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Review: Image Contrast in the Scanning Electron Microscope

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Already the scanning electron microscope is used extensively in the fields of materials science and the life sciences, but it is still being rapidly developed. This paper is an up-to-date review of the types of contrast that can be detected and of the mechanisms that give rise to them. The effect of the type of collector and display system used is discussed together with the possibility of improving the images to show enhanced contrast.

1. Introduction

Although the scanning electron microscope has rapidly developed into a powerful and extremely versatile tool that has significantly expanded the field of microscopy, there has not been an accompanying development in our detailed knowledge as to how contrast arises in the instrument. The wide range of use of the scanning electron microscope can be readily seen by studying the proceedings of the annual symposia on scanning electron microscopy held at the Illinois Institute of Technology Research Institute [1, 2]. A comprehensive review of the subject was published in 1965 by Oatley, Nixon, and Pease [3] but the subject has rapidly expanded in the meantime. A more recent review has since been written by Nixon [4].

The basic action of the scanning electron microscope is that a highly focused electron beam is scanned over the surface of an object and the interaction of the beam with the material excites simultaneously a number of physical processes. Variations in the magnitude of any of these excitations may be converted by suitable transducers to corresponding variations in an electrical signal which is used to control a display. The result is an image of the specimen containing information about the spatial variation across the specimen surface of the efficiency of the interaction processes excited.

It is the discernible difference between neighbouring regions of the displayed image that is the contrast we observe. This contrast has been defined by Everhart [5], but there is little to be gained at the present time in using a quantitative approach to contrast formation, in a review, as there is little quantitative information available on the mechanisms operating that give rise to the observed contrast.

As the contrast observed by the operator of the microscope is seen on a display, the actual observed contrast depends on five main factors. Firstly it depends on the nature of the specimen, secondly on the type of interaction being detected between the specimen and the electron beam probe, and thirdly on the number of electrons incident on each picture element of the surface. The two further factors are the characteristics of the transducer or collector system and of the display system. Their effect on the contrast observed is described in section 14.

The interaction of the electron beam with the specimen is complex and gives rise to many different detectable types of signal. Each type of signal may be used to display an image of the specimen and each may be used as a basis for a different mode of operation of the instrument. In the following section the main modes of operation of the scanning electron microscope are briefly described. In succeeding sections individual contrast mechanisms are described.

2. Operational Modes of the Scanning Electron Microscope

2.1. The Emissive Mode

When the microscope is operated in the emissive mode, the electrons emitted from the specimen surface are collected and after amplifica-

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*At present on leave of absence at the Cavendish Laboratory, Cambridge tion the current is used to form an image. Fig. 1 shows the energy distribution of the emitted electrons from a surface that is being bombarded by electrons of energy E_0. (The exact shape of the distribution depends on the type of specimen.) There are two important features of this distribution. Firstly, there is a peak at low energies. Electrons with such energies are referred to as secondary emitted electrons and are arbitrarily defined as having energies between 0 and 50 electron volts. The second feature of the distribution is the narrow peak near to the primary beam energy. These electrons are referred to as back-scattered electrons and are the result of large angle scattering of the primary electrons.

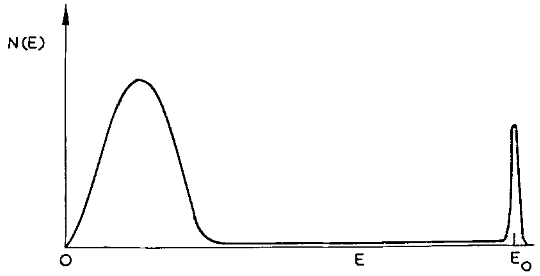


Figure 1 A sketch showing the number of electrons $N(E)$ emitted with energy E from a target on which a beam of electrons of energy E_0 is incident.

The back-scattered electrons give information about the elemental constituents of the specimen and its surface topography. The secondary electrons give information about the topography of the specimen and about the presence of electric and magnetic fields near to the specimen surface.

By using a suitable collector arrangement so as to detect only the back-scattered electrons an image may be formed. When such an image is displayed the microscope is said by some workers to be operated in the reflective mode.

The very recent publication by MacDonald [6] on Auger electron spectroscopy in the scanning electron microscope indicates that it will soon be possible to form an image of a specimen using the Auger electrons only. Auger electrons are electrons that are emitted with energies characteristic of the emitting atom [7, 8], and hence can be used to identify the atom. Although Auger electron analysis has developed rapidly to a stage where it is possible to identify surface elements and has demonstrated a sensitivity to fractional monolayer coverage [9], it has been restricted to large areas (≥ 1 mm^2). MacDonald's work shows that this highly sensitive analysis can be extended to a microscopic technique with a sub-micron resolution. Such a microscopic analysis technique will provide an extremely powerful extension to our knowledge of surfaces and to the value of the scanning electron microscope.

2.2. The Absorbed Current Mode

If the specimen is isolated from earth potential by an amplifier, the current flowing from the specimen to earth can be amplified and used to form an image of the specimen. The microscope is then operated in the absorbed current mode. The absorbed current may be accounted for in the following way. If the current in the primary beam is I_b and the total current emitted by the specimen is I_e, then in order that Kirchoff's Law is satisfied, so that no current build up takes place, a current of magnitude $I_b - I_e$ must flow through the specimen to earth.

2.3. The Beam-Induced Conductivity Mode

To operate the instrument in the beam-induced conductivity mode electrical leads are connected to the specimen and a voltage applied. The current flowing is then used as the detected signal. The interaction of the electron beam with the specimen produces additional charge carriers within the specimen. This causes changes in the local conductivity and thus gives differences in the current flowing through the attached leads. This mode is especially suitable for examining semiconductor specimens.

2.4. The Cathodoluminescent Mode

Certain materials are cathodoluminescent, i.e. they emit light on electron irradiation. When such specimens are examined the light emitted can be collected and a signal formed using a photo-multiplier. Either all the light may be collected irrespective of wavelength or particular wavelengths may be selected using a monochromator.

2.5. The X-ray Mode

If instead of collecting the light emitted by materials when irradiated with electrons, the X-radiation is collected, an image may be formed in a similar way. This image contains information about the elemental constituents of the specimen. This mode is the basis of the electron probe X-ray micro-analyser technique and will not be discussed further in this review.

2.6. The Transmission Mode

In contrast to the other modes of operation of the scanning electron microscope, only thin foils of material can be used in the transmission mode. This is because only those electrons that completely penetrate the specimen are collected and provide an image-forming signal.

3. Contrast Resulting from Surface Topography

The most important factor affecting the number of electrons collected from a surface is the variation in the angle between the incident electron beam and the local normal to the surface of the specimen. This effect was first investigated for back-scattered electrons by McMullan [10]. Everhart [5] carried out similar experiments to study the effect of surface orientation on the secondary electron yield. His results show that the number of secondary electrons emitted is sensitively dependent on the orientation, particularly for incidence angles around 45°. An example of this effect is seen in fig. 2, where the orientations of the fractured ends of the fibres are at different angles to the beam. Those fibres whose ends are inclined at the greatest angles to the direction of the electron beam appear brightest. (The view of the specimen in the micrographs is that which the observer would see if he were looking at the specimen along the incident electron beam.)

Figure 2 The fracture surface of a copper matrix-tungsten fibre composite. The brightness of the fractured fibres depends on their inclination to the electron beam.

The work of both McMullan and Everhart showed that as the angle between the incident beam and the normal to the specimen in the vicinity of the electron beam progressively increases, so does the signal collected increase.

The reason put forward to explain this increase may be summarised as below [11]. As the primary electrons enter the specimen they are scattered and lose energy until they have penetrated into a roughly pear-shaped volume. All along the paths of the primary electrons, secondary electrons are created which will travel in all directions. Some of these travel in the direction of the surface but lose energy as they move, and unless they have sufficient energy on reaching the surface to surmount the surface potential barrier they cannot escape and be collected. According to Bruining [12] the number of electrons N which after travelling a distance x from their point of generation retain sufficient energy to escape from the surface is given by

$$N = N_0 \exp(-\alpha x)$$

where α is a constant. Experimental results [13, 14] suggest that α is greater than 0.01 Å^{-1} and probably greater than 0.05 Å^{-1}. This means that nearly all the secondaries which escape will have originated from within 100 Å, and probably within 50 Å, of the surface.

Using the relationship of Bruining, Everhart [11] has calculated the distribution of the secondary electrons over the surface of the specimen as a function of the distance from the point of entry of the primary electrons and shows that more than half of the secondary electrons are emitted within a distance of 0.5α of the point of entry of the electron beam.

From these results it is possible to see how it is that the number of secondary electrons emitted increases with increasing angle of inclination. It is simply that as this angle increases the length of the primary electron path within 100 Å of the surface increases and so does the number of secondary electrons created which are capable of escaping.

This contrast formation is analogous to the way in which an image is formed in an optical system. Because the mechanisms of contrast formation are analogous, the scanning electron micrographs generally are similar to those obtained in low-powered optical microscopes.

Such similarity is of importance because it enables the scanning electron micrographs to be easily interpreted when the contrast is caused by variations in surface topography.

An interesting result of the penetration of the electrons is that when part of a specimen is thin enough for some of the primary electrons to penetrate through to another part of the specimen and generate further secondaries, a double image may be formed. In fig. 3 red blood cells can be seen through an evaporated carbon film that has separated from the cells in a number of places.

