on the surface finish. A plate with a perfect surface requires a fairly large stress to break it. In a perfect plate we have to nucleate a crack. In an imperfect plate we only have to extend an existing crack, which is much easier. Because we know the elastic constants of quartz, we can measure the breaking strain, rather than the breaking stress. We measured this strain by applying a thermal shock. We heated crystals in a water bath so that they were uniformly hot and plunged them into a cooler bath. If we cool them very rapidly by ΔT °C the surface contracts an amount $\alpha \Delta T$, where α is the thermal expansion coefficient. The corners are under a rather larger tension (about three times the tension at the surface) so that cracks nucleate most easily there. The result obtained is shown in *fig. 6*. The correlation is clear but we were able to show that the dislocation density is also important [5]. The importance of the breaking strain becomes obvious when we consider *figs 6 and 7*. *Fig 7* shows the yield of unbroken 0.5 mm thick plates in a production process.

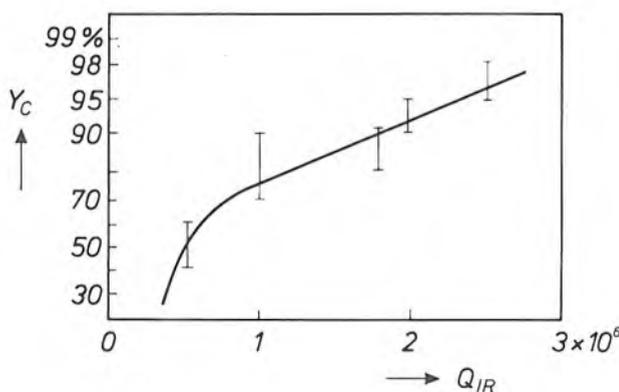


Fig. 7. Yield Y_C of unbroken 0.5 mm thick plates in a production process as a function of Q_{IR} . The data are for plates made with reciprocating slurry saws. When rotating wheels are used, yields are worse [6]. Note that the graph was drawn on probability paper so that the scale of Y_C varies in a nonlinear manner.

[3] For a detailed description of our procedure for measuring the infrared quality factor see: J. C. Brice, Crystals for quartz resonators, Rev. Mod. Phys. 57, 105-146, 1985.
 [4] If the results found are written as a list in order of increasing numerical value, then if the list has an odd number of entries, the median is the one in the middle. If the list has an even number of entries, the median is the average of the middle two. The median value is exceeded by half the sample and is often more meaningful than the arithmetic mean. Consider a sample containing the values 0.5, 0.7, 0.9, 1.0, 1.3, 1.5, 10. The median is 1.0 but the mean is about 2.3.
 [5] J. C. Brice, The specification of quartz for piezoelectric devices, Proc. 38th Ann. Frequency Control Symp., Philadelphia 1984, pp. 487-495.

We believe that during our processing procedures we expose the plates to stresses equivalent to the strain produced by a 50 °C shock. We therefore subjected every bar (46 000 in total) in a number of batches to a 50 °C thermal shock. Fig. 8 gives the results that we

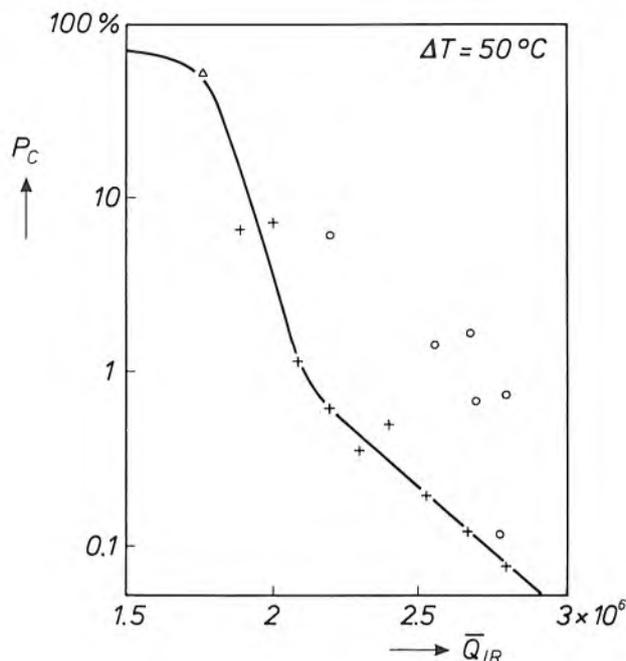


Fig. 8. The probability P_C that a bar will break with a 50 °C shock as a function of the mean Q_{IR} of the batch. Up to 30% of bars with $Q_{IR} < 1$ million survive a 50° shock. The crosses represent the results from normal batches and the circles represent the results for batches which contained noticeable numbers of deformed bars. The point marked Δ is taken from fig. 6. It is the value of Q_{IR} for which $\Delta T = 50^\circ$. A batch with a mean Q_{IR} of this value would have a failure rate of 50%.

found. In this figure the crosses represent the results from normal batches and the circles represent the results for batches which contained significant numbers of deformed bars. Clearly, these batches contain a significant excess of bars which break with a 50 °C shock (on average they contain 6 times as many bars which break).

Fig. 8 uses a batch mean Q_{IR} to describe the material. For this to be meaningful, we also need to know how the Q_{IR} of individual bars in a batch vary. These data are given for two suppliers in fig. 9.

The final piece of statistical evidence that we need to know is how homogeneous the crystals are. When we look at this we find that only in one direction is there an appreciable variation. Parallel to the z-axis of the crystals, the hydrogen content decreases as we move outward from the seed. Fig. 10 gives the data for two suppliers in the form of a graph of the gradient of α^* , the extinction coefficient, as a function of Q_{IR} . Data for most of the other suppliers lie between these two curves.

