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1972

SCANNING ELECTRON MICROSCOPY/1972

Proceedings of the

Part I (April 25, 26, 1972)

5th ANNUAL
SCANNING ELECTRON MICROSCOPE SYMPOSIUM

and

Part II (April 27, 1972)

WORKSHOP ON BIOLOGICAL SPECIMEN PREPARATION
FOR SCANNING ELECTRON MICROSCOPY

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IMPORTANT

Readers of these proceedings should see the Preface (pages vii and viii) for important information about the content and organization of these proceedings.

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FIFTH ANNUAL SCANNING ELECTRON MICROSCOPE SYMPOSIUM

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WORKSHOP ON BIOLOGICAL SPECIMEN PREPARATION FOR SCANNING ELECTRON MICROSCOPY

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PREFACE

The readers of these proceedings should be aware of the following important information:

(i) The proceedings contain papers on SEM instrumentation, techniques, interpretation and theory. Papers on SEM applications were not accepted for the 5th Annual SEM Symposium.

(ii) All contributors to the biological specimen preparation workshop were invited and received the following guiding statement in preparing their papers, "...the main purpose of the workshop is to present specimen preparation techniques and their critical discussion. Results are to be presented only for the evaluation of the technique. Any medical or biological significance of your results are outside the scope of this meeting and should be avoided".

(iii) There are many review papers discussing some of the important topics for scanning electron microscopists. Some of these are e.g., specimens for resolution standards (Ballard, p. 121), specimen coating for nonconducting materials (Echlin and Hyde, p. 137), charging artefacts (Pawley, p. 153), revealing crystallographic defects (Humphreys et al., p. 205), comparison of stereo methods (Howell and Boyde, p. 233), and particulate matter techniques (Johari and DeNee, p. 249). In addition, all papers in Part II also include a review of the literature. For a complete list of review papers at the Symposium, please see the program on p. 443.

(iv) Each paper for the proceedings was reviewed by at least two reviewers. Papers found unacceptable were either totally rejected or substantially altered by the authors. Many papers were also retyped in whole or in part to improve their presentation. Every effort was made to correct all errors, some probably still remain, and we apologize for these.

(v) The Discussion With Reviewers feature as the last item of each paper arises as follows. After receipt of the paper at IITRI, they are sent to the reviewers with the following statement. "Supposing you are an attendee at a conference where this paper as written is presented. Please write down the questions you would ask the author." The questions, as well as reviewers comments, are sent to the author. To have his paper published, the author is required to answer all questions--some also answered comments or took them into account by revising their papers. These questions and answers were edited here and were made part of each paper. We apologize to the reviewers and the authors if some shade of meaning might have been lost or misinterpreted in editing.

Considering that we received most papers between February 15 and March 1, and that the book is ready for distribution by April 25, the preparation of the proceedings is possible only through splendid cooperation between the authors and the reviewers. We thank them wholeheartedly.

We believe that in this very rapid process of making the proceedings available at the meeting, this system of reviewer-author interaction is the fairest method to introduce a critical element in the acceptance of papers, and in bringing out much additional information.

(vi) Each paper was limited to six pages of material to be supplied by the author. All abstracts and discussions were edited and typed at IITRI.

(vii) These proceedings also contain a complete bibliography of SEM literature. The bibliography was kindly compiled by Dr. O. C. Wells from the reprints received by him and us. We apologize if your paper is not included, but suggest that you send us reprints following the procedure outlined on p. 375.

(viii) For the benefit of the readers, we have also republished a paper reviewing the highlights of the 1968-1971 symposia. (See p. 365).

(ix) For all micrographs, magnification is indicated by micron marks or by field of width, since the photographs are reduced during reproduction.

(x) There are many stereo-pairs throughout the proceedings. To view them, use of a simple wire stereoscope or similar device is recommended.

