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DETECTORS FOR QUANTITATIVE ELECTRON BEAM VOLTAGE MEASUREMENTS

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Abstract

Qualitative voltage contrast is produced without difficulty in any SEM. Complete separation of the voltage contrast from other sources of contrast is not a straightforward matter because of the nonlinear relations between the phenomena causing contrast and the video signal.

Quantitative measurements depend on the availability of electron energy analysers which can detect accurately the shift in secondary electron energies due to potentials appearing on integrated circuit tracks, without being affected by transverse fields due to potentials on other conductors or insulators. The principles underlying existing detectors are explained, their effectiveness assessed, and a new form of electron detector is suggested.

KEY WORDS: Scanning electron microscope, voltage contrast, electron beam testing, electron energy analyser, integrated circuit.

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Principles of Quantitative Voltage Contrast

Voltage contrast appears in any standard SEM when signals are applied to an integrated circuit specimen, a phenomenon which has been known for many years (Oatley and Everhart, 1957). The brightness of the image appears, for potentials of a few volts about zero, to be roughly proportional to the negative voltage on the specimen and so the most obvious approach is to process the video signal in such a way that a direct reading of the specimen voltage can be obtained. Unfortunately, this is not as straightforward as it might appear, as the grey levels in an SEM have no absolute meaning; they happen to form a very good topographical image when used in that mode, but normally they cannot be used to imply any particular numerical value of a parameter. In a reasonably well-arranged set-up it is usually true that the image becomes steadily brighter as a negative voltage is applied and vice-versa. However, saturation sets in after a few volts and it is possible for the polarity of the contrast signal to actually reverse. In real circuits, there is also the effect that the field due to potentials on adjacent conductors or charged oxide surfaces can influence the result.

In order to make voltage contrast quantitative, as is required in electron beam testing (EBT) machines, two avenues of approach present themselves: (i) Primary beam voltage contrast; the effect of surface potentials on the energy of the low-energy primary beam is detected, as in a Vidicon TV camera tube, described by Flemming (1968). This approach has not become widely used, probably because of the electron-optical problems which arise in attempting to produce adequate spatial resolution. (ii) The effect of surface voltages on low-energy secondary electrons (below 15 eV). This is the method normally used, as voltages of around 5 V or less on the circuit will have a significant effect on the secondaries as they leave the surface of the specimen. (iii) The effect of surface voltages on Auger electrons, which have considerably higher energies than secondaries and therefore have no difficulty in escaping from retarding fields at the specimen surface. This method has been used by Macdonald (1970), but it has not been widely employed because of the relatively low number of such electrons compared with secondaries.

Electrons leaving a specimen as the result of irradiation by an electron beam are conventionally divided (e.g. Reimer, 1985) into two broad classes: 'backscattered' electrons having energies between 50 eV and the primary beam energy, with a narrow peak at the primary beam energy. 'secondary' electrons having energies below 50 eV, with a peak in the energy distribution curve at around 3 eV, as indicated in Fig. 1. The position of the peak of the curve depends on the composition of the specimen surface and can be described adequately by the formula due to Chung and Everhart (1974),

$$\frac{dN}{dE_s} \propto \frac{E_s}{(E_s + \Phi)^4}$$

where E_s is the energy of the secondaries and Φ is the work function of the material. If the surface of the circuit is clean metal at all points to be probed, then consistent static and dynamic voltage measurements should be possible. In practice, contamination effects and differences in surface composition affect the achievable accuracy.

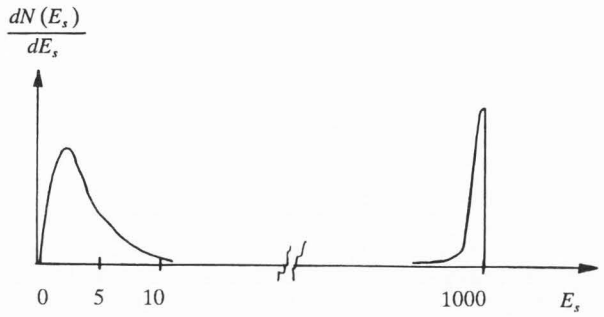

Fig.1 General form of the energy spectrum for electrons emitted as a result of a 1 keV primary beam.

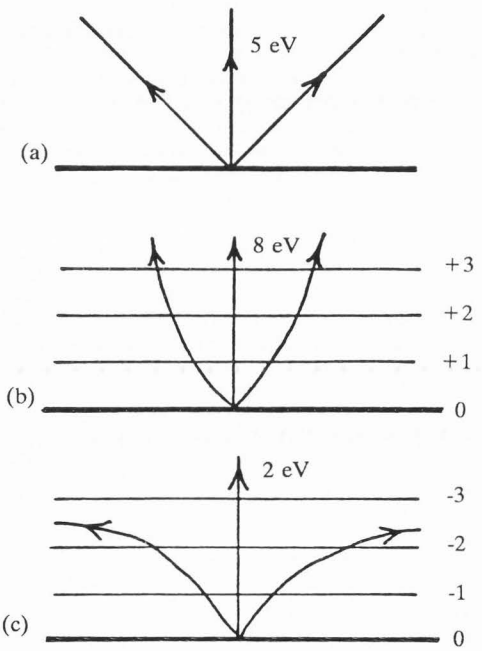

Fig.2 The effect of planar fields on secondary electrons, showing the paths of 5 eV secondaries emitted normal to the surface and at 45 degrees to the normal for:
(a) zero field
(b) accelerating field as a result of a negative surface
(c) retarding field as a result of a positive surface.

For normal incidence of the primary beam, secondaries leave the surface in all directions, with an approximately cos(θ) intensity distribution with respect to the normal to the surface. As indicated in Fig. 2, if the secondaries encounter an electric field above the surface, they will gain or lose energy depending on the polarity of the field. It is this change in energy which is detected in order to produce quantitative voltage measurements.

One of the most significant advantages of instruments which form an image by raster scan methods is that the parameter imaged can be a wide variety of phenomena induced by the primary beam, which itself need not be an electron beam. Voltage contrast methods are at present largely confined to the use of a primary electron beam in SEM-type instruments, though optical beams are now being investigated for this purpose (Seitz et al, 1986). One advantage of optical beams is that laser technology allows the generation of very short pulses, in the sub-picosecond region, which are useful for the investigation of very high speed devices. Optical devices also have the advantage of not always requiring the specimen to be placed in a vacuum, though if secondary electrons are to be used to detect voltage contrast, this advantage obviously does not apply.

The commonly used detector in the topographic imaging mode is some form of that described by Everhart and Thornley (1960), employing a scintillator at a positive potential of about 10 kV to provide virtually noise-free amplification of the electron stream entering the collector cage. The location of the cage in relation to the specimen and its voltage bias will clearly affect which electrons are detected and hence the appearance of the topographical image. A positive bias on the cage enhances the collection of secondary electrons while a negative bias suppresses these and the image is then formed from the backscattered electrons. The electric or magnetic fields close to the specimen surface will also affect the numbers and energies of the electrons which reach the detector, as indicated in Fig. 3. In the case of an integrated circuit with voltages present, therefore, the resulting image will be a mixture of topographical information, voltage information and material information, as the secondary and backscattered emissions vary with different materials.

So far as the topographical information is concerned, interpretation is straightforward as the image presented on the SEM screen is very similar to the type of image which the human eye is accustomed to dealing with. The most important matters are the dimensions of features, which can be accurately determined because the beam position is precisely determined by the scanning system and the heights of features can be determined by stereoscopic methods if required. However, separating out the voltage contrast information to give quantitative levels of voltage is not a straightforward matter, if one attempts to do this on the basis of the number and energy of electrons reaching a detector placed in the conventional manner. This is because many of the electrons reaching such a collector have been generated in various places by various mechanisms other than being secondary electrons emitted from the point of interest on the specimen. We must ensure that the measurement system measures the energy only of the latter group and not of 'tertiary' electrons emitted, for example, by the impact of backscattered electrons on the final lens polepiece. Neither is it completely effective to produce a pure 'voltage-contrast image' by subtracting a topographical image from the image containing a combination of topography and voltage contrast by methods such as described by Oatley (1969). The electron trajectories are different in the two cases of 'voltage-on' and 'voltage-off', so that a nonlinear relationship exists between voltage and image brightness which cannot be completely removed by simple subtraction.