The results of our experiments show a qualitative relation between the infrared quality factor on the one hand and the other parameters of interest (impurity concentration, dislocation density, strain and homogeneity) on the other. The best yield of the production process will be reached if quartz with a high infrared quality factor ($Q_{IR} > 2$ million) is used. All the other requirements are then automatically satisfied.

In selecting our material we take the following line. First of all, every bar from each batch is inspected visually. We reject bars which contain clusters of inclu-

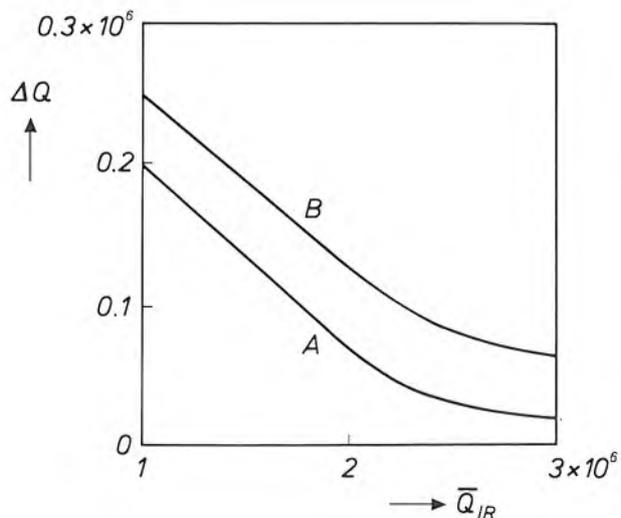


Fig. 9. The variation of Q_{IR} in batches as a function of batch mean Q_{IR} . In this figure ΔQ is the standard deviation of Q_{IR} in a batch. Curve A is for the supplier giving the greatest uniformity. Curve B is for the supplier referred to in fig. 8. Note that the data are actual variations of Q_{IR} . Because we measure Q_{IR} in three independent ways we know the experimental errors absolutely^[5] and can therefore eliminate their effect before presenting the data.

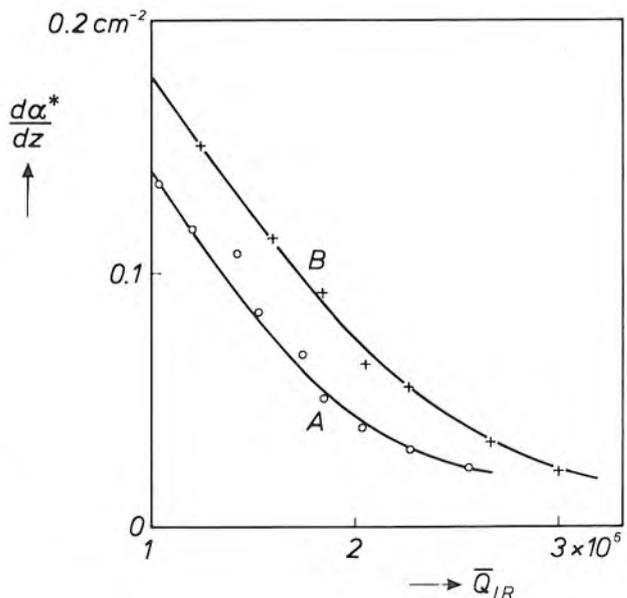


Fig. 10. The gradient of α^* (the extinction coefficient) in the z-direction as a function of the batch mean Q_{IR} . For A and B see caption of fig. 9.

sions large enough to be visible with the naked eye or which are grossly misshaped. Then we determine Q_{IR} for a small number of the remaining bars of each batch. The exact number depends on our knowledge of the suppliers' production process. If we believe that we know the standard deviation of Q_{IR} values in the batch (i.e. the appropriate curve on fig. 9) we can manage with a very small number (between 3 and 6 bars from a batch of 1000 or more). If we know nothing about the production process more bars should be examined, but only rarely do we need more than 12. Finally, every batch is subjected to a 50 °C thermal shock test on a 100% basis. For this test we have a tentative reject level of 10% but we have seen only one batch which had more than 10% breaking *and* a

Q_{IR} over 2 million. Batches passing the tests can be used to make devices to very tight technical specifications with high yields (95%).

Summary. To meet the high specifications usually required, quartz resonators must be made from quartz of a high quality. In this article the different aspects of this quality are discussed and the outcome of the investigations into the selection criteria are reported. Three simple tests appear to be sufficient for an accurate selection. Every quartz bar is inspected visually for gross defects and is exposed to a temperature shock of 50 °. For a small number of bars the infrared absorption at a wavelength where hydrogen absorbs infrared light is determined. Thus an infrared quality factor is assessed. Bars that do not show gross defects, do not break as a result of the temperature shock and come from a batch with a mean infrared quality factor of 2 million or more, can be used to make devices with the required technical specifications in production processes with high yields.

Looking at interfaces

F. Meijer

The address below was delivered by Dr F. Meijer at his inauguration on 7th March 1986 as Visiting Professor of Heterogeneous Catalysis at the University of Leiden. In his address Prof. Meijer does not confine himself to his own special field, but gives us, in a light-hearted style, a refreshingly relative view of the science of interfaces. The more objective sphere of the research he discusses includes measurement methods such as TEM and STM, which now approach or even reach the limit where atoms can be observed individually.

The concept of interface

Interface is a word that springs readily to the lips of technical people nowadays. The Oxford Dictionary gives the following two meanings of interface:

'surface forming common boundary between two regions',

'place or piece of equipment where interaction occurs between two systems'.

Both definitions are germane to my use of the word in the title of this inaugural address. The first definition brings out the essential aspect from which interface phenomena must be studied: the 'common boundary'. The second aspect, the interaction, the 'place where interaction occurs', follows immediately from this. The two aspects of the interface interact with one another.

A great deal goes on at interfaces.

In interface chemistry this includes all chemical reactions in heterogeneous systems. Heterogeneous means that there are two or more phases: a solid and a gas, or a solid and a liquid, or two different solids in contact with each other.