(xi) If felt necessary, an errata to these proceedings may be published. TO RECEIVE YOUR COPY, PLEASE ADVISE US OF THE ADDRESS TO WHICH IT SHOULD BE SENT. (See p.ii)

Many persons have contributed to these proceedings and programs, and we gratefully acknowledge them now--Dr. N. M. Parikh, our director for his continuous interest and guidance, Miss Joan Young, Mrs. Mary Dineen, and Mrs. Betty Williams for their secretarial help, and Mr. G. S. Perkins and his staff at Chicago Press for their special efforts in printing a high quality volume in time for the meetings. The organization of this meeting would have been impossible without the hard work of the chairmen (listed on p. iii) of various sessions and Dr. E. B. Small. We also immensely benefited from suggestions of our keynote speaker, Dr. K.C.A. Smith, and all four past keynote speakers from 1968 to 1971, Dr. Alan Boyde, Dr. Alec Broers, Dr. W. C. Nixon and Dr. T. E. Everhart. The favorable considerations and support of the N.I.H., and particularly of Mr. Elward Bynum of the National Institute of General Medical Sciences in cosponsoring the Biological Specimen Preparation Workshop is gratefully acknowledged.

The list of others who contributed and advised would be very long indeed. Many of our reviewers also acted as advisers during various phases of the organization of the meeting. The names of those who reviewed more than two papers are listed below.

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The preparation of this volume would have been impossible without the hard work and many hours spent by our colleague Joseph Staschke in taking care of all the small and large changes in almost all the papers. In appreciation of his tremendous help, we dedicate this volume to him.

Chicago, Illinois
25 April 1972

Om Johari
Irene Corvin

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SCANNING ELECTRON MICROSCOPY: THE NEXT TEN YEARS

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KEYNOTE PAPER

SCANNING ELECTRON MICROSCOPY: THE NEXT TEN YEARS

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Introduction

Twenty years ago it was my privilege to see a scanning electron microscope for the first time. It was being demonstrated by Denis McMullan in a form more-or-less as shown in Fig 1. to a group of prospective research students in the Cambridge University Engineering Laboratory. It would have required a bold and imaginative person to have predicted the advance of the SEM in the intervening twenty years since that day; the many generations of research students who were to follow McMullan at Cambridge and elsewhere and the growth of the application of the instrument which was to lead to international conferences of this nature. However, with the instrument now firmly established the main lines of development over the next ten years may be predicted with greater confidence.

McMullan's instrument, although rudimentary in form, represented a radical departure from any previous instrument. It incorporated almost every essential feature of present-day instruments. Vacuum tube electronics have since given way to solid state; electrostatic lenses to magnetic; the secondary electron multiplier detector has given way to the more flexible scintillator/photomultiplier secondary electron detector; and with these changes the facility with which pictures of high quality can be taken has improved enormously. But most instruments operating today suffer from essentially the same basic limitations with regards to resolution, field of view, contrast, picture exposure time, and so on, as did the original instrument, and in absolute terms their performance is not all that superior. There are indications, however, at the present time that this situation is unlikely to persist for very much longer and that over the next few years we are likely to witness improvements in the SEM almost as radical as those heralded by this pioneer instrument.

The grounds for this belief lie in the pattern of development which has already been established by those working in the field at the present time. The proceedings of this Conference and its immediate predecessors foreshadow most of what is to come over the next ten years. An excellent and comprehensive review of the art, based largely on work presented at the IITRI Conferences, has already been published by Johari[1]. This contains many constructive and imaginative suggestions concerning the future directions of scanning microscopy.

The most important single factor which is likely to differentiate the past two decades from that on which we are about to embark is the replacement of the tungsten hairpin-filament cathode by other types, capable of providing greatly increased beam brightness. It is this, and the consequences which stem from it, that forms the main topic of the present paper.

Resolution

The resolution obtainable in the SEM depends primarily upon the diameter of the scanning probe and upon the way in which the scanning beam interacts with the specimen to produce the video signal. These factors are related in turn in a complex fashion to other parameters such as the required field of view, the picture recording time, the required threshold contrast and so on. Several discussions of the various factors which affect resolution are to be found in past proceedings of the IITRI Conferences, notably those by Broers,[2] Nixon,[3] and Pease[4], and reference must be made to these papers for a more complete account than that given here. For the present purposes of seeing how the newer cathodes and guns are likely to influence the performance of the SEM, it is sufficient to consider a single expression for the diameter of the probe. (Smith[5,6])

$$d_{min} = A\, C_s^{\frac{1}{4}} \lambda^{\frac{3}{4}} \left(1\cdot 52.10^{-6} \frac{N^2}{c^2 T_s} \frac{T}{j} + 1 \right)^{\frac{3}{8}} \text{cm.} \quad (1)$$

where A is a coefficient approximately equal to unity.