It is therefore necessary to find methods of measuring the energies of the secondary electrons with a sufficiently high degree of precision. In order to do this, practically useful analysers have hitherto performed the energy filtering process on the secondary electrons as close as possible to the specimen, before the generation of excessive quantities of unwanted low-energy electrons can occur. The higher energy electrons have been prevented from entering the detector by judicious use of grids and placement of the electron detector. However, this situation is changing as the simple two-grid planar filter arrangements are found to give inadequate performance under today's conditions.

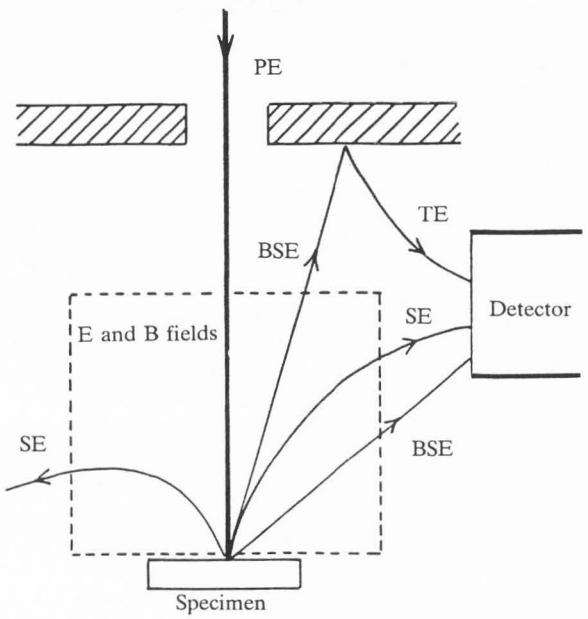

Fig.3 The primary electrons (PE) release low-energy secondary electrons (SE) which are influenced strongly by the fields above the specimen surface. High-energy backscattered electrons (BSE) are little affected by these fields and they release low-energy tertiary electrons (TE) which may reach the detector. Few BSE reach most detectors used in voltage-contrast work.

Measurements in practice

Supposing that some means has been found to extract all the secondaries from the specimen surface and to separate them from all other electrons, the energy spectrum will have the same form whatever the specimen voltage, but will be shifted sideways by an amount proportional to the specimen voltage, as indicated in Fig. 4.

In order to detect this sideways shift in the energy spectrum, two general types of energy analyser have been used so far: A. The 'band-pass' filter, described by Wells and Bremer (1969) and by Hannah (1974), outlined in Fig. 5. This allows electrons within a chosen narrow band of energies to pass to the detector. B. The 'high-pass' filter, used by Feuerbaum (1979) and many other workers and incorporated in several commercial EBT systems, which allows electrons above a certain chosen energy to pass to the detector, outlined in Fig. 6. Computer simulations of various such analysers have been made by Khursheed and Dinnis (1984).

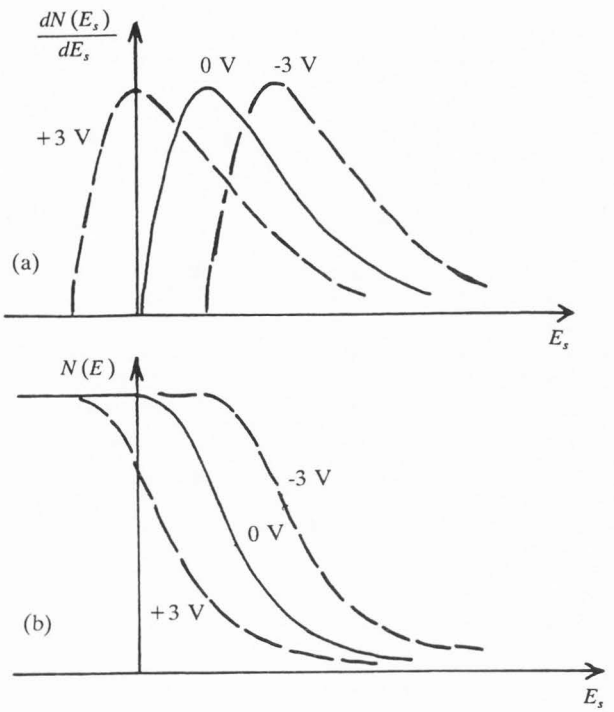

Fig.4 Secondary electron energy distributions for surface potentials of 0 V, +3 V and -3 V.
(a) Plot of number of electrons dN in the energy interval dE against electron energy, as would be measured by an ideal 'band-pass' energy analyser.
(b) Plot of the total number of electrons N(E) above a given energy against energy E, as would be measured by an ideal 'high-pass' energy analyser.

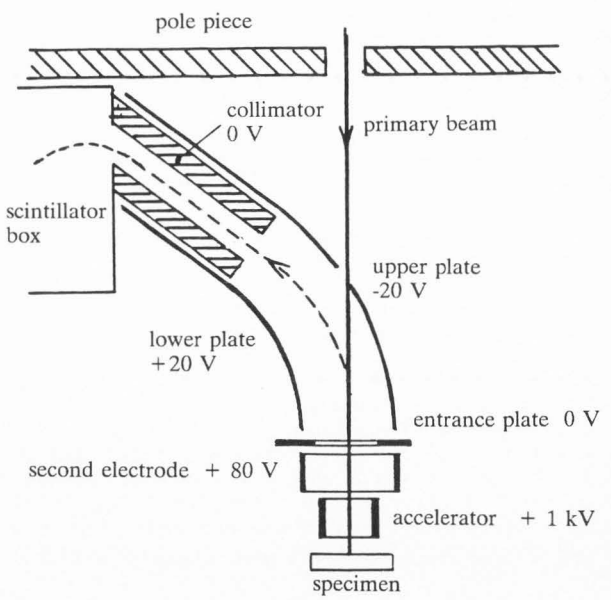

Fig.5 Arrangement of 63 degree energy analyser and accelerating electrode as used by Hannah (1974).

Both types can give acceptable results, and the minimum detectable voltage for both types can be found by the method given by Gopinath (1977). This voltage is dependent on the characteristics of the detector but is ultimately limited by shot noise and is therefore dependent on the amount of current which can be produced in the primary beam at the specimen. This in turn is dependent on the spot size, dictated by the dimensions of the device, and on the brightness of the electron source. Lanthanum boride cathodes are commonly used for this purpose, though it is inevitable that field emission sources will eventually become the preferred ones because of their considerably higher brightness. Although measurement precision in the order of a few millivolts is achievable on a good specimen, in practice measurement to 0.1 V is adequate in most cases, where signals of several volts are usual. For ECL (emitter-coupled logic) circuits, where the voltage swings are a few hundred millivolts, matters are obviously more critical and improved precision is also required for measurements on analogue circuits.

Most existing analysers are of the 'high-pass' type and this function is carried out by a retarding field grid of some sort. In many cases, this grid is a planar one lying parallel to an extraction grid, as indicated in Fig.6. The function of the extraction grid is to remove most of the secondary electrons from the surface of the device even when this is at a positive potential, and so retain the shape of the 'S-curve'. The S-curve is obtained by applying a ramp voltage to the retarding grid and so is closely related to the integral of the secondary-electron energy distribution curve, shown in Fig. 4. The S-curve moves along the voltage axis as the specimen voltage is varied and therefore the shift in the specimen voltage is exactly this shift in the S-curve.