Corrosion, for example, such as the rusting of the metal of your car, is a chemical reaction at the interface of metal and humid air. Another phenomenon of practical importance is the adhesion between different materials, the adhesion of paint to a metal, or the adhesion of a metal film on a plastic substrate, as in the case of the Compact Disc. The word adhesion immediately brings out the concept of interaction.

There is also the very important field of heterogeneous catalysis, which concerns chemical reactions

at the interface of a gas or liquid with a solid, the catalyst. I shall return to this subject presently.

In physics and engineering the interface plays the leading role in the working or processing of a material; turning on a lathe, grinding, polishing, sputtering are all actions that take place at the interface. A sculptor is an artistic interface mechanic. He shapes the work at the interface between the tool and the stone. In a sense one might speak of the interaction between the sculptor and his material.

In the medical world the successful implantation of prostheses in the body, such as artificial hip joints and substitute arteries, depends to a very great extent on the interface between implant and body.

The word interface has also entered the language of electronics, defined as 'place or piece of equipment where interaction occurs between two systems', for example the interface between two computers or between a computer and a terminal. One of these two systems can be a human being, giving us the man/machine interface and the concept of 'user-friendliness'. The social sciences have also discovered the word interface and will undoubtedly add to its connotations.

There are many kinds of interface, and something usually happens at them — and that 'something' is worth examining more closely. 'Taking a closer look' is the subject of this address.

However, before I confine myself to a few examples of 'looking at interfaces' in chemistry and physics, I should say something about the interfaces between these disciplines. According to the secondary-school text-books there is a distinct difference between chemi-

cal and physical phenomena. In the first kind the molecules change in composition, in the second kind they do not. This is a characteristic example of a boundary between chemistry and physics — an artificial boundary. Nature did not itself create the separation between chemistry, physics and engineering. Man required it for classification. However, now that we are penetrating deeper and deeper into natural phenomena and understand more about them, the lines of demarcation between the old disciplines are rapidly becoming less distinct, and indeed they are often a nuisance. Between interface chemistry and interface physics there is no dividing line to be drawn. Nowadays we draw other dividing lines, for example between low-energy physics, the world in which atoms are the building blocks, and high-energy physics, the world contained within the atomic nucleus.

Heterogeneous catalysis

There is a direct connection between looking at interfaces and the subject of my own discipline 'heterogeneous catalysis'. What is heterogeneous catalysis?

A catalyst is a substance that speeds up a chemical reaction, without itself being consumed in the process. In heterogeneous catalysis the catalyst is a solid surface, while the reaction partners are in the gaseous or liquid phase. The chemical reaction does not take place in the gaseous or liquid phase, or only to a very slight extent, but the reaction is vastly accelerated if the reaction partners, the reacting molecules, meet at the surface.

The surface acts as a meeting place. You might compare it with a marriage bureau, where men and women enter alone and leave in pairs or as married couples, whereas the bureau, the catalyst, remains unaffected. The reaction does not take place in the outside world, but at the surface, the interface, the barrier is lowered and the reaction is able to take place there. To understand how this works, it must be possible to measure and look at the interface. The problem here is that one should really look at the system actually working during the reaction. This is a considerable scientific challenge.

Catalysis is of considerable economic importance, because it opens up reaction routes that give faster reactions, can work at lower temperatures and can be more specific, that is to say cause fewer side-reactions, less fuss.

In addition to the familiar fields of catalysis in the bulk-chemicals industry and in biochemistry (enzymes) a completely different and interesting field has emerged: the growth of thin films on a substrate that acts as a catalyst. A gaseous mixture is conducted

over a surface in a state (temperature and pressure) in which it does not react in the gaseous phase, but does react at the substrate surface, and in such a way that the reaction product remains on the substrate in the form of a closely defined thin layer, or film. The surface of each newly formed layer catalyses the subsequent reaction and the layer can continue to grow from the gaseous phase. This process is known as chemical vapour deposition, CVD, and has come into such wide use that in some quarters anyone using the process is said to be 'CVDing'. An example of the process is the growth of thin layers of silica by the reaction $\text{SiCl}_4 + \text{O}_2 \rightleftharpoons \text{SiO}_2 + 2\text{Cl}_2$.

Other applications are to be found in many areas, ranging from the application of extremely hard coatings to tools to the growth of single-crystal layers on semiconductors for integrated circuits and lasers. In general, the keywords in catalytic reactions are: subtle molecular reaction mechanisms, which take place at interfaces. This brings me back to my theme: 'looking at interfaces'. The catalyst here can take all manner of forms, from very small grains on a carrier material to crystalline solids with 'large' surfaces.

The examples I have chosen relate to interfaces where one side is a solid and the other can be solid, liquid or gaseous, with 'vacuum' as a special case.

Clean surfaces

The simplest interface can be produced in a hypothetical experiment if I draw a line on a sheet of white paper and write the word 'solid' on one side of it. The other side is empty and represents an ideal vacuum, absolute 'nothingness'. This does not imply, however, that absolutely nothing happens there. The atoms at the surface of the solid are not surrounded in the same way as their friends deep inside the solid. These outer atoms will therefore have different bonds, with different bond lengths, and they will therefore occupy different positions and have a different electron structure, causing changes in all kinds of chemical and physical properties: chemical properties such as chemical reactivity and physical properties such as effective optical constants. The interface does not react *with* the vacuum, but *on* the vacuum.

As soon as we take a step towards reality and break away from the theoretical line on the sheet of paper, we see that the interface becomes more complicated. There is no such thing as an ideal vacuum; it is really a very greatly reduced gas pressure, which we describe as ultra-high vacuum. The pressure is in fact 10^{-12} to 10^{-15} atmospheres. Figures like this do not mean much except to the vacuum specialist. A vacuum with a pressure of 10^{-13} atmospheres would therefore be

better described, I think, as something one can buy for about 5000 dollars per litre (a stainless-steel shell with pumps) and as a situation in which an atom at the surface of a solid inside this vacuum will only collide with a gas molecule once every three hours. Many of these collisions will cause a chemical reaction, and the surface of the solid will very slowly become 'dirty'. There is time enough, however, to look at it in the clean state.