- C_s (cm) is the spherical aberration coefficient of the final probe-forming lens.
- λ (cm) is the electron wave-length.
- T_s (sec) is the picture exposure time.
- N is the number of lines in a square picture (field of view).
- c is the fractional threshold contrast.
- T (Kelvin) is the cathode temperature.
- j (A/cm^2) is the cathode emission current density.

This expression gives the minimum probe diameter for the case where the chromatic

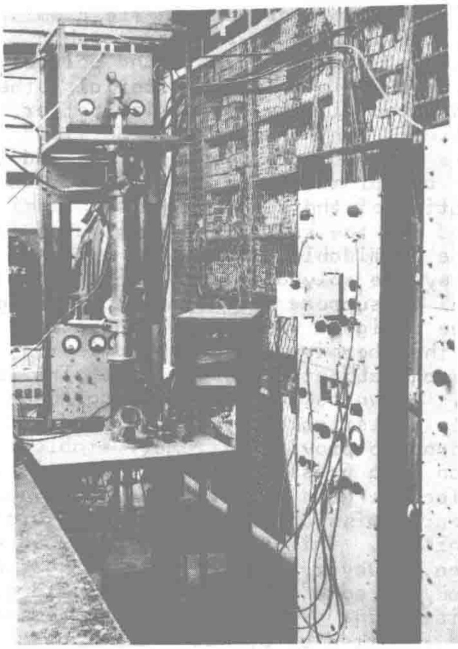

Fig 1. McMullan's first SEM at Cambridge

effect is negligible compared with spherical aberration and diffraction. In the derivation of this expression certain simplifying assumptions are made, in particular that interaction between electrons is negligible (Davey[7]) but these do not affect significantly the conclusions which follow.

Taking the typical values:
$N = 400$, $c = 0.1$, $T_s = 100$s, and assuming $A = 1$.
(1) becomes:

$$d_{min} = C_s^{\frac{1}{4}} \lambda^{\frac{3}{4}} \left(0\cdot24 \frac{T}{j} + 1 \right)^{\frac{3}{8}} \text{ cm.} \qquad (2)$$

The significance of cathode temperature and emission current density can be clearly seen. If the left-hand term within the brackets is sufficiently small, the probe diameter tends to the limiting value $C_s^{\frac{1}{4}}\lambda^{\frac{3}{4}}$, the so-called 'resolution parameter', which depends only on the gun accelerating voltage and the spherical aberration coefficient of the final probe-forming lens.

The expression in this form allows a comparison to be made between the tungsten hairpin cathode and the newer types of cathode which are now becoming available.

Considering first the lanthanum hexaboride cathode reported by Broers[8] and Ahmed[9]. The ratio of T/j given by the latter author for this type of cathode is 1863/50 which may be compared with a ratio of 2800/2 for the tungsten hairpin (lifetimes approximately 200 hours and 20 hours respectively).

The respective probe diameters are then:

d_{min} = 9 x (resolution parameter) for tungsten hairpin

d_{min} = 2.4x(resolution parameter) for LaB_6 cathode

A representative _ re for the resolution parameter would be about 20Å (C_s = 2cm, V = 20kV). Thus, the probe diameter would be reduced, for the conditions specified above, from a figure in the region of 180Å to one in the region of 50Å.

The other type of electron source, which provides even greater gains in terms of reduced probe diameter, utilises the field emission phenomenon. Field emission was discovered in the last century and its theory well established by Fowler and Nordheim in 1928, but it is only comparatively recently that advances in ultra-high vacuum techniques have made it a practical possibility for instruments like the SEM. The work of Dyke[10] has contributed significantly to modern developments in the application of field emission cathodes.