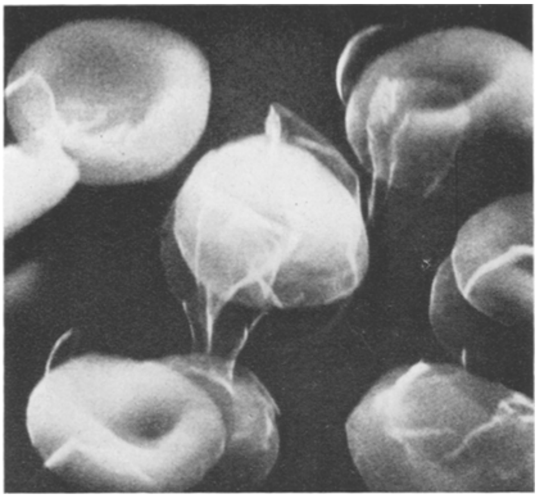
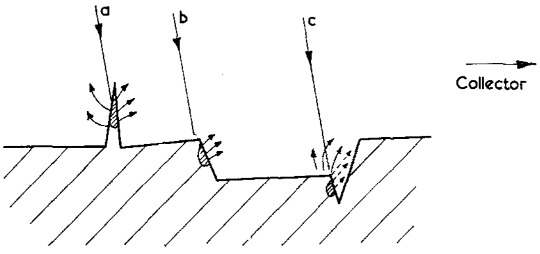


Figure 3 Red blood cells covered by a carbon film. In parts the carbon film has peeled away from the cells and both the film and the cells underneath have been imaged (× 2800).

A second cause of variation in the number of electrons emitted is irregularity in the surface on a scale similar in size to that of the pear-shaped volume penetrated by the primary electron beam. In this case a part of the pear-shaped excitation volume is cut by the specimen surface leading to not only a higher number of back-scattered electrons being collected but also more secondary electrons escaping from the surface. This effect is a maximum when the electron beam impinges on a spherical particle smaller than the penetration volume of the primary electrons. The effect was first described by Everhart [5] and called by him specimen modulation. It is shown schematically in fig. 4 for rays in positions "a" and "b". Specimen modulation can be seen in fig. 2 where the ridges between the fibres and the small circular blobs on the surface of the fibres appear brighter than their immediate neighbourhood.



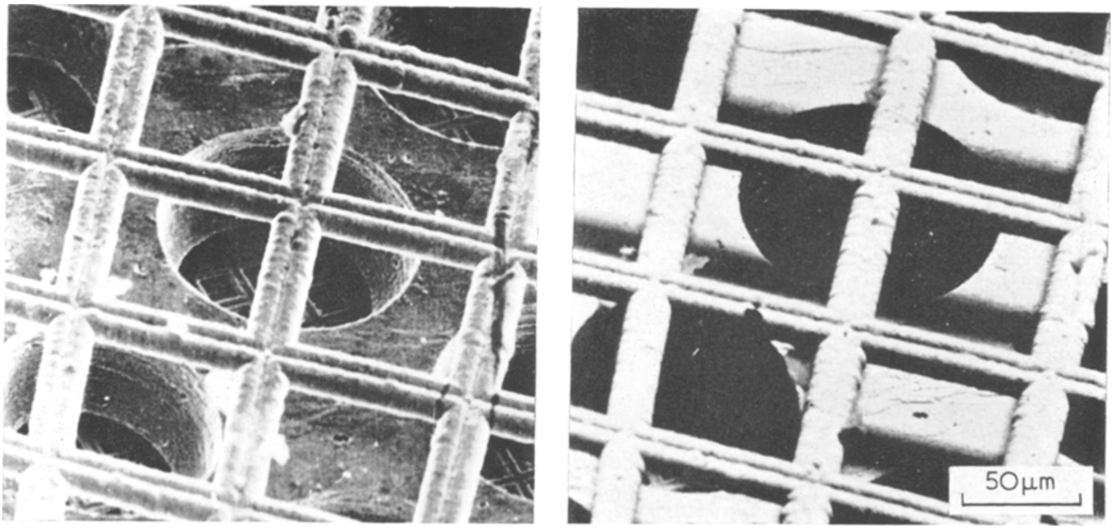
Dotted lines represent electrons collected by specimen and not detected.
Full curved lines represent electrons detected.

Figure 4 Schematic diagram to illustrate specimen modulation and specimen collection. Specimen modulation; when the electron beam is in positions "a" or "b" a large proportion of the secondary electrons formed can escape because the pear-shaped generation volume is exposed by the surface topography. When the electron beam is in position "c" a proportion of the secondary electrons leaving the surface re-enter the specimen before they can reach the collector. This is known as specimen collection.

The electrons giving information about the surface topography can be divided into two groups. The first group of electrons are ones generated close to the entry point of the primary beam and the number generated will depend on the local orientation of the surface to the primary beam. Those in the second group include those which would not have escaped from the specimen if the surface had been plane and not included gross irregularities. In most instances this second group of electrons merely distorts the contrast of the image by highlighting.

At very high magnifications the production of secondary electrons by the back-scattering electrons can reduce the contrast possible in their absence. These secondary electrons are created at points remote from the point of entry of the electron beam and if they are further from the entry point than half the size of a picture element they are effectively a noise signal which blurs the image.

One of the principal advantages of the scanning electron microscope is the ability to image parts of the specimen that are hidden from the line of sight of the collector. This is because the paths of the secondary electrons are determined by the



(a) (b)

Figure 5 Three transmission electron microscope grids lying on one another observed in the emissive mode. In (*a*) both the secondary electrons and the back scattered primary electrons are used to form the picture. In (*b*) only the back scattered primary electrons are used. (By courtesy of S. Kimoto, Japan Electron Optics Laboratory.)

applied electric field from the collector and so the electrons can be drawn round the obstacles. This has the effect of decreasing the contrast by imaging parts that could not be seen in an equivalent optical system, but does increase the total information in the picture. This point is illustrated in figs. 5a and b. Fig. 5a shows three transmission electron microscope grids lying on top of each other and imaged using secondary electrons. Fig. 5b is of the same region but imaged without the secondary electrons and it is noticeable that regions of the specimen hidden from the electron collector, such as the bottom grid, are not imaged.

Not all the secondary electrons emitted are collected by the action of the applied electric field. Some obstacles are so big that a number of emitted secondary electrons re-enter the specimen by collision with the obstacle. This is termed by Everhart [5] as specimen collection and is shown in fig. 4 by the ray in position "c".

4. Atomic Number Contrast

When a flat specimen containing regions of material of different atomic number is examined in the emissive mode contrast exists between those areas of different material. The contrast seen is greater when only the back-scattered electrons are collected than when the secondary electrons are also used to form the image. This was first studied in the scanning electron microscope by Wells [15] who used a smooth section of a composite rod of brass in a duralumin tube. An example of atomic number contrast is shown in fig. 6.

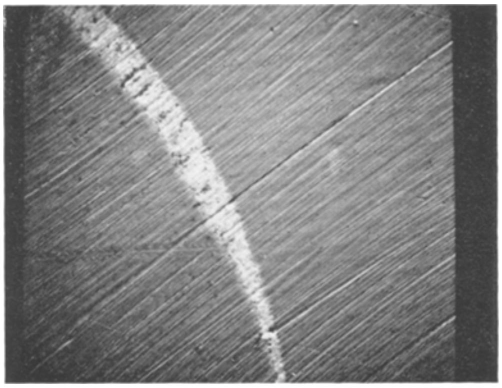
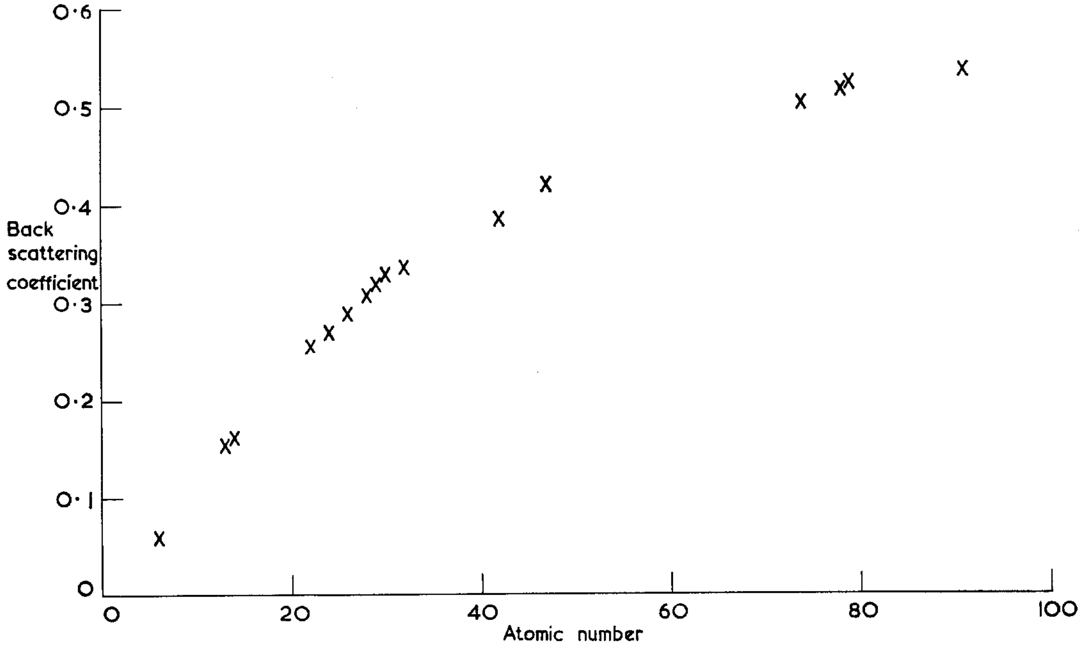


Figure 6 Illustration of atomic number contrast. A view of the soldered boundary between two concentric brass tubes. The soldered joint appears much brighter (× 47).

That the proportion of electrons from the primary beam that are reflected is dependent on the atomic number of the material was suggested by Palluel [16] and Sternglass [17]. The fraction of the number of incident electrons back-scattered, progressively increases with the atomic number, z, of the material, as is shown in fig. 7 using data obtained by Bishop [18]. As an



DATA DUE TO BISHOP [18]

Figure 7 The variation in the back-scattering coefficient of elements as a function of their atomic number at an incident electron energy of 30 keV. (By courtesy of H. Bishop.)

example of the sensitivity of the contrast to atomic number it will be seen that in going from $z = 26$ to $z = 28$ (i.e. from iron to nickel) there is a change of about 7% in the number of electrons back-scattered.

There is a similar relationship, but of a smaller magnitude, between the number of secondary electrons emitted and the atomic number. This explains the observed difference in contrast obtained in flat specimens between the emissive and reflective mode.