To look at such surfaces we need measurement methods that provide specific information about the outer atomic layers. Investigations of this kind were first started in the late fifties. They made use of the strong interaction between low-energy electrons or ions and a solid. Scattering, reflection, emission and diffraction of such particles give specific information about the surface but not about the bulk material beneath it, because the particles cannot penetrate into the bulk and then emerge again to bring information back to the detector. Examples are Low-Energy Electron Diffraction (LEED), Secondary-Ion Mass Spec-

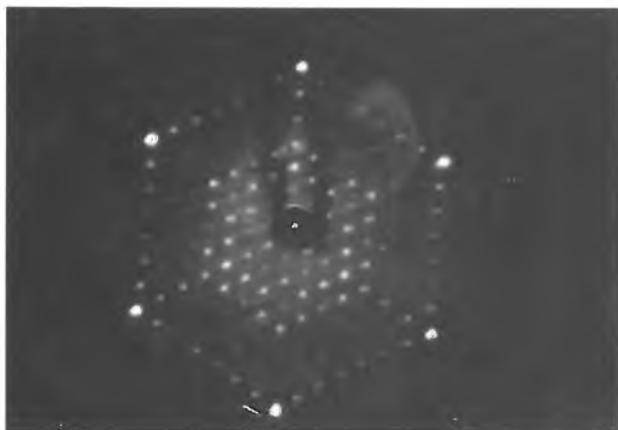


Fig. 1. The diffraction pattern of low-energy electrons (38 eV) obtained from a clean (111) silicon surface. The very bright reflections correspond to a structure that would be expected from the arrangement of the atoms inside the crystal. In between there are weak reflections at $1/7$ the spacing of the bright reflections. The fainter reflections show that the unit cell at the surface is 7×7 times larger than the unit cell corresponding to the atomic arrangement in the rest of the crystal. Diffraction micrographs such as this led to the proposal in 1959 of a model with the 7×7 structure for the surface of clean silicon, as shown in fig. 2.

trometry (SIMS), and Electron Energy-Loss Spectroscopy (EELS)^[1]. These methods give information about atomic arrangement, atomic species and molecular structure.

The use of these measurement methods relies on a relatively high vacuum, since the electrons and ions cannot travel freely in a gaseous atmosphere or a liquid. This gave a considerable impetus to research on solid/vacuum interfaces. Surfaces in vacuum could be de-

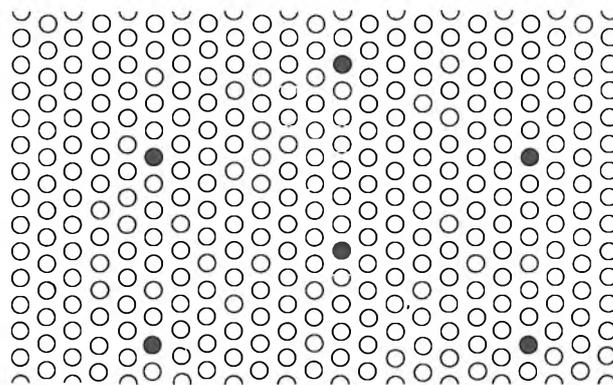


Fig. 2. Diagram of the atomic arrangement in the (111) surface of annealed silicon (the 7×7 structure). The diagram shows the arrangement for a minimum deviation of the positions of the atoms, corresponding to a diffraction pattern as in fig. 1, with open circles for the normal positions and filled circles for the deviant positions^[2].

finer more exactly, and vacuum-measurement methods became available, especially for those with generous budgets.

Many very interesting effects were found, and the phenomenon of 'surface' became much better understood. The snag was, however, that the research had a strong bias towards the use of model systems. The initial optimism that the model system could be translated into a real system was frequently followed by disappointment.

For instance, the adsorption of oxygen on an atomically clean single-crystal silicon surface provided little information about the growth of thin oxide layers in the processes for making transistors and integrated circuits. You might compare this to some extent with the situation in which a creature from outer space finds himself on receiving instructions to study the behaviour of human beings on the surface of the Earth. His attempts to do so are so hampered by clouds, rain, wind and mist that instead he writes a voluminous report on his study of two astronauts in vacuum on the surface of the moon. His conclusion is that the most important human activity is picking up stones and putting them into numbered sacks. The moral of this tale is that with good observations you can still be completely wide of the mark if you elevate your model system to the status of reality.

A familiar example of a solid/vacuum interface where the changes with respect to the bulk were directly observed is the surface of silicon. As long ago as 1959 it was demonstrated, from the diffraction of low-energy electrons, that the 'clean' silicon surface was a 'reconstructed' surface, and in fact reconstructed in a very complicated manner (*fig. 1*)^[2]. The unit cell on the silicon (111) surface was found to be 7×7 times larger than that of the bulk. This means that the atoms in the surface layer arrange themselves dif-

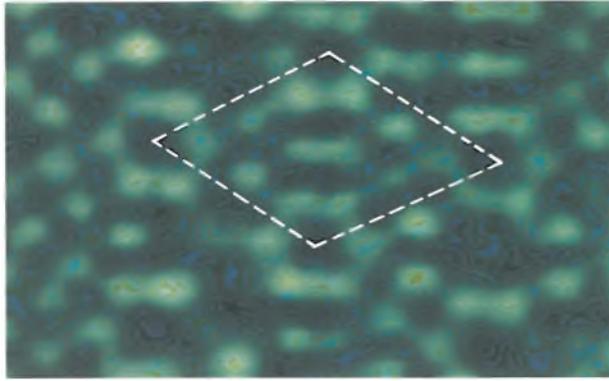


Fig. 3. A recent STM micrograph of the (111) surface of annealed silicon, in which the separately observable silicon atoms exhibit the 7×7 structure, where the dashed white line represents one unit cell. The dimensions of this unit cell were derived in 1959 from diffraction results, but this arrangement of the atoms could not be uniquely predicted from the experimental information. (Made available by courtesy of J. E. Griffith, J. A. Kubby and R. S. Becker of AT&T Bell Labs, Murray Hill, NJ, U.S.A.)