Little attention has so far been paid to the use of multichannel or 'dispersive' analysers, which would appear to offer the potential advantage of better signal-to-noise ratio as they would detect all the electrons rather than rejecting a large proportion as the bandpass and high-pass types do (Dubbeldam and Kruit, 1987). By employing suitable signal-processing on the signals from the detectors it should be possible to obtain reliable results even for changes in secondary electron current due to such causes as fluctuating primary beam current, contamination buildup etc. A scheme for a two-channel electrostatic analyser is shown in Fig. 7 and a system involving through-lens detection and a variable-axis lens has been described by Kruit and Dubbeldam (1987).

In the case of a 'band-pass' analyser, if the pass-band is relatively narrow, the output signal resulting from a voltage ramp applied to the analyser will approximate to the original shape of the secondary-electron distribution curve shown in Fig. 4 and the change in specimen voltage is equal to the voltage shift of the peak of this curve.

These detectors can give accurate results provided that there are no appreciable transverse fields above the specimen surface. If an electron is emitted with or acquires a transverse velocity near the surface, this component will remain when it reaches the retarding grid and will affect its chance of passing through the grid. Retarding grid spectrometers rely for their accuracy on the electrons reaching the retarding grid at normal incidence. If the distribution of angles remains constant, it is still possible to make reliable measurements. However, transverse fields above the specimen can change the angular distributions of the electrons seriously and therefore affect the measurement accuracy of the analyser (Fujioka et al, 1981). Transverse fields frequently arise because of the high density of conductor tracks on the surface of integrated circuits. A typical situation is a 'bus line', where signals travel along a number of parallel tracks and it is required that the signals on these tracks are measured. Such a case is shown in Fig. 8, where the electric fields above the tracks and the resulting

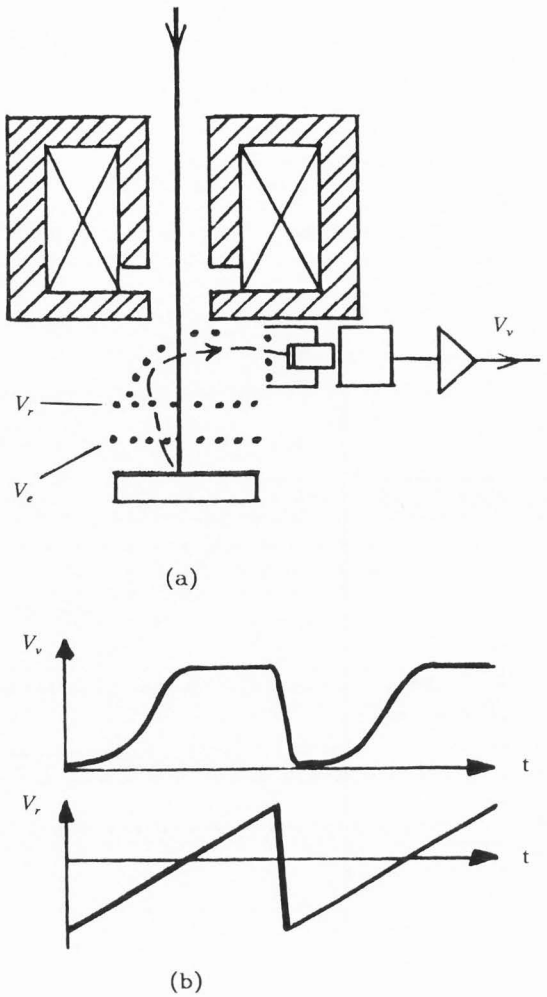

Fig.6 (a) Typical arrangement of retarding-field energy analyser. The extraction grid is maintained at a positive potential Ve, while the retarding grid has a sawtooth voltage applied to produce the 'S-curve' characteristic of the video signal Vv, as shown in (b).

electron trajectories are shown. Not only does this effect give rise to inaccuracy in the measured value of the voltage on the chosen conductor, it also means that any waveform measured on one conductor is likely to have superimposed on it interference from signals on adjacent conductors.

An increase in the extraction field will reduce the number of electrons which are turned back to the specimen before reaching the extraction grid but cannot in itself overcome the problem of transverse velocities at the retarding grid.

An apparent solution would be to replace the planar retarding grid with a spherical one centred on the apparent source of emission, similarly to the arrangement described by Tee and Gopinath (1976). Such an arrangement, similar to that shown in Fig.9, with the extraction grid placed close to the specimen and a relatively large radius spherical retarding grid has been suggested by Menzel and Kubalek (1983), Goto et al(1981) and Nakamae et al (1985) and simulations of a similar system have been carried out by Dinnis and Khursheed (1985). A major disadvantage of employing a spherical retarding grid of adequate dimensions is that it increases the

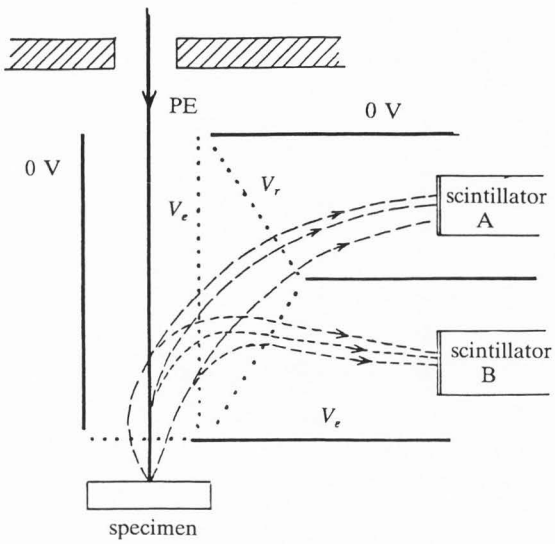

Fig.7 A two-detector 'dispersive' analyser. The higher energy secondaries reach the upper detector while the lower energy ones are collected on the lower detector. Changes in the potential of the emission point on the specimen therefore alter the distribution of the current between the two detectors.

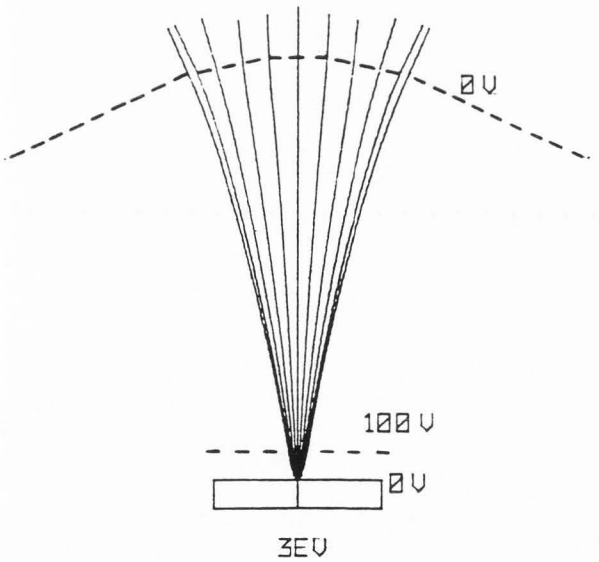

Fig.9 Modified hemispherical field analyser with extraction grid. Trajectories of 3 eV electrons emitted from 0 V surface.

working distance between the final lens and the specimen by a significant amount. Also, the spherical geometry is only correct for a point at the centre of the sphere.

Some recent developments in voltage-contrast detectors involve the immersion of the specimen in a magnetic field.