When the specimen is not flat then the image contrast observed is that due to surface topography superimposed on the atomic number contrast. As most materials emit more secondary electrons than back-scattered electrons, especially when the material is rough, this means that the atomic number contrast is often concealed by the contrast due to variations in the surface topography.

Although one cannot identify individual elements from the atomic number contrast observed the resolution obtainable is some five to ten times better than when the instrument is operated in the X-ray micro-analysis mode where the resolution is limited to about 1 μm.

5. Voltage and Electric Field Contrast

When specimens which contain areas at different potentials are examined in the scanning electron microscope the contrast seen in the image reveals the presence of the potential distribution over the surface of the specimen. The use of the scanning microscope to investigate variations in potential was first reported by Oatley and Everhart [19]. The contrast can be seen only if the secondary electrons are collected, and generally the lower the potential of a region the greater the number of electrons that are collected [19]. The type of contrast seen from regions at different potential is shown in fig. 19.

Generally it is not possible when observing specimens with areas at different potentials to determine how much of the contrast is due to the potential and how much is due to the disturbance of the trajectory of the secondary electrons by the local fields produced by the applied potentials. The effect of a transverse electric field at the specimen surface will accelerate secondary electrons in a direction parallel to the specimen surface and can cause them to miss the collector completely. The change in the number of secondary electrons collected from regions at different potentials is caused by the discrete shift of their energy distribution relative to the collector potential [5]. As the energy of the back-scattered electrons is much greater than that between neighbouring regions at slightly different potential, the number of back-scattered electrons collected is unaffected by the presence of regions at differing potentials.

It is known that the collected signal increases with increase in collector potential. The exact dependence will vary with specimen inclination and with collector position for a specimen surface at a constant potential. It also depends on the position of the specimen relative to the earthed parts of the specimen chamber. In effect the field between the specimen element and the collector acts as a crude electrostatic velocity analyser. Everhart [5] studied the effect of neighbouring surfaces at differing potentials on the field between the specimen and collector using an electrolytic tank model. His results were peculiar to his instrument as the fields will vary from one type of microscope to another, but they do show the importance of the presence of surfaces at different potentials on the number of secondary electrons collected.

Very little is known about the effect local fields on the specimen have on the collected current, although the contrast arising from very high electric field strengths has been studied [20].

If the present interpretation of voltage contrast is correct then the important factors are the difference in potential between two neighbouring surface elements; this determines the difference in the collected signal, and also determines the effective collector voltage which in turn affects the magnitude of the signal.

Apart from the work by Everhart on an electron trajectory simulation the only other analytical work on voltage contrast has been carried out by Kimoto and Hashimoto [21]. Using a very simple specimen arrangement consisting of two flat copper blocks separated by a narrow gap (50 μm) they have studied the effect of biasing and specimen geometry upon the number of secondary electrons collected. When the voltage between the blocks is increased the number of electrons collected from the positively biased block decreases monotonically at a large rate. However, when the voltage is made more negative the number of electrons collected increases only slightly. The number of electrons from the grounded block similarly changes but the variation is not so large as that from the biased surface. Kimoto and Hashimoto's results are shown in fig. 8. The position of the blocks with respect to the collector was then varied and they showed that whatever the arrangement was, provided that the surface was positively biased, the relationship between the number of electrons collected and the surface potential remained similar. If the surface of one block was grounded

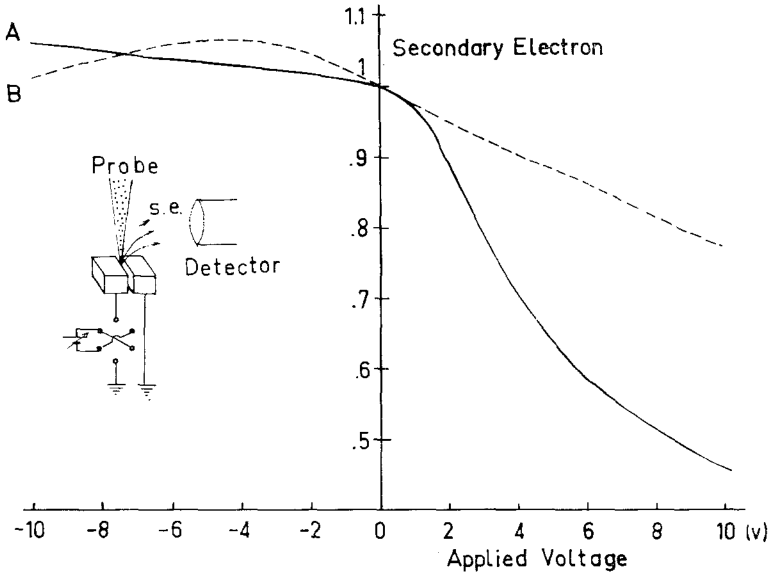


Figure 8 The variation in the number of secondary electrons collected as a function of the applied voltage between two copper blocks. (By courtesy of S. Kimoto, Japan Electron Optics Laboratory.)

and that of the other block negatively biased the relation between the surface potential and the number of electrons collected varied considerably.

The difficulty of separating voltage contrast from surface electric field contrast may soon be overcome by a recent advance. MacDonald [6] has shown that it is possible to measure the potential of a surface without the signal detected being affected by the electric fields at the surface. Instead of collecting all the secondary electrons emitted by the specimen, MacDonald placed an energy selector in front of the electron detector and collected the emitted Auger electrons.

An applied potential on the surface of a specimen causes a shift in the energy of the emitted Auger electrons and the shift increases linearly with the applied voltage. Furthermore the shift is insensitive to transverse electric fields on the specimen. The comparison of a linear dependence on applied voltage with the curves obtained by Everhart, and Kimoto and Hashimoto demonstrates how useful the technique could become. A further advantage over the normal method of observing potential contrast is that it is probably capable of a higher spatial resolution. In the normal method one relies on having an observable difference between the number of electrons collected from neighbouring regions, whereas in the emitted Auger electron mode, each Auger electron gives information about the surface potential because each Auger electron's energy is shifted. Altogether the technique of Auger electron spectroscopy in the scanning microscope offers many advantages for voltage measurement and fault finding in the study and testing of electronic devices.

6. Magnetic Contrast

The presence of magnetic fields on the surface of specimens may be detected [22-26] when the scanning electron microscope is operated in the emissive mode.

The contrast is sensitive to the voltage applied to the collector; if too little is applied no contrast is observed. If no voltage at all is applied, i.e. the instrument is operated to collect only the backscattered electrons, then again no contrast is seen. In addition, no contrast is observed when the absorbed current mode is used rather than the emissive mode. This suggests that the magnetic field variations do not have an effect on the total number of secondary electrons produced; the contrast is therefore due to variations in the number of electrons reaching the collector from different parts of the specimen. This is confirmed by the fact that the contrast seen can be improved by placing apertures in front of the collector.

When the secondary electrons leave the surface of the specimen they pass through a region of strong magnetic field and are deflected in the field by the Lorentz force. As the field varies over the specimen surface the secondary electrons which have been created at different parts of the surface are deflected by different amounts and in different directions.

No magnetic contrast would arise if the electron detector collected all the electrons emitted irrespective of the deflection they had suffered in passing through the surface demagnetising fields. Contrast can only occur when some of the electrons have been deflected sufficiently by the Lorentz force not to enter the collector. This is the reason why the contrast seen from magnetic specimens can be increased (albeit by reducing the total signal level) by aperturing the collector.

The best resolution reported to date is of the order of 1 micrometre [22]. It is thought that superior resolutions are limited by the astigmatism of the primary beam caused by the magnetisation of the specimen. An example of a cobalt foil showing magnetic contrast in the scanning electron microscope is shown in fig. 9.

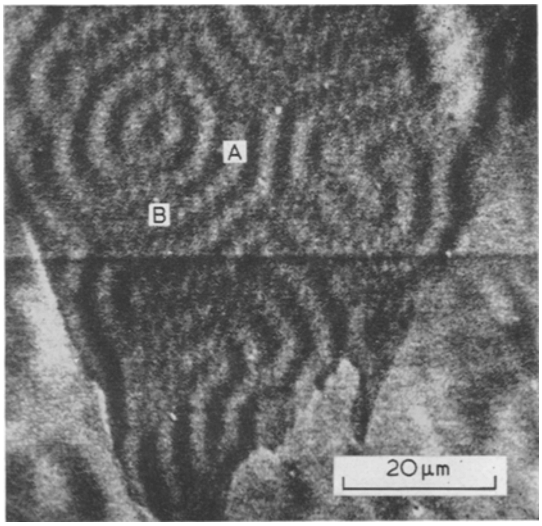


Figure 9 Single crystal cobalt foil showing magnetic contrast due to internal domains (at A) and surface domains (at B). (By courtesy of D. C. Joy.)

7. Beam-Induced Conductivity Contrast

The basic principle of the beam-induced conductivity mode operation of the instrument, as outlined in an earlier section, is that as the electron beam is scanned over the surface of a specimen, across which a voltage is applied, the resulting current through the specimen is used to form an image; contrast arises if there are variations in the resulting current. The mode of operation is limited mainly to semiconductor materials.

On an atomic scale the action of the electron beam is to excite atoms in the material so that electrons in the valence band receive sufficient energy to be raised to the conduction band. Under the influence of the applied electric field both the newly created current carriers, the electron just promoted to the conduction band and the hole in the valence band, move. This movement is a current induced by the electron beam. The current is detected by a suitable circuit and amplified to form the image.

There are two particular types of electrically active defect. The first is the recombination centre, which may be a vacancy, a small defect, or an impurity. They exist in large numbers, even in the purest of semiconductors and cannot be resolved individually because they are too small. Their effect is observed however in the scanning electron microscope as an averaged lifetime for the specimen. If they are not distributed homogeneously throughout the specimen then their variation will affect the induced current that will flow. The second type of defect is the dislocation which has long been known to enhance the recombination of electrons or holes in semiconductors [27, 28].