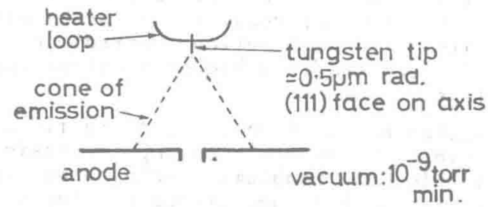

Fig 2. Field-emission diode gun

The essential elements of the field emission gun are shown in Fig.2. Application of a voltage, of the order of 1 - 3 kV, between emitter and anode gives rise to a field at the surface of the emitter sufficient to cause emission by tunnelling and the resulting emission current density is extremely high in comparison with thermionic emission. Electrons are emitted into a large solid angle of the order of one steradian so that most of the electron flux is intercepted by the anode; only a small fraction passes through the anode aperture and is utilised by the electron optical system. The emission current distribution is non-uniform being highly dependent on the local crystallographic orientation at the emitter surface. It is necessary, therefore, to manufacture the emitter from oriented wire to ensure that a high-intensity emission face is presented to the axis of the system.

The diode configuration of Fig. 2. is often followed by a further electrode, at a higher potential than the anode, which serves to both accelerate and focus the beam.

The effective diameter of the field emission source is only of the order of 100Å and this leads to special requirements in the imaging system. The efficiency with which the current available from the source can be utilised decreases as the size of the imaged probe increases until, at a probe diameter of about 1000Å, the current which a field emission source can provide is no greater than that which can be provided by a tungsten thermionic cathode, (Cosslett and Haine[11]; Drechsler, Cosslett and Nixon[12]). Equation (1) does not apply without restriction to a field emission system, however, it does provide an adequate basis of comparison where probes well below 100Å are concerned.

From results obtained by Crewe [13] and others it appears that an equivalent T/j of at least three orders of magnitude smaller than that from a thermionic cathode is obtainable using a field emitter. The term in brackets in equation (2) then differs by an insignificant amount from unity and the resolution-parameter limit is reached. Further reduction of probe size requires a lower spherical aberration coefficient and/or a higher accelerating voltage.

Although microscopes employing field emission sources are becoming increasingly available, many problems remain to be overcome before their advantages are fully realised under routine conditions. One problem is that during operation the tip adsorbs molecules and ion bombardment damages its surfaces. Thus, it is necessary to clean and smooth the tip periodically by passing a carefully controlled current through the heater wire on which the tip is mounted. The vacuum conditions in the tip-anode region are very critical since pressures higher than about 10^{-9} torr give rise to instability in the emission current. This may occur, even though the pumps are capable of achieving an adequately low gun chamber pressure because the current falling on the anode causes outgassing and the production of ions, and this can lead to a high local pressure and a high rate of ion bombardment. Consequently, in present-day guns, the emission current is limited to a few microamps only and this restricts their performance somewhat. Even under the most favourable conditions, residual beam current fluctuations of 2-5% are observed and this of course impairs the threshold contrast in the SEM picture. Flashover in the gun or associated H.T. supply can cause destruction of the emitter, a problem which becomes worse at higher voltages.

Further developments in field emission guns will lie in achieving more stable operation at higher currents and possibly worse vacua. To this end materials other than tungsten will be found with better properties. Lanthanum hexaboride field emitters have already been operated and the results are promising (Windsor[14]) but the preparation of the single crystal material required and the subsequent etching of the tip pose formidable problems at present. When they are solved it is perhaps not too fanciful to suppose that a multipurpose gun might be designed which could operate in either the thermionic or field emission mode or a combination of the two. The latter, which is known as T-F emission, has been recently investigated by Swann[15] and it has been found to provide extremely stable emission at a pressure of 10^{-8} torr although the effective gain in brightness over pure thermionic emission is only about an order of magnitude. This result was obtained with tungsten, however, and it is quite possible that LaB_6 or some other material would give a greater gain. The thin-film field emission cathode reported by Spindt[16] also has interesting possibilities.

We have seen that with a field emission source the resolution-parameter limit may be readily attained. Reduction of this parameter, at a given beam voltage, requires that the specimen be brought closer to the probe-forming lens and ultimately, for probes of less than about 10Å, it is necessary to operate with the specimen immersed inside the magnetic field of the lens. This in turn makes it more difficult to arrange for the efficient collection of the secondary electron signal.