ferently, so that the regularity repeats only after seven atomic spacings (*fig. 2*). The lattice-work pattern has become a pattern of large diamonds. The frustrating aspect of the method was that, while it was very simple to observe the 7×7 structure, the theory was inadequate — and still is — for determining the new atomic positions, for understanding how exactly the 49 atoms in the large diamond-shaped unit cell are arranged, whether atoms are missing or additional ones are present, and so on.

This gave researchers a free hand to devise models, and through the years there were no lack of imaginative proposals. Fierce debates were heard at congresses and no one was able to prove that he or she was right while no method was available that could make the atoms at the surface directly visible. The breakthrough came in 1983, when the results of Scanning Tunneling Microscopy^[3] were published, a novel method, to which I shall return presently. The microscope scans the surface 'on an atomic scale', resulting in a relief map of the surface, on which the individual atoms are visible. It turned out that one of the many structures proposed was reasonably in agreement with this 'direct' observation (*fig. 3*). The matter now seems to be settled, although even with this method there are still a few reservations about the interpretation, particularly on the part of those who have a different model in mind.

As yet, however, there is not a single practical application to be found for this specific knowledge of the silicon surface, except of course for the manufacturers of surface analytical equipment, who display the Si(111)- 7×7 structure as a distinguishing feature on their publicity material. The immediate utility of the elucidation of such a structure is rather the better un-

derstanding of matters such as the behaviour of electrons in solids. Clean surfaces present theoreticians and experimenters with a problem they can really exercise their talents on.

The understanding achieved does not have to be specifically applicable. It provides the broad substructure that technical applications will be able to extend.

Measurement methods

The ideal measurement method

In my discourse so far I have shown that 'clean' surfaces in vacuum can readily be studied, but that they are not entirely satisfactory as models of the reality. Looking at 'true' interfaces calls for different methods of measurement. What would the ideal method look like?

The ideal measurement method would not disturb the interface, and would determine the chemical composition and molecular structure along it, in the x - and y -directions, and in the z -direction as a function of the distance from the interface. The ruler for measuring x , y and z has divisions in angstroms.

The main problem is the requirement that the method of measurement should be non-destructive. This means that the interface must not be disturbed either in the preparation of the specimen or during the measurement itself. The measurement must be made *in situ*.

If this requirement is left out, a great deal can be done at present. I shall touch briefly on two methods that provide information on an atomic scale, but are limited in this non-destructive, *in situ* aspect.

TEM

The first method that will 'observe' on an atomic scale is Transmission Electron Microscopy (TEM). High-energy electrons are fired through a thin specimen and form an image. Diffraction can also occur and the resultant diffraction image can be interpreted as an image of the atoms.

There are two methods of looking at an interface with TEM. For solid/gaseous or solid/liquid interfaces the solid has to be made thin enough for the electrons to pass right through it; this implies a thickness of a few dozen microns. The specimen is then introduced into the vacuum of the microscope and the solid side of the interface is observed. In the second method, which is used primarily for solid/solid interfaces, a cross-sectional specimen is made; this is again ex-

[1] H. H. Brongersma, F. Meijer and H. W. Werner, Philips Tech. Rev. 34, 357-369, 1974.

[2] R. E. Schlier and H. E. Farnsworth, J. Chem. Phys. 30, 917-926, 1959.

[3] G. Binnig, H. Rohrer, C. Gerber and E. Weibel, Phys. Rev. Lett. 50, 120-123, 1983.

tremely thin, and the interface now runs like a line through the surface of the specimen.

An example of the first method is an examination of the nucleation of a surface with palladium, so that another metal, such as copper, can be catalytically grown on the surface. The palladium nuclei are observed on a titanium-oxide layer a few microns thick. The titanium oxide itself is supported by a silicon-nitride film about ten microns thick^[4]. The nuclei consist of a few hundred palladium atoms (*fig. 4*). The crystal structure and the distances between the atoms can be determined

and the arsenic hydride. The crystal is built up layer upon layer.

The results of the synthetic activity can be analysed afterwards by TEM. The specimens, slices of material perpendicular to the interface, are etched to make them extremely thin, so that the electrons can pass through the specimen and form an image. The TEM micrographs show layers with a resolution of one atomic layer, and even the step in the interface of one atomic layer can be seen. TEM measurements of this kind provide useful information about the CVD process.

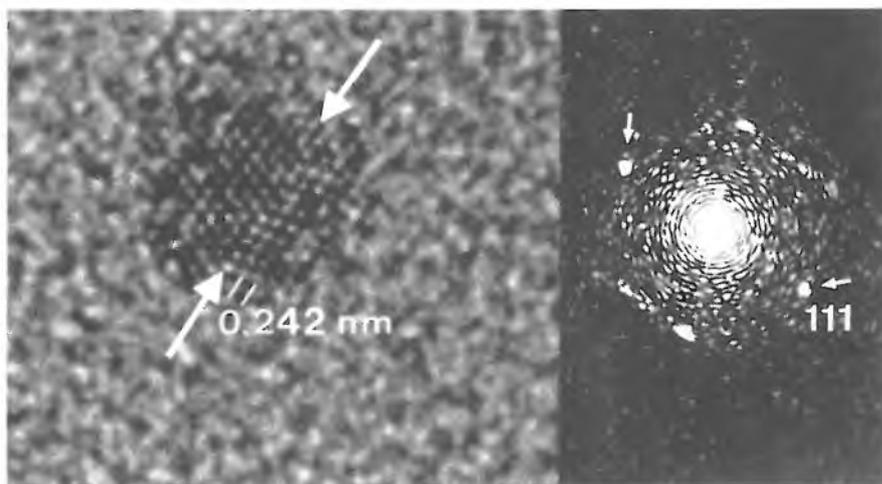


Fig. 4. *Left:* TEM micrograph of a metallic nucleus consisting of no more than a few hundred palladium atoms (obtained on a titanium-oxide layer a few microns thick, supported by a silicon-nitride film a few tens of microns thick). It can clearly be seen that the nucleus has a crystalline structure, in which the familiar effect of 'twinning' has taken place (the mirror plane corresponds to the direction of the arrows). *Right:* TEM diffraction micrograph of the nucleus^[6].