The main type of defect to be observed has been the edge dislocation in doped silicon and germanium [29-34]. Whether the contrast is due solely to the space charge of the dislocation has been doubted and recent work [35] has shown that impurity atom segregation at dislocations can cause contrast in the beam-induced conductivity mode image. In fig. 10 crystallographic defects can be seen in a silicon specimen imaged in the conductivity mode.

The regions of interest in most semiconductor devices are the junction region and the depletion regions, and it is in studying these regions that the beam-induced conductivity mode has been used most. This has only been possible because better contrast is achieved in these high field regions. It is only when the electron-hole pairs are created in high fields that the effects of significant differences between lifetimes of electrons can be seen.

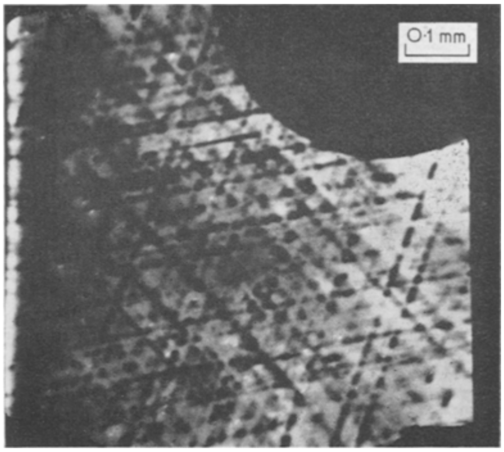


Figure 10 Silicon specimen (n-type, 1 ohm-cm resistivity) showing diffused square, in the conductive mode. Visible are crystallographic defects. Boron impurity of a surface concentration of 5 × 10^{19}. (By courtesy of A.M.B. Shaw.)

8. Crystallographic Orientation Contrast

The previous sections have described the contrast mechanisms on the basis that the nature of the crystal lattice of the material does not affect the image observed.

The first observation that suggested that the crystallographic orientation of a specimen with respect to the electron beam could affect the contrast observed was made by Duncumb in 1962 during an investigation into X-ray emission from thin foils. In 1965 Shaw, using a scanning electron microscope, looked at a number of single crystal gold films, of thicknesses of 100 to 800 Å, in the emissive mode of the scanning electron microscope [35]. The foil was buckled and the observed image showed dark regions crossing the surface as in fig. 11. Shaw found that the contrast decreased with increasing specimen thickness. The contrast observed was also a function of the tilt of the specimen, which suggested that the contrast was not due to variations in surface topography. The similarity between the image contrast observed and that seen when observing buckled foils in the transmission electron microscope was noted.

In 1967 Coates [36] first reported that orientation contrast could be obtained from bulk specimens in the scanning electron microscope when operated at low magnifications and in either the emissive or absorbed current modes.

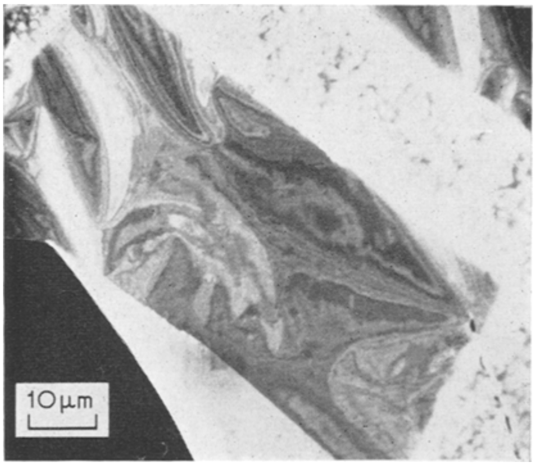


Figure 11 Thin epitaxial gold film in the emissive mode. (By courtesy of A.M.B. Shaw.)

Coates first called the contrast patterns "Kikuchi-like reflection patterns". They have been variously called "Pseudo-Kikuchi orientation patterns" [37, 38] and "scanning electron beam anomalous transmission patterns" [39] but now they are generally referred to as electron channelling patterns. This name can remind one of the mechanism underlying the formation of the patterns.

Published with the original paper by Coates, it was reported by Booker, Shaw, Whelan, and Hirsch [40] that the contrast can be understood in terms of anomalous absorption of the electron beam when incident close to the Bragg angle of the specimen. This model was originally proposed by Hirsch, Howie, and Whelan [41], and was used by them to predict an anomalous dependence of X-ray emission from thin foils, which was subsequently verified by Duncumb [42].

The model may be described as follows: When an electron beam is directed at a single crystal at an angle so that the beam is diffracted strongly in one direction only, then the electrons in the crystal can be described by the sum of two Bloch wave functions. One of these wave functions (the type I wave) has its nodes at the atomic positions in the lattice, and the other (the type II wave) has its antinodes at the atomic positions. As the wave functions describe the probability that the electron has of being at a particular position, the type II wave has the greater probability of interacting with the positive ions of the crystal lattice and hence losing energy. This means that the type II wave is more likely to be absorbed. The relative proportions of the two waves excited depends on the deviation (s) of the incident beam direction from the exact Bragg position, i.e. the angle which the beam makes with the Bragg reflecting planes. When $s > 0$ the wave with minima at the atomic positions is excited preferentially, while when $s < 0$ the wave with maxima at the atomic positions is preferentially excited. So for the transmission of electrons through thin foils there is enhanced transmission when $s > 0$ and reduced transmission when $s < 0$. This is the cause of the bend extinction contours seen when buckled foils are observed in transmission, where the incident angle of the beam to the foil effectively varies; the result is a series of dark regions with $s < 0$, adjacent to bright regions of anomalous transmission with $s > 0$.

The situation is similar where contrast is observed from buckled thin gold films in the scanning electron microscope [35]. In the regions where $s < 0$ there will be a larger proportion of type II wave excited. This means that there will be a greater probability of high-angle back-scattering events occurring when $s < 0$, which will in turn produce a greater number of high-energy back-scattered electrons. In addition there will be a greater probability that secondary electrons will be created and subsequently emitted. Thus the image of the buckled foil will be made up of a series of dark regions where $s > 0$, adjacent to bright regions of anomalous absorption where $s < 0$. This is the reverse of the contrast seen in the transmission electron microscope.

With bulk specimens which have a plane surface the variation in the angle of incidence of the primary beam (twice the Bragg angle) required to produce the channelling patterns, at the operating voltages of the microscope, is quite large and is of the order of 5 to 20 degrees. This variation can only be obtained in commercial instruments by operating at very low magnifications. Whereas the bands are irregularly spaced when thin foils are observed because they are usually bent, the bands are very regular when bulk specimens are examined because the angle of incidence of the beam varies regularly over the specimen and its regular lattice spacing. The geometrical ray diagram for the interaction of the beam with foil and bulk specimens is illustrated in fig. 12.

The contrast obtainable varies with orientation of the specimen but is typically 2 to 8 % when the image is formed with both the back-scattered and the secondary electrons. An example of the

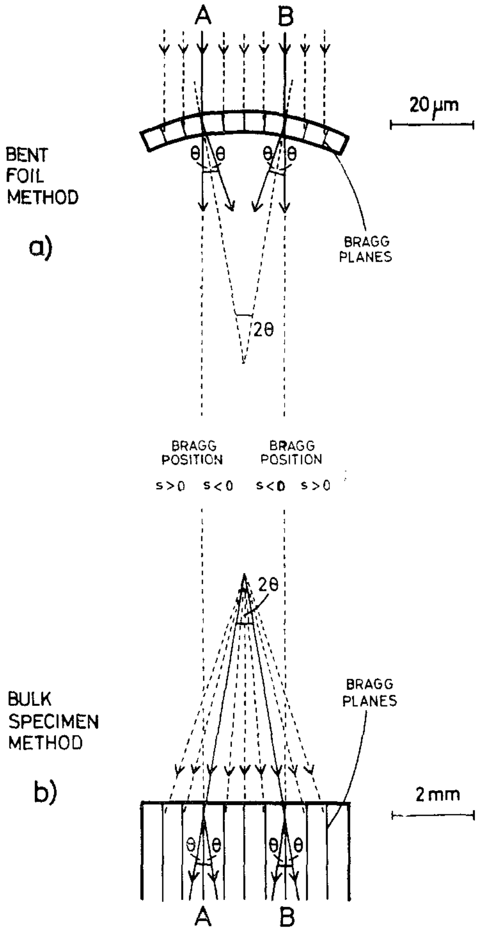


Figure 12 Schematic diagram illustrating the electron beam and specimen geometry under the conditions of electron channelling. (*a*) Bent foil method, (*b*) bulk specimen method. (By courtesy of G. R. Booker.)

contrast seen in channelling patterns is shown in fig. 13. Channelling patterns obtained using the specimen-absorbed current are complementary to those obtained in the emissive mode. (Originally it was thought that they were not but the discrepancy was explained in terms of the different detection and amplification circuits used by different investigators [43].)

The optimum conditions for the generation of the channelling patterns have been discussed in detail by Schulson and Essen [44], but the main requirement for patterns of highest angular resolution is that a compromise is reached between using the smallest possible convergence of the scanning beam and having as high a current in the beam as possible.

The original limitation of the technique for generating channelling patterns was that in the commercial instruments low magnifications had to be used in order that the maximum deflection of the beam be greater than twice the Bragg angle, and that the specimen could not be taken close to the objective lens without drastically limiting the signal collected in the emissive mode. These two difficulties have been overcome by bringing the cross-over point of the double-deflection system of the Stereoscan onto the surface of the specimen [44] and by operating in the specimen current mode. This has made possible the observation of channelling patterns from regions as small as 50 μm across [44]. An alternative way of overcoming the above difficulties has been demonstrated by Coates [37] who mechanically rocks the specimen under a stationary incident beam and uses the specimen current mode.

The determination of the orientation of the crystal from the observed channelling pattern has been described by Schulson [45].