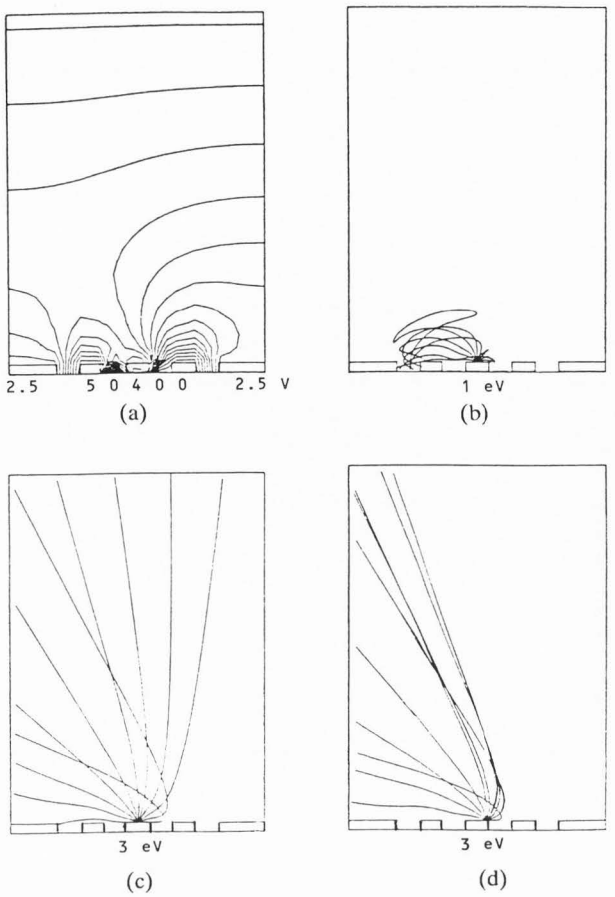

Fig.8 Computer plot of the transverse field effect.
(a) Equipotential plot.
(b) 1 eV electrons emitted from centre of +4 V conductor.
(c) 3 eV electrons emitted from centre of +4 V conductor.
(d) 3 eV electrons emitted from edge of +4 V conductor.

This happens to some extent in any case when the working distance is reduced to obtain the maximum spatial resolution; in fact the specimen is sometimes placed within the bore of the final lens for this purpose. The use of wide-bore lenses to give a larger scanned area also leads to immersion of the specimen in a magnetic field. This can give rise to complications if the specimen is in any way magnetic, as is often the case with IC packages, as the primary beam will be affected by the resulting non-symmetrical magnetic field pattern.

If the specimen is within the lens field, it is obvious that there will be severe difficulty in incorporating a conventional retarding-field analyser. The expedient adopted is to place the analyser on the other side of the lens from the specimen, as indicated in Fig. 10, so that the electrons must travel through the lens field to reach the detector (Menzel and Buchanan 1984, Kawamoto et al 1984). The lens field is relatively strong as it must focus the primary beam (of about 1keV energy) whereas the secondaries have energies of less than 15 eV as they leave the specimen surface. The secondaries therefore describe tight spirals around the lines of magnetic flux. Many of those electrons which are not returned to the specimen describe progressively larger spirals as they emerge from the top of the lens and are then passed into the analyser, as

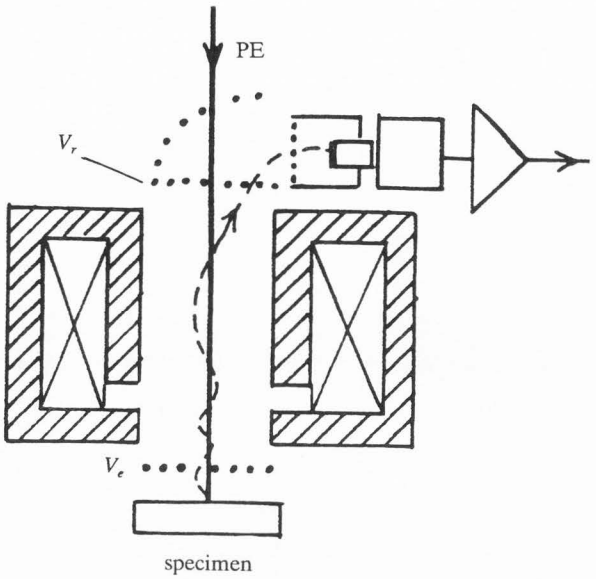

Fig.10 Arrangement of 'through the lens' analyser. The retarding grid and electron detector are placed above the final lens, so that secondary electrons must pass through the magnetic field of the final lens.

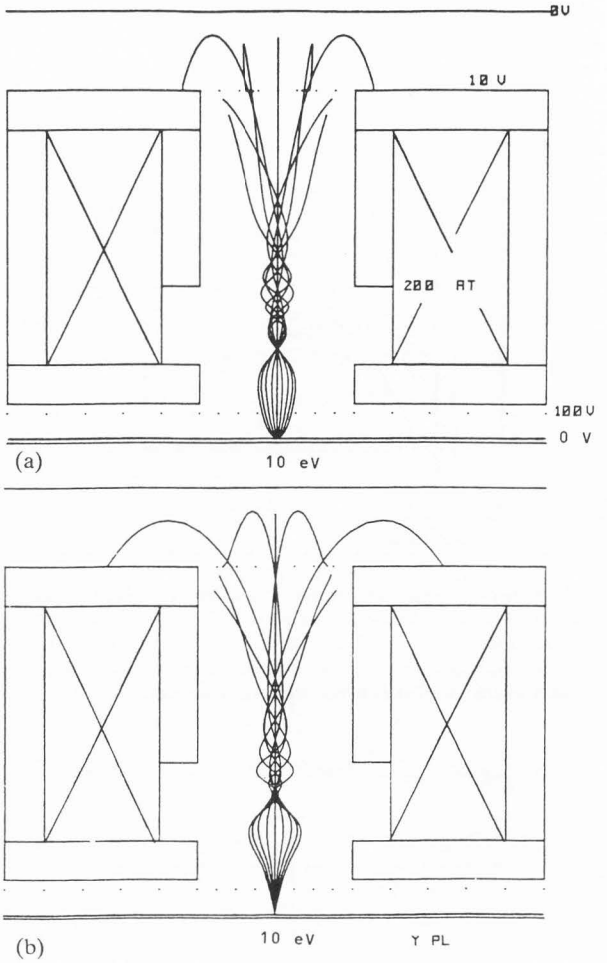

Fig.11 Computer plot of trajectories of 10 eV electrons passing through the magnetic field of the final lens in a hypothetical example of a through-the lens analyser.
(a) XZ plane (b) YZ plane

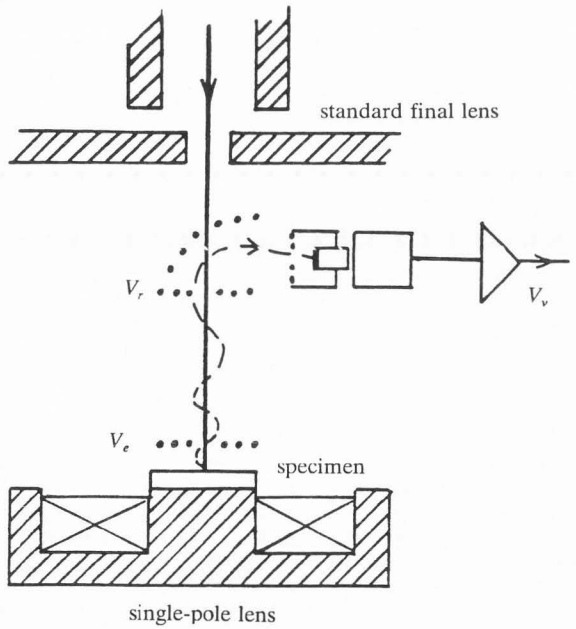

Fig.12 Electron energy analyser incorporating a 'single-pole' final lens. The specimen is located at the region of most intense magnetic field, so that electrons which escape from the surface perform spirals of steadily increasing radius as they approach the retarding grid.

shown in Fig.11 for a hypothetical case. It is advantageous to use an extractor electrode in order to increase the axial velocity of the electrons and improve their probability of passing through the lens. The detector described by Plies and Schweizer (1987) uses such an extractor to accelerate the secondaries back through the final lens to focus them at the centre of a hemispherical grid analyser placed above the lens and deflection coils.