Before research and development proceed along these lines the question must be asked whether beam-penetration and spreading effects occurring within the specimen will not limit the resolution to values which can, in any case, be attained easily at large specimen-to-lens distances and with relatively modest resolution-parameter limits. Following the work of Everhart[17] and Wells[18] this question has recently been the subject of a theoretical investigation by Catto[19]. He has considered the detection and resolution of particles on the surface of a smooth flat solid, assuming beam incidence normal to the surface and that the whole of the secondary electron signal is collected. He has estimated that under these ideal conditions a resolution of about 5Å is theoretically possible if a 5Å probe is used with a field emission source. This estimate was made for the rather favourable element, copper. While too much emphasis should not be placed on this figure, the theory does indicate that it will be worthwhile investigating ways and means of achieving higher resolution in the secondary emissive mode. Apart from the instrumental aspects of the problem a great deal will depend on being able to prepare specimens in a way which allows approximation to the idealised conditions assumed in the theory. High resolution will not be achieved with the type of rough and irregular specimens which are commonplace in SEM practice today. Higher resolution operation will also demand a better vacuum environment for the specimen to prevent contamination.

Signal Detection

More precise and discriminating methods of detecting the secondary electron and other signals which arise in the SEM are bound to become increasingly exploited over the next ten years. Types of detector such as, for example, that of Banbury[20] which discriminates between secondaries issuing from the specimen in different directions, or that of Wells[21] which provides energy discrimination, will allow the operator an extra degree of freedom in setting up his SEM to provide maximum information in the emissive, voltage, and magnetic contrast modes.

The method of 'low-loss' imaging recently suggested by Wells may also provide an alternative means of achieving high resolution. It appears that one of the major tasks of research in the immediate future will be to find ways of combining these high-contrast detectors with high power lenses of low spherical aberration whilst at the same time maintaining a reasonable degree of flexibility in specimen manipulation.

Methods of detecting X-ray and cathodoluminescence signals are now firmly established and advances here seem likely to be of degree rather than of kind. Much work on Auger electron spectroscopy remains to be done, however, following the work of MacDonald[22] and here the new guns and better vacua will help considerably.

Operational Improvements

The slow-speed visual scan rates used in the majority of SEM's until very recently leave much to be desired. Display at TV rates has improved the situation somewhat but this does give rise to an increased noise level in the picture and/or increased beam current and poorer displayed resolution. Here again the new guns should help but a limit may be imposed at the higher currents owing to the occurrence of specimen damage. Increasing use is therefore likely to be made of forms of storage system, such as the scanconverter tube, video disk or computer which allow the electron beam to be switched off after the picture has been built up.

In the opinion of Boyde[23] the most significant advance in the SEM field, at least for biological users, will be the continuous, truly three-dimensional image presentation. Two-tube stereo displays or single-tube two colour stereo displays, with and without storage systems, will no doubt become commercially available over the next decade. These systems together with the higher information rates made possible by the new guns will make the information in the SEM picture much more directly and readily accessible to the operator. Hopefully, the age in which it has been necessary to take 'a dozen micrographs where one would have done' is drawing to an end.

It goes almost without saying that quantitative and analytical interpretation of the SEM image will be enhanced by the use of small but powerful computers which will provide all the conventional signal-processing facilities now available today as well as others not yet thought of.

Applications

It is also a truism that new and unexpected applications of the SEM will be found and new and novel methods of specimen preparation will be developed. The rather unexpected application of ion etching in the field of biology will find parallels during the next ten years and it will pay the research worker to be on the alert for their occurrence.

There are many areas in biological and metallurgical research which will benefit from the new gun technology, and not simply through improved ultimate resolution alone. In many specimens, for example, edge penetration and charging effects impair picture quality. It is well known that reduction of beam voltage is advantageous under such circumstances but the price paid is a reduction of resolution owing to increased probe size. The deterioration of performance with reduction of voltage will not be nearly as marked with the new guns.

Another example is the selected area channelling pattern method in which, with conventional guns, the angular resolution is severely limited even at probe sizes of several microns (Booker[24]). Here again very useful gains will be made by the use of LaB_6 or field emission guns.

The dynamic applications of the SEM will be further extended by the use of differentially-pumped specimen chambers which may be operated not only at ultrahigh vacuum but also at high pressures with the capability of handling large throughputs of gas and vapour (Banbury[20]). This facility will be of particular importance in the field of micro-circuit fabrication, in which the electron probe is used to expose electron resists or to carry out chemical decomposition.