9. Contrast in the Transmission Mode

When all the electrons transmitted by thin foils are collected in the scanning microscope, contrast results for two separate reasons. Firstly, for a homogeneous material and for a constant accelerating voltage of the beam, variation in the thickness of the specimen will cause the number of electrons transmitted to vary; the thicker the specimen the smaller the proportion of the incident beam that will be transmitted. Secondly, the fraction of the beam current that passes through a specimen will depend on the atomic number of the material. Most of the theories on penetration ranges of electrons in materials that have been reported have to be extrapolated to the relatively low accelerating voltage used in the scanning electron microscope. It is only recently that a theory of electron penetration in solids has been put forward [46, 47] which is entirely relevant to the particular case of the scanning microscope. A picture taken in the transmission mode of operation of the scanning electron microscope is presented in fig. 14.

With high-resolution scanning transmission electron microscopes an additional contrast has been observed: diffraction contrast [48, 49]. Features such as Fresnel fringes, phase contrast, the imaging of lattice fringes and bend contours (fig. 15) have all been seen. Cowley [49] has shown that such contrast formation can be

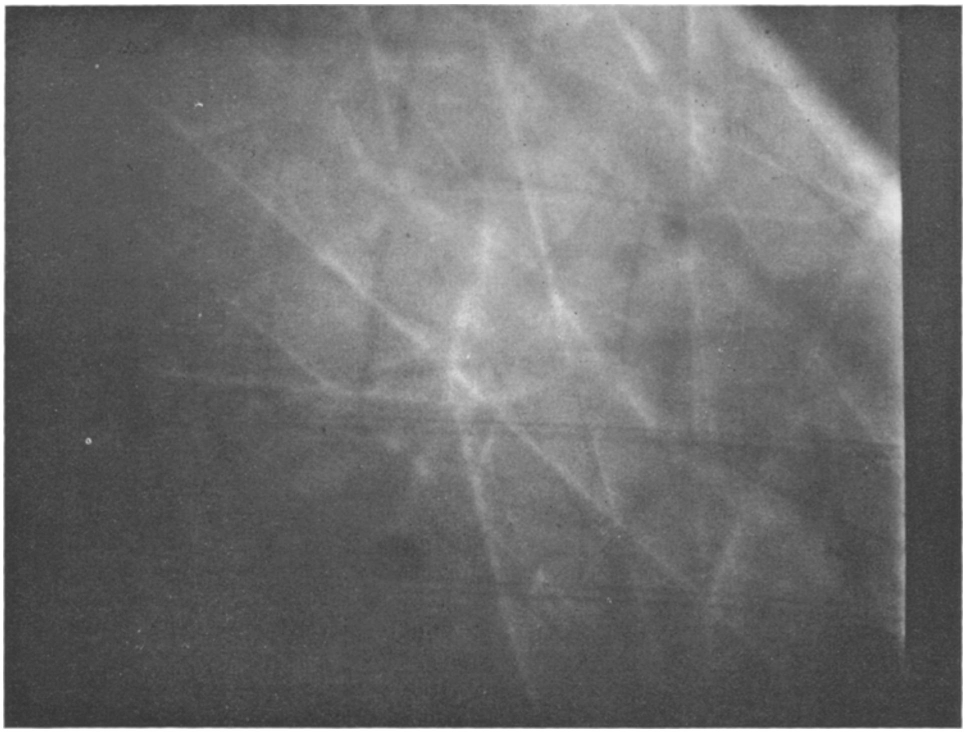


Figure 13 Channelling pattern from a n-type silicon (111) surface (× 24).

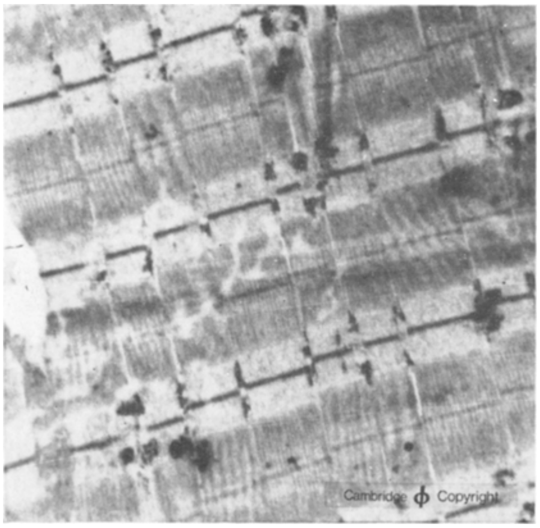


Figure 14 Muscle fibre observed in the transmission mode (0 × 14200). (By courtesy of Cambridge Scientific Instruments Limited.)

understood by comparing the imaging conditions in the scanning transmission microscope to those in a conventional transmission microscope and using the principle of reciprocity.

An alternative approach to just collecting all the transmitted electrons has been used by

Figure 15 Bend contours in electro-polished austenitic stainless steel observed in the transmission mode (× 64) (By courtesy of Cambridge Scientific Instruments Limited).

Hashimoto and Kimoto [50]. They have made use of the fact that the transmitted electrons can be divided into two groups; ones that penetrate the specimen without being scattered, and the rest that suffer one or more scattering events. Kimoto and Hashimoto separate the two groups by using a circular aperture between the specimen and the detector to pass the unscattered electrons, or an annular aperture to pass the scattered electrons. Using the terminology of conventional transmission electron microscopy the two images obtained are known as the bright field and dark field images.

The main feature of the image obtained in the scanning transmission microscope is that for a given specimen thickness the image has a higher contrast and brightness than that obtained in the conventional transmission microscope at the same accelerating voltage. It is also possible to image thicker specimens. There are two reasons for this image improvement. Firstly the detector acts as a built-in image intensifier and secondly it is possible, electronically, to subtract from the image the constant background intensity so that low contrast levels can be seen more easily.

An alternative method of obtaining additional contrast has been demonstrated by Crewe [51]. He placed an energy analyser after the specimen to separate the inelastically-scattered electrons from those that had been elastically scattered.

10. Contrast in the Cathodoluminescent Mode

When operating in the cathodoluminescent mode it is usual to collect all the photons emitted irrespective of their wavelength. The contrast seen is then due to the variation in the number of photons detected over the surface. If, however, only those photons of a particular wavelength are collected then contrast exists between areas not emitting and those emitting at the chosen wavelength. By incorporating a monochromator in the detector an optical micro-analysis of materials can be carried out in a manner analogous to the electron probe micro-analyser [52, 53].

The operation of the scanning electron microscope in the cathodoluminescent mode has been described thoroughly by Thornton [54] and the phenomenon of electroluminescence has been described in detail elsewhere [55]. However, it is possible using a simplified approach to the basic processes occurring to understand qualitatively how contrast arises.

The electron beam on interaction with the material excites the lattice and creates electron-hole pairs by impact ionisation of the host lattice or of impurity atoms. The beam-induced carriers then move in the material until they recombine, with the emission of a photon. In order that this radiation is detected it must be emitted from the specimen. Two factors can prevent the photons being detected: total internal reflection at the surface and absorption by the material between the points of creation and emission. The presence of local regions of different composition with associated variations in local rates of recombination and absorption will lead to a consequent contrast being observed. A similar effect is caused by the presence of voids, cracks, contamination and precipitates in the specimen. Defects that affect the rate of recombination of current carriers, such as dislocations, have been expected to give rise to contrast in cathodoluminescent micrographs [54]. However, to date, dislocations and dislocation arrays have been observed because of impurity segregation around the defects [56]. A typical cathodoluminescent micrograph showing a dislocation array is given in fig. 16.

As the energy of the electrons required to excite luminescence is smaller than that required to stimulate the emission of secondary electrons, the effective volume excited (the volume in which sufficient energy can be transferred to excite a transition) in the cathodoluminescent mode is larger than that for the emissive mode at constant beam voltage. Thus the resolution of cathodo-

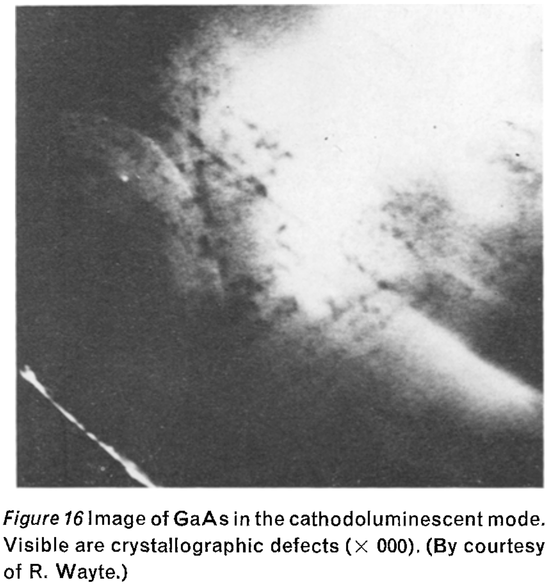


Figure 16 Image of GaAs in the cathodoluminescent mode. Visible are crystallographic defects (× 000). (By courtesy of R. Wayte.)

luminescent images is poorer than those obtained in the emissive mode.

11. Contrast due to Temperature Variation

An additional contrast that has been suggested to occur is that due to local variations in temperature. Thornton has reported [57] that in the beam conductivity mode contrast can be seen between regions of surface and this may be due to differences in temperature which were known to exist. No explanation has yet been proposed as to the cause of this form of contrast.

Temperature has very little effect on the secondary electron emission yield of metals and a decrease of 5% for germanium between 20 and 600° C is the largest reported [58]. In insulators the change is slightly larger. Dekker [59] has shown that the mean escape distance of secondary electrons in a material is inversely proportional to the square root of the absolute temperature of the material. Thornton has stated [54] that if sufficient care is taken with surface preparation the observed secondary electron emission can be fitted approximately to Dekker's theory.