A variation of the 'through-lens' detector is that described by Garth et. al. (1985), where a 'single-pole' lens of the type described by Mulvey (1973) is employed as the final lens, as indicated in Fig.12. The magnetic field is therefore at a maximum at the specimen. The consequence of this is that all the secondaries which escape from the immediate vicinity of the surface travel away from the specimen in a diverging magnetic field so that the spirals become progressively larger and the trajectories become more nearly parallel to the axis. A flat grid placed normal to the axis is thus an effective retarding field analyser, at whatever angle the electrons leave the specimen. This arrangement shows excellent rejection of adjacent conductor effects, even on tracks having dimensions of the order of one micron. The lower energy secondaries are

not extracted from positive conductors, as the extraction electrode is kept at about 50 V. The area over which the beam can be scanned while using the single-pole lens is restricted but if large areas must be scanned it is switched off and the beam is focussed by a conventional lens above the analyser.

Current Developments

The use of EBT is now firmly established among semiconductor manufacturers, but it is still a relatively new technique and requires much development if it is to realise its full potential in the testing of IC's and investigation of individual devices. So far as IC testing is concerned, the chief concerns affecting the actual measurement process at present are the improvement of the measurement accuracy of voltage levels on submicron conductors, the elimination of the adjacent conductor effect and the development of reliable methods for measuring through insulating layers so that measurements can be made on passivated devices and on the lower levels of multilevel devices.

The interaction of the beam with a metal track is fairly straightforward but, just as the trajectories of electrons are affected by adjacent conductors, they are affected by charge on the field oxide between tracks. There is often some charge on this oxide because it is usually scanned for some period in order to form an image for location purposes. This charge can be helpful, as a small positive charge will help to extract electrons from the metal track, as indicated in Fig. 13. On the other hand, it can be destructive; for example an asymmetrical charge pattern will distort trajectories in the same way that an adjacent conductor can. Some means of managing this charge is therefore essential and this remains true even in those schemes where the beam should never scan the adjacent oxide, as some secondaries emitted from the track can find their way on to the oxide.

The management of surface charge is also crucial when detecting voltages through layers of insulator on passivated and multilevel devices. It is a well-established fact that electrical activity can be detected in this case (Kotorman, 1980) and some progress has been made in quantifying it (Görlich et al, 1985) but quantitative measurements are not at present reliable.

The process which takes place when a passivated device is irradiated with a low energy beam is as follows. There will generally be an extractor electrode or, at least, a positively-biased collector, in the vicinity of the specimen which will collect some fraction of the secondary electrons. Some of the secondaries will, however, return to the specimen and this fraction will depend on the potential of the specimen. The situation is therefore quite complex (Taylor 1978, Nye and Dinnis 1985) but if we simplify it to the case shown in Fig.14, some conclusions may be drawn. Assume there is a planar grid at $+V_e$ close to a uniform conducting specimen coated with a thin layer of insulator the surface of which is charged to a potential V_s. Initially, $V_e = V_s = 0$, and there is no field above the specimen. All secondaries leave the insulator surface, which will therefore start charging positively provided the secondary emission coefficent $\delta > 1$. If the beam is held stationary or scans a relatively small area, as in Fig 14a, high fields will be developed near the point of impact of the beam and, if the beam is held stationary for a period of a few seconds, a long-lasting charge remains and this remains visible when the raster scan is re-started and an image formed. Therefore, if measurements are to be made with the beam held stationary, it must be stopped for only a few milliseconds if this effect is to be avoided. If, on the other hand, we consider the state of charge on the surface if the beam is scanned over a raster which is comparable in size with the spacing between the extraction grid and the specimen, a more tractable situation arises. On the first raster (Fig 14b), substantially all secondaries pass through the extraction grid, so that V_s becomes slightly positive. This produces a retarding field between the specimen and the grid, so that on the subsequent raster scans, some of the emitted secondaries return to the specimen surface. The process continues, with V_s rising towards an equilibrium value (Fig 14c) where there is a balance between the total electron current striking the scanned area (beam current + secondaries returning to surface) and that leaving it (secondaries passing through grid + backscattered electrons).

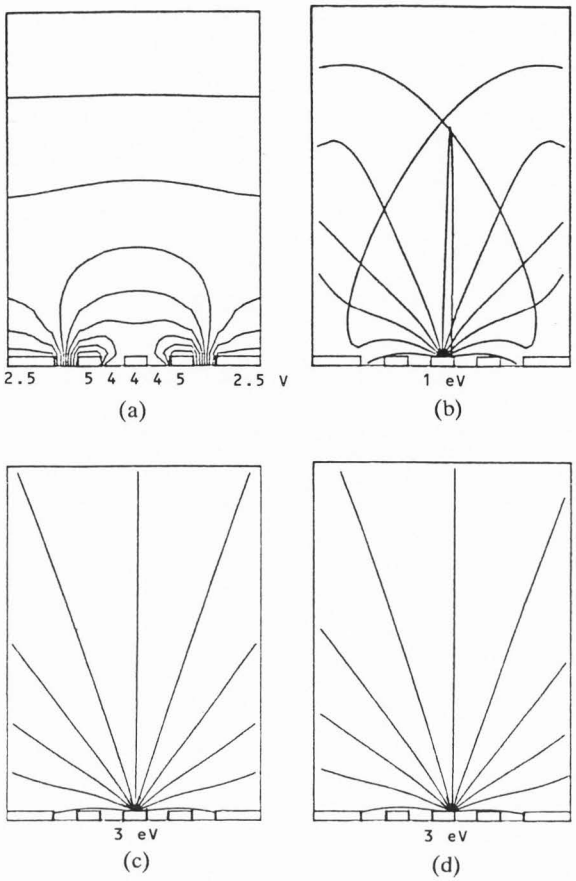

Fig.13 (a) Equipotential plot for a 4 V conductor between two 5 V conductors, with the oxide assumed to be charged to +4 V. (b) Trajectories of 1 eV electrons emitted from centre of track. (c) Trajectories of 3 eV electrons emitted from centre of track. (d) Trajectories of 3 eV electrons emitted from edge of track.

In practice, with the beam currents normally used to form images, this process occurs quite rapidly, so that after a few raster scans the surface of a passivated device becomes a uniform dark grey on the display screen. If the potential on a conductor beneath the passivation has its d.c. value switched, then voltage contrast is visible on the conductor but it rapidly dies away as charge equilibrium is re-established. The contrast dies away more rapidly as the magnification is increased because of the increased irradiation density. It is important not to use an excessive extraction voltage as this can allow the surface of the insulator to charge to dangerously high positive potentials. The design of the analyser must take account of this aspect and it must not, for example, return large numbers of secondaries back to their point of emission; electrons which are turned back at a retarding grid should be absorbed within

the analyser rather than being sent back to the specimen.

Any new analyser design must also incorporate the design of the final lens, as it is inevitable that the secondaries must travel through some part of the final lens field. The secondary electrons must be removed efficiently from the region of the lens without affecting the focussing of the primary beam and without generating extra tertiary electrons which will confuse the analysis process.