from the diffraction of the electrons. In this example it was concluded that what was observed was indeed metallic palladium with the normal crystal structure. A palladium particle of a few hundred atoms behaves like a piece of metal. In some cases, especially after oxygen adsorption, an expansion of the lattice of 5 to 10% could be measured^[5]. This information is immediately relevant to the understanding of the catalytic action.

Another example is to be found in semiconductor materials. Beautiful micrographs have been made of cross-sections of epitaxial layers of GaAs and AlGaAs (*fig. 5*)^[6], where metal-organic compounds were used to grow successive monoatomic epitaxial layers on a substrate surface.

'Epitaxial' means that the crystal lattice continues from one composition, GaAs, to the next, AlGaAs. The metal-organic compounds, such as trimethyl gallium, dissociate on the surface and the gallium atom arrives at exactly the right place in the crystal lattice. The same thing happens with the triethyl aluminium

Transmission electron microscopy has aspects of the ideal measurement method. It does however require an elaborate preparation technique, followed by measurements in vacuum. Still pictures are obtained after the event, rather than a cinematographic record of events as they take place. The method tells us a good deal about the solid side of the interface, but hardly anything about the chemical structure of the molecules that react with the surface of the catalyst.

STM

Another method I shall touch on briefly, after TEM, is Scanning Tunnelling Microscopy, STM, a relatively new method with resolution on an atomic scale.

Electrons from the surface of a specimen tunnel towards a very sharply defined point of metal, located at a distance of a few angstroms. The tunnelling current depends very closely on the distance between surface atom and metal point. By scanning the surface with the point, at a constant tunnelling current, in the *x*-, *y*- and *z*-directions, an atomic topograph is obtained.

The method depends entirely on the fantastic mechanical precision with which the metal point can be manipulated in the sub-angstrom range. In this way, for instance, the 7×7 structure mentioned earlier of the silicon surface has been observed.

The STM method is used in vacuum, but in principle it can also be applied in a gaseous atmosphere or even in a liquid. The method has certain aspects of the 'ideal' measurement method, but it will never be possible to use it on solid/solid interfaces. Nor is it likely that it can be used to follow the reactions directly at

boundary faces. One of the principal advantages of this is that we can then study dynamic phenomena, reactions taking place at interfaces. In this respect there is still nothing that even approaches an 'ideal' method. Likely methods include those that use 'light', X-rays or acoustic vibrations.

The interesting thing about optical methods is that photons, unlike the electrons and ion beams I was discussing just now, interact very little with matter. In methods that use electrons or ions, however, the surface sensitivity is a direct result of the strong interac-

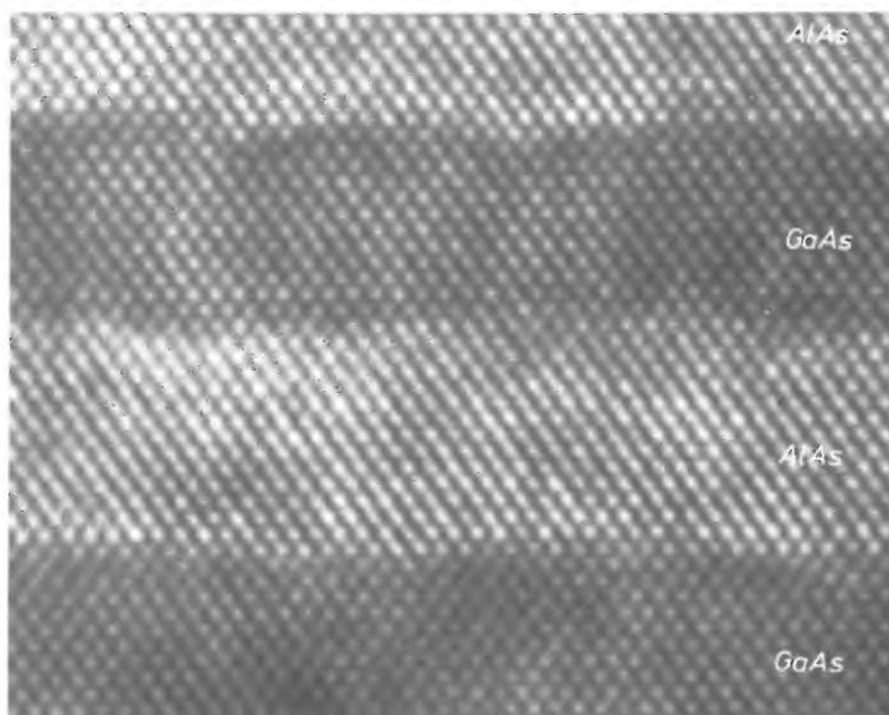


Fig. 5. TEM micrograph of a cross-section of epitaxial layers of GaAs (dark layers) and AlAs. The resolution is never less than two atoms: Ga and As or Al and As. The crystal lattice continues uninterrupted at the transition from one composition to the other, and here and there a step in the interface of one atomic layer can be seen^[6].

interfaces. TEM and STM are examples of highly advanced measurement methods that provide information about the atomic structure from surfaces. These methods and various other analytical techniques, each with their own strengths and weaknesses, have undoubtedly led to a better understanding of interface phenomena. More scientific challenges have still to be met, however, and much research of practical relevance remains to be done.