12. Contrast Caused by Specimen Irradiation

Another recently-observed contrast is not yet understood qualitatively. It has been observed that if part of certain insulators such as glass and diamond are exposed to a low-pressure glow discharge or to an electron beam irradiation the electron emission can be altered [60]. The way in which the emission is altered depends on the type of gas in which the discharge occurs. In the particular cases of soda-lime glass and silicon if the discharge is made in oxygen or air the emission is enhanced; if the gas is nitrogen or hydrogen the emission is decreased. An example of the contrast observed can be seen in fig. 17 from an uncoated diamond that received no treatment prior to examination in the scanning electron microscope. Immediately after putting the diamond in the microscope it looked evenly dark but after a few minutes the contrast in fig. 17 developed, and was thus caused by the

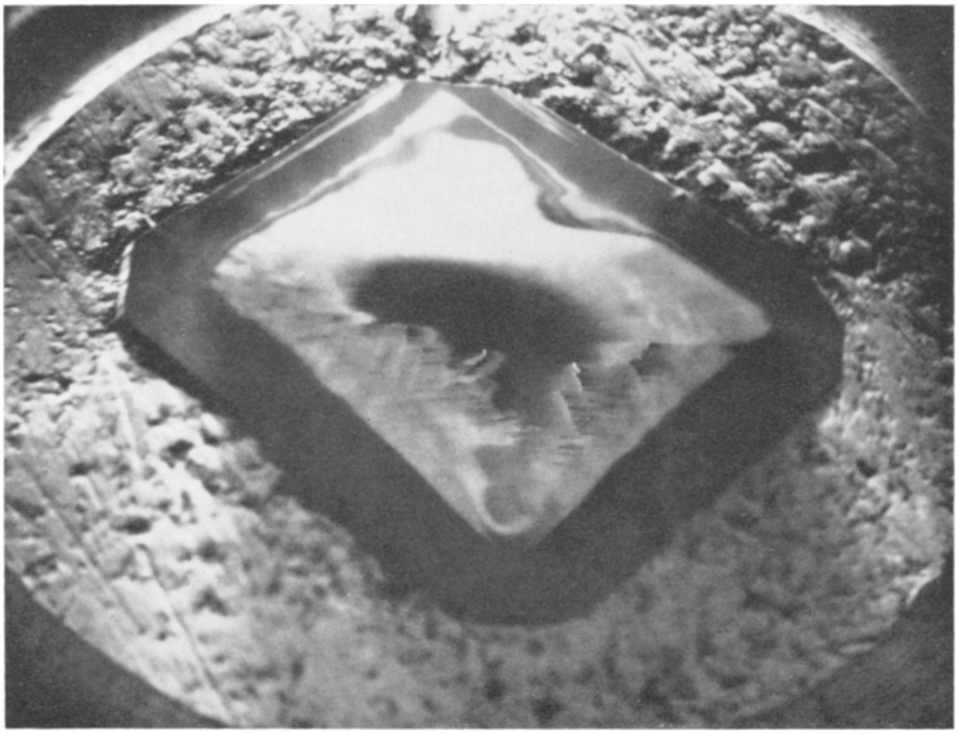


Figure 17 Diamond, embedded in conducting resin, after being under the electron beam for a number of minutes. At first the diamond was evenly dark but after exposure to the electron beam of the scanning microscope the bright contours and regions formed (× 35).

electron beam. As all areas of the diamond received an equal number of electrons the contrast must have been due to a variation in the susceptibility of the diamond to irradiation. It is perhaps noteworthy that the edges of the diamond do not display an increased brightness.

13. Anomalous Contrast Formation

In the normal operation of the scanning electron microscope, the irradiations excited by the interaction of the electron beam with the specimen are detected. In very rare circumstances the electron beam of the microscope can be deflected into the electron collector and give an image of the Faraday cage of the collector. The first reported instance of this occurrence is due to Everhart [5]. He was trying to detect magnetic field contrast by placing a magnet under the electron beam. At sufficiently high magnetic field strengths the electron beam was deflected into the collector and gave an image of the wire mesh of the collector. More recently Clarke and Stuart [61] have shown that certain insulating materials can charge up sufficiently for local regions of the surface to act as an electron mirror and deflect the electron beam into the collector. They have also described the conditions under which the surface can act as an electron mirror. At high magnifications details of the surface of the electron collector can be clearly seen. The image observed can be seen in fig. 18. In addition to the image of the collector, which may take up a variety of contorted shapes and lead to misinterpretation of the picture, the image formed of the surface can be very distorted due to the uneven charging of the surface.

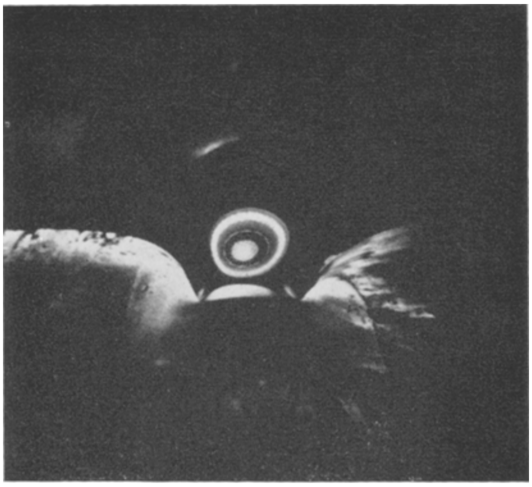


Figure 18 Anomalous contrast effect. The circular object in the centre of the picture is an image of the electron collector of the microscope. Below and to both sides is a distorted image of a straight, sharp edge of a MgO crystal. Picture formed using secondary electrons with a primary beam energy of 3 keV. (General field of view × 11).

14. Contrast Enhancement by Improvements of the Collector and Display Systems

14.1. Improvements in the Collector System

Although the contrast obtained from surfaces in the emissive mode is partly directionally dependent, the commonly used detector systems are insensitive to such directionality. As was pointed out in an earlier section surface electric and magnetic fields will deflect the secondary electrons emitted by the surface and thus will impose some preferred directionality to the electron trajectories. Also the emission may be anisotropic or modified by the inclination of the local surface to the electron beam.

Two directional detectors have been described [62, 63] in which the small directional content of the observed contrast is enhanced. In the detector arrangement of Banbury and Nixon [62] the conventional Thornley-Everhart collector is combined with an additional electrode structure that surrounds the specimen. The structure is made up of several electrodes that may be individually biased to different potentials. The voltages applied to the electrodes produce electrostatic fields and these control the trajectories of the secondary electrons. In this way the electrons that have a preferred directionality can be detected with a greater sensitivity. A less sophisticated detector in which the specimen is almost completely surrounded by a single apertured electrode has been shown by Speth [63] to display enhanced magnetic contrast. His detector could probably also give enhanced voltage contrast from electronic devices but there is no report of such a use.

14.2. Improvements in Display Systems

As with the improvements to the collector system, the display system cannot of course add true contrast to the image seen but it can display the contrast so that the user of the instrument can more easily perceive small variations in signal.

In the conventional arrangement the output of the collector-detector system is used to modulate the intensity of an electron beam in a CRT, so that the variation in signal from the specimen is shown as a variation in brightness on the screen of a display CRT. The contrast observed relies on the differences in brightness seen on the face of a CRT and the number of levels distinguishable to the eye is limited. In addition, the relationship between these "shades of grey" or distinguishable levels is purely qualitative. The advantage of this type of display is that it gives a picture that is similar to that obtained using an optical microscope or a television camera, and thus easily interpreted.

A number of attempts have been made to display the image so that the contrast between two picture elements can be seen quantitatively. The earliest attempt [64-66] is now known as scan modulation display or y-modulation display. The signal from the detector is displayed by deflecting the beam in a CRT in the vertical direction a distance proportional to the amplitude of the signal. The image observed is now of constant brightness but with the variation of the line from a straight line giving a measure of the strength of the original signal. The main disadvantage of the scan modulated display is that if measurements are to be taken from the micrograph then the scan lines must not overlap. This means that the number of lines used to form the picture is limited, which in turn limits the amount of information that can be displayed at any one time.

A rather different approach to the problem of displaying the microscope signal so that changes in signal may be easily seen has been made by Flemming [67]. He uses a coding circuit between the detector circuits and the display that takes a series of measurements of the signal averaged over a small area as the beam is scanned over the specimen. The circuit can not only generate the normal intensity modulated display but also the signal as a quantised intensity-modulated picture. It is also possible to show the signal as a contour map in which the regions between the contour lines are intensity-modulated. Examples of these different forms of display of the same region are shown in figs. 19 and 20. It can be readily seen that figs. 21 and 22 display far more contrast and hence useful information than the usual displays of figs. 19 and 20. Although Flemming originally developed the circuit for a low-energy electron beam scanning instrument, he has outlined a method of overcoming the higher noise levels in the SEM and has demonstrated its applicability to the SEM [68].

15. Contrast Separation

Unless an energy analyser, such as a monochromator or spectrometer, is used to collect the irradiation emitted by the specimen it is not possible, under normal operating procedure, to select the type of contrast that is being observed. Such a departure from the usual operating methods has been used by Oatley [69] to separate voltage contrast from other forms of contrast. The basis of the operation that he suggested is to chop the electron beam and apply the necessary bias to the device under observation in synchronism with the pulses of electrons arriving at the device. The signal is collected and amplified with the normal system but the output is fed to two electronic gates in parallel rather than directly to the display. The gates are opened alternately at the instants that the electron beam is pulsed. The output of both gates is fed via a differential amplifier to a display system. The collected signal is made up of a series of rectangular pulses of two heights, one resulting from all the contrast mechanisms operating and the other from all the contrast mechanisms minus the voltage contrast. The function of the parallel gates and the differential amplifier is to subtract the pulses of differing heights and give an output that corresponds to only the voltage contrast mechanism operating.

16. Improvement in Contrast by Image Processing

The image of the scanning electron microscope is particularly suited to treatment because the information obtained is in a serial form and is an electronic signal.

The earliest techniques used were to vary the characteristics of the amplification of the detected signal, for instance logarithmic amplification [70], and the subtraction of the constant background intensity [70]. A later technique, applied first to channelling patterns, was to display not the signal but a differentiated form [43]. These methods are all intended to render low contrast more visible and so making the image more useful.