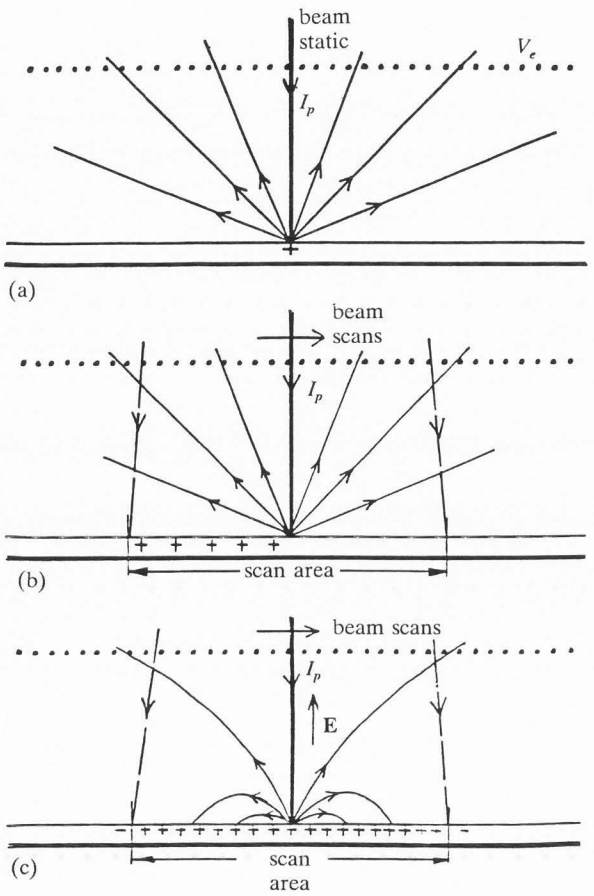

Fig.14 Stabilization of charge on insulator surface. For a low primary beam voltage, the emitted current , Is > Ip, so the insulator surface begins to charge positively.
(a) Stationary beam; the point of impact charges positively.
(b) Initial raster scan; most secondaries pass through the extraction grid and the surface starts to charge positively.
(c) The equilibrium state is achieved after a number of raster scans. A retarding field has been built up which influences the trajectories of secondaries so that charge balance occurs.

One way of separating out the secondaries is suggested in Fig 15, where the final lens is constructed in two successive halves with opposite directions of axial magnetic field. This type of lens has been used in the past (Stabenow, 1935) to produce a 'non-rotating' magnetic lens, but the purpose in this instance is to produce a magnetic field which is directed radially outwards at the mid-section of the lens. The low-energy secondary electrons leaving the surface of the circuit initially spiral about the axial magnetic field, until they approach the mid-point of the lens where the magnetic field falls to zero. Here, a suitable electrostatic field is produced which causes

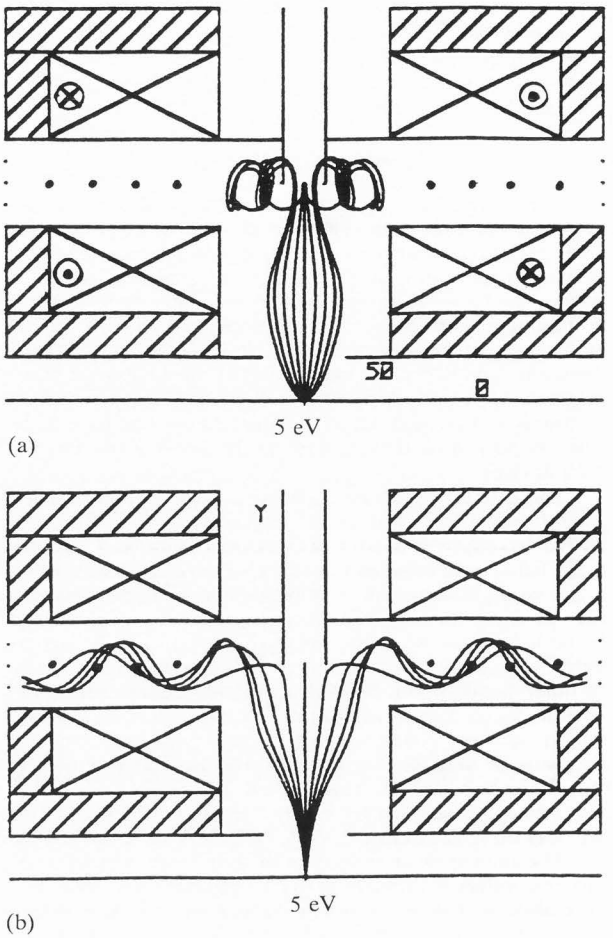

Fig.15 Electron trajectories in non-rotating final lens. The lens focuses 1 keV primary electrons on the specimen surface. Trajectories of secondary electrons having initial energies of 5 eV are shown for 50 V on the extraction electrode.
(a) Trajectories in XZ plane (b) Trajectories in YZ plane.

the electrons to acquire some additional radial velocity and to spiral around the radial magnetic field. The secondaries are thus transported efficiently to the periphery of the lens system where there is sufficient space to incorporate an effective energy analyser. This arrangement also has the advantage that changes in the fields within the energy analyser section have no effect on the focus or position of the primary beam. Electron trajectories are shown for an extractor at 50 V, which is suitable for observation of passivated specimens. If higher extraction voltages are necessary, then an additional high-voltage extraction electrode must be placed between the 50 V extractor and the specimen.

Given an appropriate analyser, therefore, observation of voltage-contrast in these circumstances and its measurement are crucially dependent on proper management of the surface charge by an appropriate combination of beam intensity, switching and scanning. In any case, it is essential that the beam should not remain stationary for more than a few milliseconds while on an insulator, as serious negative charge buildup then occurs, even when using a 1 keV electron beam.

It is possible to observe clear images of high-frequency voltage-contrast in the stroboscopic mode, originated by Plows and Nixon (1968), by careful adjustment of beam operating

parameters and extraction voltage, without any special beam management equipment. However, this is very much a trial-and-error process and is clearly not suited to an EBT system to be used on a routine basis.

Devices can be provided without passivation, particularly in the situation where EBT is being used at the design validation stage, so that there is no obstacle to viewing top-layer metal tracks. Multi-level devices still require to be viewed through one or more layers of insulator, though ideally direct access should be provided by the designer to known critical test-points. It will always be useful to observe electrical activity even though this may be only of a semi-quantitative nature and a good estimate can be made of the relation between the surface potential and the underlying conductor voltage using simple field concepts, as described by Herrmann and Kubalek (1986).

For certain applications, there is a requirement for improvement in the high-frequency measurement capability over the best value of 50 ps quoted by manufacturers of commercial equipment (Schmitt and Winkler, 1986). Silicon IC's are continually being upgraded in frequency performance and there is also great interest in such devices as GaAs IC's for operation at frequencies in excess of 1 GHz. For good resolution of waveform shapes in these cases, timing resolution in the order of one picosecond or better is required. One limitation on ultimate frequency resolution is the minimum electron beam pulse length which can be achieved and there is the possibility of improvement by the use of more sophisticated electron beam chopping or the use of a photoemissive cathode which is stimulated by very short laser pulses. The ultimate limit is, however, likely to be set by the transit time of secondary electrons through the time-varying microfields above the surface of the conductor being probed.

A simple illustration of the effect can be given in the situation depicted in Fig. 16. Electrons which escape from the region of the surface field will be collected, but those which are emitted close to the rising edge of a pulse will not travel far enough before the retarding field due to the positive surface affects their energy. The case shown has been chosen so that the field due to the signal-carrying conductor decays fairly rapidly above the surface. It is assumed that once an electron has reached a height of 10 microns above the surface, it will continue onwards into the electron analyser. For an electron emitted normally to the surface with an initial energy of 3 eV and with an extraction field of 1 kV/mm, the time to travel 10 microns is 6.3 ps. Electrons emitted at other angles will take longer and so a time resolution of no better than 10 ps could be expected in this case. In real circuits the situation could be worse, depending on the circuit layout and on the extraction electrode arrangements. Clearly, the closer the extraction electrode can be positioned the better the result is likely to be, and so specialised detectors with extraction grids almost in contact with the specimen surface must be developed if the technique is to be extended well into the GHz region.