Non-destructive measurement methods

It seems to me that a field still lies fallow for non-destructive measurements on interfaces. With such measurements, interfaces can be observed without first separating them, without having to make two

measurements with matter, and this has the disadvantage that the measurements have to be performed in a vacuum, since the electrons and ions are scattered in air or any other medium. With light rays (or, to be more accurate, electromagnetic radiation in certain wavelength ranges) there is no such limitation, yet specific information about the interface can nevertheless be obtained in addition to the signal that comes from the bulk. We can explain this in general terms with an example.

^[4] J. W. M. Jacobs and J. F. C. M. Verhoeven, *J. Microsc.* **143**, 103-116, 1986.

^[5] J. W. M. Jacobs and D. Schryvers, *J. Catalysis* **103**, 436-449, 1987.

^[6] M. P. A. Vieggers, A. F. de Jong and M. R. Leys, *Spectrochim. Acta* **40B**, 835-845, 1985; M. R. Leys, M. P. A. Vieggers and G. W. 't Hooft, *Philips Tech. Rev.* **43**, 133-142, 1987.

A light ray is reflected when it encounters an optical change. This need not be associated with energy absorption; even the clearest non-absorbent glass reflects sun-rays. The reflected light ray contains information about the interface, because the interface is *different*, is different from the bulk. A nice example of this is the reflection of light at the surface of a silicon crystal. Silicon has a cubic crystal structure and is therefore optically isotropic, that is to say it behaves identically in all directions. The surface, on the other hand, is anisotropic because of the fact that it is a surface. In a recent experiment ^[7] measurable changes in the reflection coefficient were observed by rotating the surface around the axis perpendicular to the surface. These changes must be due to optical anisotropy and therefore contain direct information about the surface, because the bulk material below it is optically isotropic.

Optical reflection techniques — ellipsometry is a good example — can provide precisely that information about the interface in operation, *in situ*. The ellipsometric method measures changes in both the amplitude and the phase of the light upon reflection. This may be compared by an interference method, and ellipsometry is therefore extremely accurate in showing thin layers at an interface. The resolution in the z-direction easily approaches the range of monoatomic layers. In the reaction of a clean silicon surface with oxygen and many other molecular species it has been possible to demonstrate the presence of coatings of 0.01 of a monolayer, that is to say one oxygen atom for every hundred atoms on the silicon surface ^{[8][9]}. In the x- and y-directions the resolution is not in the atomic range but in the range of square millimetres to square microns, the limit being set by the wavelength of the light. The ellipsometer is therefore eminently suited for studying reactions of flat interfaces, as for example in CVD. There are also interesting examples of oxidation reactions on solid/solid interfaces in semiconductor technology that have been studied by ellipsometry because it was possible to 'look inside' ^[10].

The speed of the method is now about a hundred measurements per second, which is sufficient for measuring many reactions on interfaces. Ellipsometry makes use of spectroscopic capabilities. Measurements can be made in the near ultraviolet, in the visible and the near infrared. A logical but experimentally difficult extension into the infrared range of molecular vibrations has not yet been achieved.

I shall conclude this somewhat more detailed account of ellipsometry with the comment that here, too, there is strength in combination. A combination of the *in situ* measurement of dynamic effects by ellipsometry with an 'atomic micrograph' subsequently obtained by means of transmission electron microscopy

or with a 'molecular structure micrograph' obtained by means of EELS can bring us quite a bit closer to the ideal measurement method.

Without further explanation, so that only the initiated will be completely in the picture, I will just mention a few other methods that are of interest, or could be, for non-destructive investigations on interfaces.

- Surface-enhanced Raman scattering and infrared reflection spectroscopy, which can provide information about molecular structures.

- Fluorescence and phosphorescence of probe molecules ^[11], where the optical effect is sensitive to the immediate environment of the molecule, for example network rigidity in polymers. Many new developments are afoot in optical spectroscopy. It is very likely that the spin-off from these developments will be useful in interface studies, in both ordinary and nonlinear optics. There are prospects of *in situ* measurements in the X-ray wavelength range as well.

- Extended-X-ray absorption fine structure or EXAFS for short, which provides information about atomic distances in matter, including amorphous substances. The application of EXAFS in the study of rhodium catalysts in their reaction environment is yielding spectacular results ^[12]. In particular, measurements have been made of reversible reactions of the rhodium particle with carbon monoxide, in which the rhodium-rhodium-bonds were broken and then restored after removal of the carbon monoxide. To get some idea of such a catalyst particle you have to think in terms of a fragment consisting of 10 to 20 atoms.

Conclusion

In my address I have sought to emphasize that, while much is already known about interfaces, the step from model system to the reality still calls for a great deal of fundamental research. 'Looking at interfaces', using methods in which destructive preparation techniques and a high vacuum are not required, is a field that is open to interesting, advanced and applied research.

Teaching at the university first concentrates on the things that are known: the theory, the facts, the existing experimental methods. By doing research the student then learns to use this knowledge actively and creatively. The impending curtailment of the duration of undergraduate studies in the Netherlands must not lead to an impoverishment of that essential experience in actually doing research.

This brings me naturally to another very interesting interface, the interface between University or Polytechnic and Industry, or more generally the Employer. For the student this interface is the transition from the

past to the future. Nor must this interface be a mere common boundary; here again interaction is essential.

It is in everyone's interest that the man or woman who leaves the university should occupy the right position in working life, in the job that exactly matches his or her interests, capacity and education. These three parameters are not numbers, they are not scalar quantities, but vectors, directions in which development can take place at the proper rate.