A more recent suggestion [71] has been to remove from the image some of the effects due to the fact that the electron beam is of a finite size. The way in which this can be done is to take the Fourier transform of the image, divide by the Fourier transform of the scanning beam spot and yield the improved picture by the Fourier transformation of the result. These operations can be

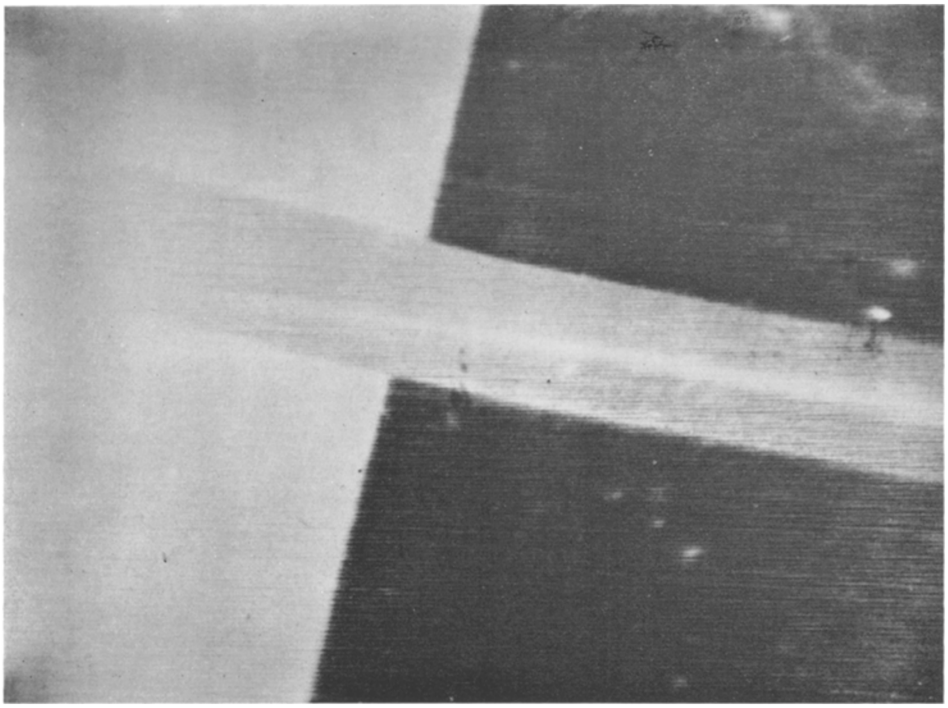


Figure 19 Intensity-modulated display of a potential distribution. (By courtesy of J. P. Flemming, Standard Telecommunication Laboratories.)

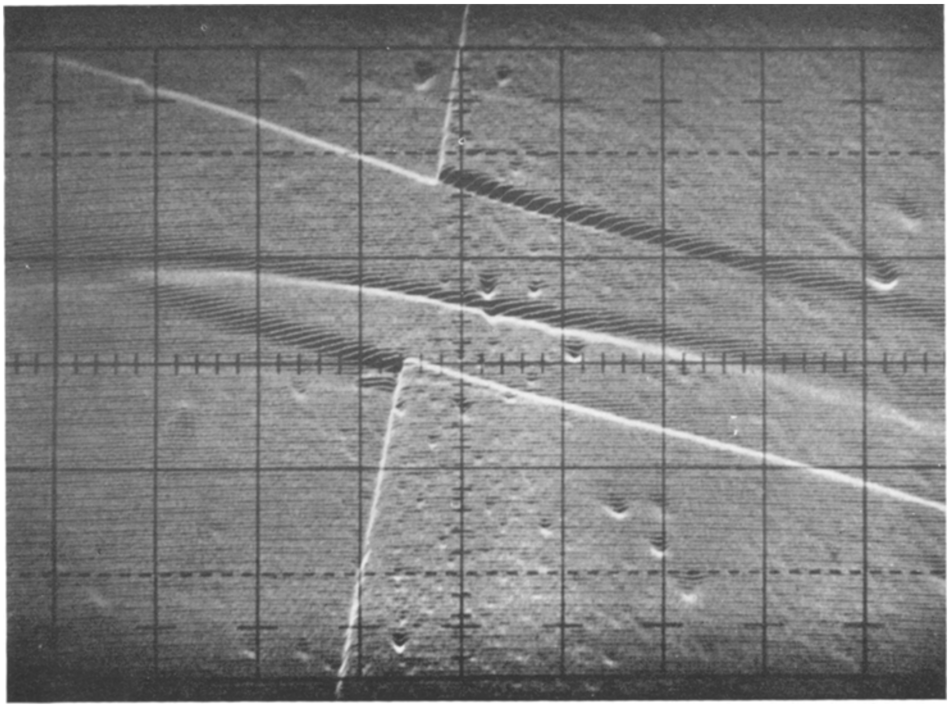


Figure 20 Deflection ('z')-modulated display of the same distribution. (By courtesy of J. P. Flemming, Standard Telecommunication Laboratories.)

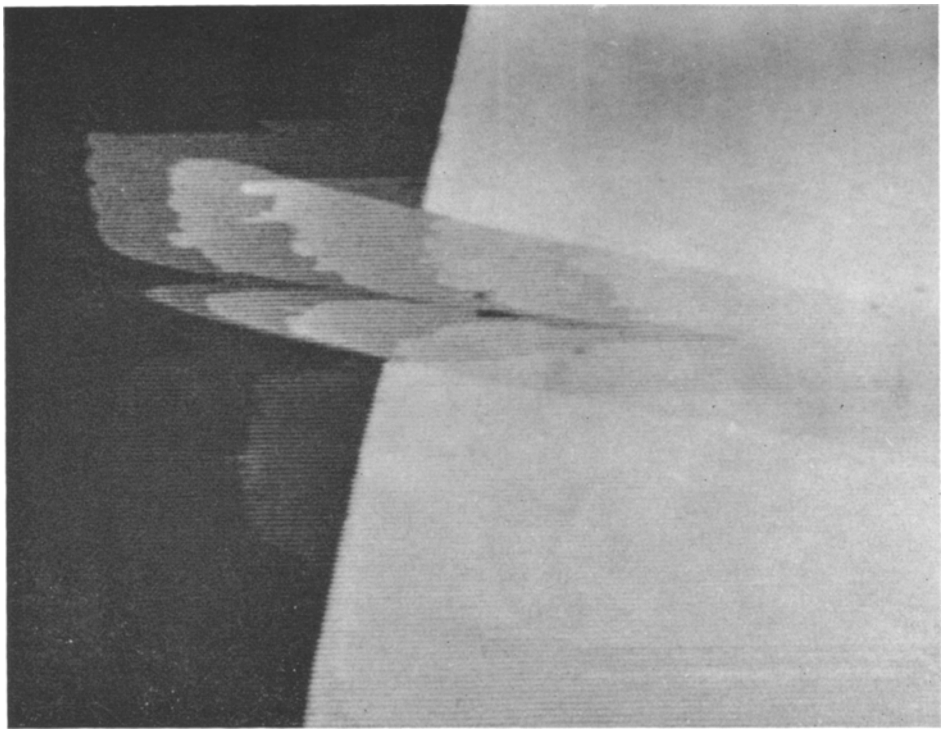


Figure 21 Quantised intensity-modulated display of the same potential distribution. (By courtesy of J. P. Flemming, Standard Telecommunication Laboratories.)

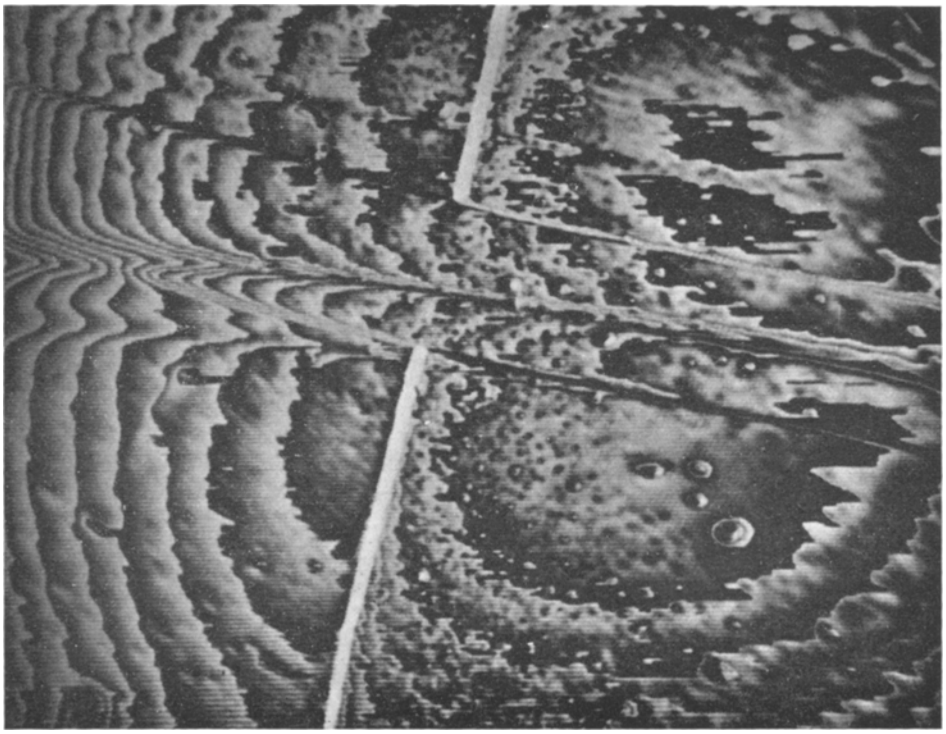


Figure 22 Contoured display of the same distribution where the space between the contour lines is intensity modulated. (By courtesy of J. P. Flemming, Standard Telecommunication Laboratories.)

performed numerically after converting the image signal to a digital form. A similar exercise to improve the quality of pictures obtained from transmission micrographs by the removal of effects due to incorrect focusing and chromatic aberrations of the lenses has been carried out by Ericission at the Medical Research Council Laboratories. Using fast Fourier techniques he is able to process pictures in under five minutes. Optical methods may also be used to yield Fourier transforms and to process the image but at present it is more promising to use computational methods.

Simon [72] has recently outlined possible image processing techniques to extract more information and achieve better resolution in the scanning electron microscope. He also defined the requirements of the electronic filters required to process the image. The action of such a passing filter has been simulated by computer processing of sample micrographs and has yielded improved images.