Conclusion

So far as instrumentation is concerned, improvements in electron optics can confidently be expected, starting with the electron gun where field emitter sources offer very much brighter sources than conventional tungsten or lanthanum boride cathodes. For very high frequency work, photocathodes excited by very short laser pulses will be used to produce electron pulses in the picosecond region. The electron optics of the voltage contrast analyser will also be steadily improved, with new designs of integrated final lens/analyser combinations and the introduction of multichannel 'dispersive' detectors. The development of lens/deflection systems capable of making voltage-contrast measurements over areas tens of millimetres square is also under way, though this does involve some compromise with spatial and voltage resolution at present. Considerable effort must be devoted to the development of

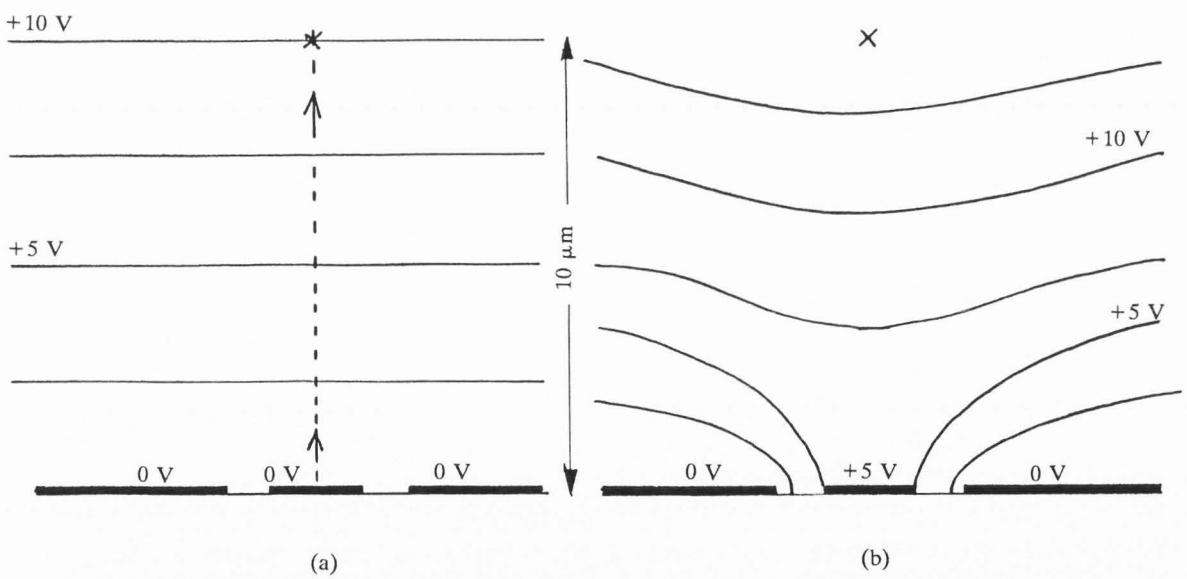

Fig.16 Effect of high-frequency fields on secondary energy. Emission from a 2 μm wide conductor stripe separated by 1 μm from a coplanar ground plane. An extraction field of 1 kV/mm is assumed.
(a) Conductor at 0V; 3 eV electron takes 6.3 ps to arrive at +10 V equipotential.
(b) Conductor switches rapidly to +5 V; electron emitted within 6 ps of field becoming established will have its energy affected.

new equipment if the performance is to keep up with the technology of manufacture and the increasing complexity of the systems which can be placed on one piece of semiconductor. However sophisticated the test methods are, they depend on a reliable voltage contrast analyser and unless the physics involved is well understood and the necessary computations required to design appropriate analysers and to correct for various circuit configurations are carried out accurately, the rest of the test system is likely to be ineffective.

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Discussion with Reviewers

J. Phang: The retarding field in the two-channel analyser of Fig. 7 is not pointing in a constant fixed direction (as in a planar retarding field analyser) or towards the centre of the hemisphere (as in the hemispherical analyser). Will this give rise to more errors than in a planar retarding field analyser in this case? If yes, is there any predictable way to account for this, and if so, will it be more difficult to account for this than in a planar retarding field analyser?

Author: I have carried out a large number of computer simulations of electron trajectories in such detectors and by empirical shaping of the grids have arrived at a design where the trajectories seem not to be significantly worse than in planar retarding field analysers simulated by the same programs. However, extensive further work is required, particularly the computation of S-curves before definite conclusions can be drawn.

A. Gopinath: The comments on the multichannel analysis are interesting. In effect, the high-pass retarding potential analyser is a two-channel system, with the lower energy fraction being collected by the extraction grid or possibly by the scintillator detector arranged in some fashion. The output of the second channel has been used for normalization of the signal previously to account for beam current drift or change in specimen composition (Tee et al. 1976). Why do you expect the signal-to-noise ratio to improve when the dI/dV (g_m) does not change?

Author: In general, I would expect the signal-to-noise to improve simply because more current is being collected. If two scintillator detectors are used, dI/dV will be of equal magnitude but opposite sign in the two channels. Thus, by subtracting one signal from the other the effective dI/dV is doubled.

A. Gopinath: The electron transit time calculations for the ultimate temporal resolution is in variance with the results of Fujioka et al (1985) and those of May et al (1988). Would you please comment.
Author: The result I give is the result of a very elementary estimate compared with the calculations employed in the two references quoted. As pointed out by Fujioka et al, the extraction field affects the matter only slightly in a conventional analyser system and it is the field due to the surface geometry of the circuit which is dominant; the finer the geometry, the shorter distance the electron has to travel to escape from the influence of the surface field. For a specimen consisting of parallel conductors with equal conductor widths and spacings, Fujioka et al suggest that the secondaries will have escaped from the surface field at about 6 times the conductor spacing. This is not inconsistent with the assumption I have used and so I believe that my resulting conclusion on temporal resolution is reasonable. As pointed out by May et al, for submicron geometries a transit time of below 2 ps is possible for an extraction field of 100 V/mm.

S.C.J. Garth: You imply that the same material will give rise to the same secondary emission curve. Can you comment on the influence of other factors, e.g. surface roughness, contamination etc, which frequently cause this assumption to be incorrect?
Author: Non-ideal surfaces have always been a problem in voltage-contrast work, though improvements in vacuum systems over the years have reduced the contamination effect. Nevertheless, time-varying contamination is frequently observed and the major effect is that the S-curve changes its magnitude with time. The S-curve also changes its magnitude with surface topography and material and so, if truly quantitative voltage measurements are to be made, it is necessary to employ a system which senses the true shift of the S-curve and not just the magnitude of the video signal as the retarding grid voltage is changed. An algorithm for doing this is described by Nye and Dinnis (1985) and an earlier scheme which detects the shift in the peak of the secondary emission curve by Hannah (1974).

A. Gopinath: One of the perceived problems with magnetic field aided extraction systems with electrostatic energy filtering is that the filtering function, which is crucial to the voltage contrast linearization, is not discussed in any detail. The imaging technique of Plies and Schweizer (1987) is probably an exception to this trend. Could you discuss how the filtering function will be performed in your split lens system? Also, could you comment on the effect of the cyclotron motion on the filtering?
Author: The filtering is at present carried out by a cylindrical retarding grid surrounding the lens structure, as indicated in Fig. 17. The cyclotron motion of the electrons is much reduced in this version and the majority of the electrons approach the grid at a similar angle. The S-curves are now of similar quality to those produced by a conventional flat-grid analyser and are a great improvement over those where the cyclotron motion was present.