In crossing the interface between university and industry these vectors must not suffer abrupt changes. This can best be guaranteed if the interface is both a 'common boundary' and the 'place where interaction occurs', as in the dictionary definitions.

Looking for a place in working life involves a choice of options, a choice by the job-seeker and the employer. The chance of making the right choice is greatest if the job-seeker has a realistic idea of what he or she wants. This idea is one that must be formed

during the years at university, and tried out and tested. It will also help the employer to assess a candidate's suitability for a particular kind of work.

The thread running through my address has been the concept of 'interface'. Looking at interfaces will greatly help us to understand the interactions we find there, and armed with this knowledge we can actively influence these interfaces. So we can prepare an efficient catalytic surface, improve the adhesion between materials, combat corrosion — and even provide chemistry students with the knowledge that will fit them for a job in industry.

'Looking at interfaces' may still be far from fully optimized, but methods both existing and new appear to offer many prospects of further progress.

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[8] R. J. Archer and G. W. Gobeli, *J. Phys. & Chem. Solids* 26, 343-351, 1965.

[9] G. A. Bootsma and F. Meijer, *Surf. Sci.* 14, 52-76, 1969; F. Meijer and G. A. Bootsma, *Surf. Sci.* 16, 221-233, 1969; F. Meijer and G. A. Bootsma, *Philips Tech. Rev.* 32, 131-140, 1971.

[10] J. B. Theeten, D. E. Aspnes, F. Simondet, M. Erman and P. C. Mürau, *J. Appl. Phys.* 52, 6788-6797, 1981.

[11] This will be the subject of a forthcoming article in this journal.

[12] H. F. J. van 't Blik, J. B. A. D. van Zon, T. Huizinga, J. C. Vis, D. C. Koningsberger and R. Prins, *J. Am. Chem. Soc.* 107, 3139-3147, 1985.

Summary. The text is based on the address delivered by the author on 7th March 1986 at his inauguration as Visiting Professor of Heterogeneous Catalysis at the University of Leiden. After discussing the 'interface' concept, heterogeneous catalysis and clean surfaces, he mentions as the characteristics of the ideal measuring method a resolution of the order of atomic distances and the capability of performing non-destructive measurements *in situ*. Methods treated that show the first characteristics are TEM and STM. Methods exhibiting the second characteristic are those that depend on light, X-rays or acoustic vibrations, with special emphasis on ellipsometry. Combining both types of method should give even better results.

Scientific publications

These publications are contributed by staff of laboratories and plants that form part of or cooperate with enterprises of the Philips group of companies, particularly by staff of the research laboratories mentioned below. The publications are listed alphabetically by journal title.

Philips GmbH Forschungslaboratorium Aachen, Weißhausstraße, 5100 Aachen, Germany	A
Philips Research Laboratory, Brussels, 2 avenue Van Becelaere, 1170 Brussels, Belgium	B
Philips Natuurkundig Laboratorium, Postbus 80 000, 5600 JA Eindhoven, The Netherlands	E
Philips GmbH Forschungslaboratorium Hamburg, Vogt-Kölln-Straße 30, 2000 Hamburg 54, Germany	H
Laboratoires d'Electronique et de Physique Appliquée, 3 avenue Descartes, 94450 Limeil-Brevannes, France	L
Philips Laboratories, N.A.P.C., 345 Scarborough Road, Briarcliff Manor, N.Y. 10510, U.S.A.	N
Philips Research Laboratories, Cross Oak Lane, Redhill, Surrey RH1 5HA, England	R

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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, No. 8, 197-212, August 1987.

As the limitations of the existing television systems become more obvious, the need grows for a new system, known as high-definition television (HDTV). This must offer increased resolution, reduced cross-colour and cross-luminance, increased aspect ratio and improved sound quality. It is ultimately of vital importance here that a compatible system is chosen, so that existing equipment can still be used. The MAC system (MAC means Multiplexed Analog Components) recently standardized for use in satellites and cable systems will permit such an evolution. This article describes — by way of example — how at the transmitting end an 'HD-MAC' signal can be generated. This signal is suitable both for reception with standard MAC equipment, and for reception with a special HD-MAC set that can display a picture of HDTV quality. The signal processing required is described with the aid of one-, two- and three-dimensional spectra. Separate attention is paid to the transmission of moving images and colour information. The article concludes with the description of a complete HD-MAC television system, a discussion of the compatibility of HD-MAC and standard MAC and a quality comparison for various television systems.

J. C. Brice and W. Koelewijn: Selecting quartz for resonators, Philips Tech. Rev. 43, No. 8, 214-219, August 1987.

To meet the high specifications usually required, quartz resonators must be made from quartz of a high quality. In this article the different aspects of this quality are discussed and the outcome of the investigations into the selection criteria are reported. Three simple tests appear to be sufficient for an accurate selection. Every quartz bar is inspected visually for gross defects and is exposed to a temperature shock of 50°. For a small number of bars the infrared absorption at a wavelength where hydrogen absorbs infrared light is determined. Thus an infrared quality factor is assessed. Bars that do not show gross defects, do not break as a result of the temperature shock and come from a batch with a mean infrared quality factor of 2 million or more, can be used to make devices with the required technical specifications in production processes with high yields.

F. Meijer: Looking at interfaces,
Philips Tech. Rev. **43**, No. 8, 220-227, August 1987.

The text is based on the address delivered by the author on 7th March 1986 at his inauguration as Visiting Professor of Heterogeneous Catalysis at the University of Leiden. After discussing the 'interface' concept, heterogeneous catalysis and clean surfaces, he mentions as the characteristics of the ideal measuring method a resolution of the order of atomic distances and the capability of performing non-destructive measurements *in situ*. Methods treated that show the first characteristics are TEM and STM. Methods exhibiting the second characteristic are those that depend on light, X-rays or acoustic vibrations, with special emphasis on ellipsometry. Combining both types of method should give even better results.

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