17. Time-Resolved Scanning Microscopy

All the contrast types described above can be detected when the scanning electron microscope is used in the time-independent modes of operation. In practical terms this means that the contrast observed does not change in periods of time long compared with the time required to scan the specimen and display the micrograph.

The development of sub-systems of improved performance for the scanning electron microscope has enabled microscopy of time-varying phenomena in materials to be carried out. The microscope is then referred to as being used in time-resolved scanning electron microscopy.

The first use of time-resolved microscopy was reported by Plows and Nixon [73] who observed the action of a ladder of MOS transistors by a stroboscopic technique of pulsing the primary beam in synchronism with the bias signals applied to the ladder. Their technique is a rather special form of time-resolved scanning microscopy because they were observing a repetitive phenomenon. The advantage of their system is that apart from the necessity of pulsing the primary beam onto the specimen no major modifications are required to the standard instrument.

However, to observe non-repetitive events, much faster detectors and display devices are required with response times shorter than the shortest time difference that is required to be observed. The requirements and design of a scanning electron microscope capable of sub-microsecond time resolution have been discussed and described thoroughly by MacDonald, Robinson, and White [74]. They used their system under computer control and demonstrated its use in the study of the motion of high electric field domains in CdS ultrasonic oscillator diodes and in GaAs Gunn effect diodes.

As yet no new types of contrast have been observed whilst the microscope is used in the time-resolved operation but there has to date been little work done on the subject.

The sophisticated approach to time-resolved scanning electron microscopy by MacDonald *et al.* was necessary because they required to observe changes in the electrical properties of electronic devices where significant changes can occur in nanoseconds or microseconds. Where changes occur in hundredths of seconds it is possible to use existing scanning microscopes with faster detector and display systems. In the study of the mechanical properties of materials, especially multi-component materials, events do occur in hundredths of seconds. Recent work at the National Physical Laboratory by the author [75] has demonstrated that basic fracture processes in composite materials can be observed in a commercially available scanning electron microscope with a faster scanning and display system. The improved scanning system developed at the National Physical Laboratory by Pugh [76] enables cine and video-graphic recording of events occurring to be made. The events can then be analysed by replaying the recordings a frame at a time. As yet no new contrast has been observed but if there are any electrical effects associated with the fracture of certain composite materials, as has been suggested [77, 78], the contrast observed will be affected.

References

1. O. JOHARI (ed.) Proceedings of the First Annual Scanning Electron Microscopy Symposium, Illinois Institute of Technology, 1968.
2. O. JOHARI (ed.) Proceedings of the Second Annual Scanning Electron Microscopy Symposium, Illinois Institute of Technology, 1969.
3. C. W. OATLEY, W. C. NIXON, and R. F. W. PEASE, "Advances in Electronics and Electron Physics" **21** (1965) 181.
4. W. C. NIXON, *Contemp. Phys.* **10** (1969) 71.
5. T. E. EVERHART, Ph.D. Thesis, University of Cambridge.
6. N. C. MACDONALD, *Appl. Phys. Lett.* **16** (1970) 76.

7. P. AUGER, *J. Phys. Radium* **6** (1925) 205.
8. E. H. S. BURHOP, "The Auger Effect and other Radiationless Transitions" (University Press, Cambridge 1952).
9. L. A. HARRIS, *J. Appl. Phys.* **39** (1968) 1419.
10. D. MCMULLAN, Ph.D. Thesis, University of Cambridge.
11. T. E. EVERHART, O. C. WELLS, and C. W. OATLEY, *J. Electronics and Control* **7** (1959) 97.
12. H. BRUINING "Physics and Applications of Secondary Emission" (Pergamon Press, London, 1954).
13. A. BECKER, *Ann. Phys.* **2** (1929) 249.
14. E. J. STERNGLASS and M. M. WACHTEL, *Phys. Rev.* **99** (1955) 646.
15. O. C. WELLS, Ph.D. Thesis, University of Cambridge.
16. P. C. R. PALLUEL, *C.R. Acad. Sci.* **224** (1947) 1492; 1551.
17. E. J. STERNGLASS, *Phys. Rev.* **95** (1954) 345.
18. H. E. BISHOP, Ph.D. Thesis, University of Cambridge.
19. T. E. EVERHART and C. W. OATLEY, *J. Electronics* **2** (1956) 568.
20. G. V. SPIVAK, G. V. SAPARIN, B. MASSARARI, and M. V. BIKOV, Proceedings of the third Regional Conference on Electron Microscopy, Prague, 1964.
21. S. KIMOTO and H. HASHIMOTO, 26th Electron Microscope Society of America Meeting, 1968.
22. D. C. JOY and J. P. JAKUBOVICS, *Phil. Mag.* **17** (1968) 61.
23. *Idem*, *Brit. J. Appl. Phys.* **2** (1969) 1367.
24. J. R. DORSEY, First National Conference on Electron probe micro-analysis, College Park, Maryland, 1966.
25. V. N. VERTSNER, *Bull. Acad. Sci.* (*USSR*) **30** (1966) 806.
26. J. R. BANBURY and W. C. NIXON, *J. Sci. Instr.* **44** (1967) 889.
27. F. KULIN, *Acta. Met.* **2** (1954) 354.
28. W. T. READ, *Phil. Mag.* **45** (1954) 775.
29. J. J. LANDER, H. SCHREIBER, T. M. BUCK, and J. R. MATTHEWS, *Appl. Phys. Lett* **3** (1963) 206.
30. W. CZAJA and G. H. WHEATLEY, *J. Appl. Phys.* **35** (1964) 2782.
31. W. CZAJA and J. R. PATEL, *ibid* **36** (1965) 1476.
32. W. CZAJA, *ibid* **37** (1966) 918.
33. H. F. MATARE and C. W. LAAKSO, *ibid* **40** (1969) 476.
34. *Idem*, *Appl. Phys. Lett.* **13** (1968) 216.
35. A. M. B. SHAW, Ph.D. Thesis, University of Cambridge.
36. D. G. COATES, *Phil. Mag.* **16** (1967) 1179.
37. *Idem*, (1969) in reference 2.
38. E. D. WOLF and T. E. EVERHART, (1969) in reference 2.
39. D. B. HOLT, J. GAVRILOVIC, and M. P. JONES, *J. Mater. Sci.* **3** (1968) 553.
40. G. R. BOOKER, A. M. B. SHAW, M. J. WHELAN, and P. B. HIRSCH, *Phil. Mag.* **16** (1967) 1185.
41. P. B. HIRSCH, A. HOWIE and M. J. WHELAN, *ibid* **7** (1962) 2095.
42. P. DUNCUMB, *ibid* 2101.
43. A. M. B. SHAW, G. R. BOOKER, and D. G. COATES, *J. Sci. Instr.* **2** (1969) 243.
44. E. M. SCHULSON and C. G. VAN ESSEN, *ibid* 247.
45. E. M. SCHULSON, *ibid* 361.
46. V. E. COSSLETT and R. N. THOMAS, *Brit. J. Appl. Phys.* **15** (1964) 883.
47. *Idem, ibid* 1283.
48. A. V. CREWE, (1969) in reference 2.
49. J. M. COWLEY, *Appl. Phys. Lett.* **15** (1969) 58.
50. S. KIMOTO and H. HASHIMOTO, (1968) in reference 1.
51. A. V. CREWE, J. WALL, and L. M. WELTER, *J. Appl. Phys.* **39** (1968) 5861.
52. P. M. WILLIAMS and A. D. YOFFE, *Nature* **221** (1969) 952.
53. *Idem*, *Phil. Mag.* **18** (1968) 555.
54. P. R. THORNTON, "Scanning Electron Microscopy" (Chapman and Hall, London, 1968).
55. *Idem*, "The Physics of Electro-luminescent Devices" (Span, London, 1967).
56. D. A. SHAW and P. R. THORNTON, *J. Mater. Sci.* **3** (1968) 507.
57. P. R. THORNTON, D. V. SULWAY, and D. A. SHAW, *IEEE Trans. Electron Devices* **ED16** (1969) 360.
58. J. B. JOHNSON and K. G. MCKAY, *Phys. Rev.* **93** (1953) 668.
59. A. J. DEKKER, *ibid*, **94** (1954) 1179.
60. D. R. CLARKE, C. T. H. STODDART, and C. J. ROBBIE, *J. Mater. Sci.* **5** (1970) 364.
61. D. R. CLARKE and P. R. STUART, to be published in *J. Sci. Instr.*
62. J. R. BANBURY and W. C. NIXON, *J. Sci. Instr.* **2** (1969) 1055.
63. A. SPETH, *Rev. Sci. Instr.* **40** (1969).
64. T. E. EVERHART, *Proc. IEEE* **54** (1966) 1480.
65. D. B. WITTRY and A. VAN COUVERING, *J. Sci. Instr.* **44** (1967) 294.
66. T. H. P. CHANG and W. C. NIXON, *J. Roy. Micros. Soc.* **88** (1968) 143.
67. J. P. FLEMMING, *J. Sci. Instr.* **2** (1969) 93.
68. J. P. FLEMMING and E. W. WARD, Third Annual Scanning Electron Microscopy Symposium, 1970, to be presented.
69. C. W. OATLEY, *J. Sci. Instr.* **2** (1969) 429.
70. Cambridge Scientific Instrument's "Stereoscan".
71. M. G. R. THOMSON and A. V. CREWE, 26th Annual Electron Microscope Society of America meeting, 1968, p. 358.
72. R. SIMON, (1969) in reference 2.
73. G. S. PLOWS and W. C. NIXON, *J. Sci. Instr.* **45** (1968) 595.
74. N. C. MACDONALD, G. Y. ROBINSON, and R. M. WHITE, *J. Appl. Phys.* **40** (1969) 4516.
75. D. R. CLARKE, P. R. BREAKWELL, and G. D. SIMS, NPL report IMS II.
76. D. PUGH, to be published.
77. W. MAHIEU, Air Force Materials Laboratory report (1968), AFML-TR-68-113.
78. D. R. CLARKE and G. D. SIMS, unpublished work

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