J. Phang: In Fig. 15, what are the typical magnitudes of the radial magnetic fields and electrostatic fields?

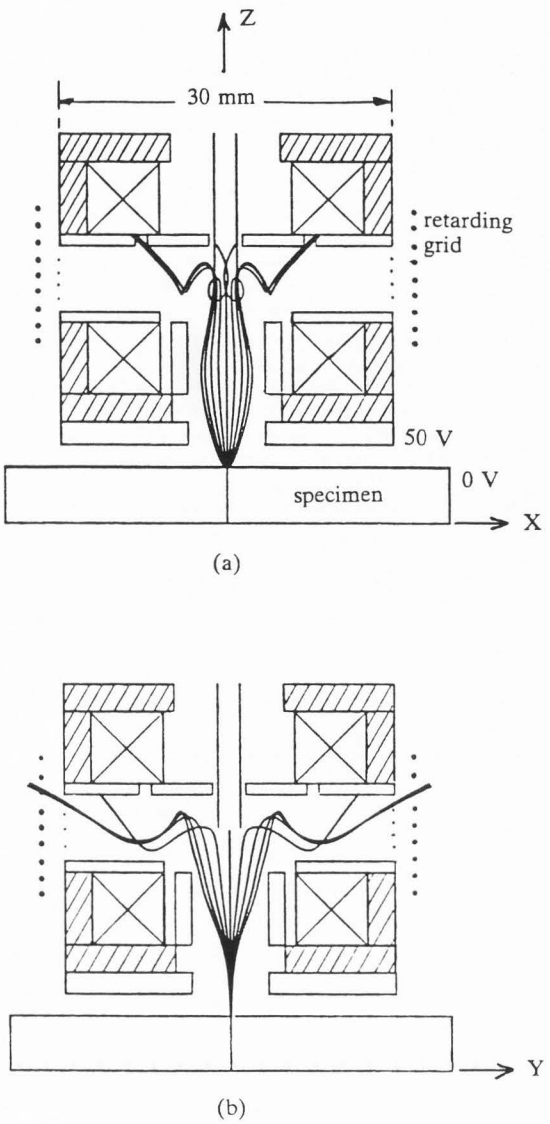

Fig. 17. Layout of lens/analyser an trajectory simulations. (a) Trajectories for 3 eV electrons with initial paths in the X-Z plane and with angles between emission directions in steps of 0.3 rad. (b) The same trajectories as in (a) but viewed in the Y-Z plane.

Author: Computer plots of typical fields are shown in Fig. 18, from which the radial fields at any point may be estimated. The magnetic field outside the body of the lens will be less than that indicated because the computation assumes that the outer boundary of the region shown has infinite permeability.

S.C.J. Garth: What do you use as a secondary electron detector in the system of Fig. 15? Do you need a cylindrical ring of phosphor and a complex light pipe to get the signal to a photomultiplier or is there and easier way?
Author: A 360 degree cylindrical scintillator is a cumbersome solution and has not been pursued. The standard scintillator in the Cambridge S-100 microscope is still being used, but

with suitable guidance electrodes so that about 50% of the electrons passing through the retarding grid reach the scintillator.

A.Gopinath: This paper has briefly mentioned optical sampling of voltage waveforms using ultra-short optical pulses. Would the author comment on the pros and cons of this technique as against the electron beam probe sampling technique for very fast risetime waveform measurement in both GaAs and Si circuits.

Author: The use of very short optical pulses to directly stimulate conduction processes in GaAs or to stimulate photoemission from the surface of devices can be very valuable in investigation of individual high-frequency devices. However, for the probing of circuits of a significant degree of complexity and with very small geometries, the electron beam probe has the advantages of high spatial resolution and flexibility, particularly in the case where a laser-pulsed photocathode is used (May et al 1988).

J. Phang: Please comment on the performance of the various detectors in terms of accuracy, local field effect errors and collection efficiency.

Author: It is very difficult to make objective comparisons between different detectors as complete information on their precise structure, conditions of use and type of specimen used is not always available. The fact that a number of these detectors are commercially available also inhibits publication of results unless these are indisputable. However, it would certainly be valuable to produce the results of computer simulations of the various broad types of analysers and it is our intention to do this in due course.

There is unlikely to be a detector which is the best in all possible circumstances, and this situation is likely to persist. Particular detectors will be designed for the requirements of different users, or classes of users; for instance, some users require moderate resolution over a large area of the specimen, while others may require the ultimate spatial and voltage resolution but over a small area of the specimen.

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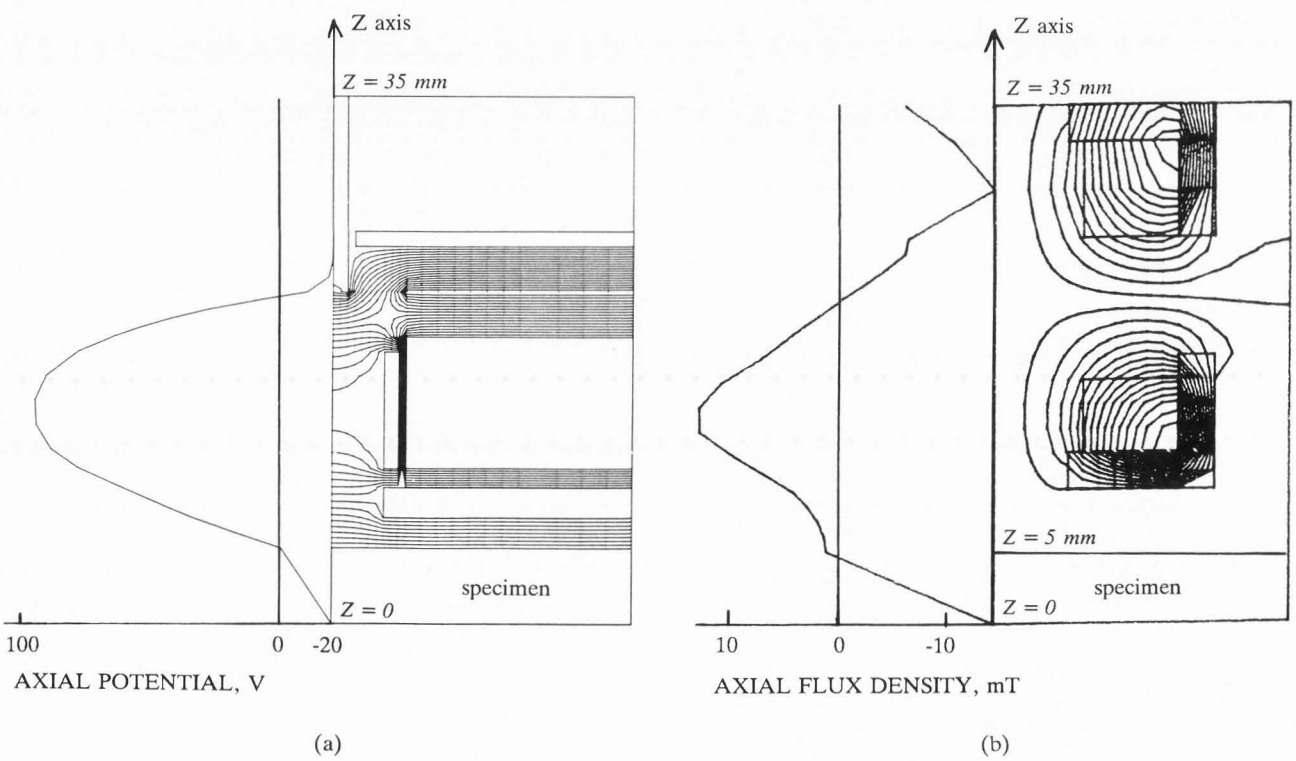

Fig. 18. Typical fields in the detector of Fig. 15. (a) Right of Z axis: equipotential plot of electric field. Left of Z axis: plot of potential magnitude on Z axis. (b) Right of Z axis: plot of magnetic flux lines. Left of Z axis: plot of magnitude of axial flux density. The discontinuities in the slope of the latter curve are due to the relatively coarse finite-element mesh size used in this instance.