So far in this paper the emphasis has been on the new technology which will extend the range of application of the SEM as a research tool. This is, at the same time, bound to increase the complexity of the SEM and its associated systems. Less obvious but perhaps equally important is the instrumental simplification which might be brought about and the extension of simple types of SEM into areas barely yet explored. The new guns will give greatly increased reliability and operational simplification. Low-noise pictures at TV scanning rates will allow of interpretation by non-skilled personnel. It is expected therefore that simple SEM's will find increasing use in routine industrial applications. Simple and inexpensive instruments will also find their way into schools and colleges.

Instrumental Combinations

A recent development in the field of electron microscopy and X-ray analysis has been the combining of various instrumental modes of operation within a single instrument. A particularly powerful combination for the future would appear to be conventional and scanning transmission microscopy at high resolution combined with electron and X-ray analysis. Present-day guns, including existing designs of field emission guns, are not capable of supplying all of the requirements in respect of probe size and current for such an instrument. However, the advent of a combined thermionic/field emission gun or field emission gun capable of supplying large currents, would render an instrument of this type feasible. An entirely universal instrument might be devised which incorporated facilities for all the operational modes now known, but such an instrument would be of real value only if it allowed examination and analysis of a selected specimen field to be carried out rapidly and without complicated specimen manipulations or changes in the instrumental set-up between operational modes.

Training and Education

The complexity of a modern scanning electron microscope installation, designed for advanced research, places formidable demands on the knowledge and skill of operators and users and there is every indication that such demands will increase. Training courses, including updating courses, for imparting the specialised skills required for using the instrument will become increasingly important. But beyond this, the growing importance of scanning principles and techniques in all branches of optics will make some familiarity with the field a mandatory part of a scientist's equipment in the not too distant future. We can therefore expect to see more frequent mention made, at university and college level, of the principles and concepts involved. Practical work for students might be provided by scanning versions of the teaching electron microscope devised by Nixon[25].

Twenty years ago there was but a single SEM and one operator; within the next ten a situation is likely to come about in which every science graduate will be familiar with the instrument and not a few will have taken a scanning micrograph!

Acknowledgements

I wish to thank Mr. L.R. Peters and Miss H. Joiner for their assistance in preparing this paper, and Dr. W.C. Nixon and Mr. J.R.A. Cleaver for several helpful discussions. Financial support from the Wolfson Foundation and from the Science Research Council is also gratefully acknowledged.

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DISCUSSION WITH REVIEWERS

*Reviewer I: How can an average reader obtain copies of theses from Cambridge University?

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Reviewers II & III: One very important application of the SEM is the fabrication of very small devices (demonstrated by Thornley and Hatzakis, Broers, Chang, and Wolf et al). How do you assess the future of microfabrication using the SEM?

Author: The SEM undoubtedly has a big future role to play in the field of semiconductor device fabrication and electron lithography. Although the principles of the techniques have been well established by the pioneering work of those mentioned, it is difficult even for the experts in the field to see the future clearly, as it is likely to depend as much on rather finely balanced economic factors as on technological and scientific ones.

Clearly, there are areas in this field, in addition to the obvious research and developmental applications, where SEM techniques are likely to become firmly established. One such area lies in the fabrication and inspection of microwave devices which require resolution limits beyond the capabilities of available optical techniques. Another is for processes requiring the highest possible flexibility of control. In this respect, the facility with which the electron beam can be shifted and switched lends itself to digital control and computer-aided circuit design techniques, providing information in a form which can be readily utilized. This combination would appear to be ideally suited to the production of masks, or for the fabrication of special devices on a one-off or small-batch basis.

But can electron beam technology supplant, over the next decade, the well established optical techniques used in the mass production of standard devices, and in which large capital sums have been invested? The processing time-factor inherent with SEM-type technology must be a decided disadvantage but, here again, the improved performance of the new types of electron gun may be of significance.

In a different but related field it will be interesting to see whether SEM techniques have any large-scale applications in the storage and processing of information. Again, many of the necessary techniques have been established but economic considerations are paramount in the face of other established methods.

Reviewer III: Do you regard the retarding field and scanning mirror electron microscopes as potentially useful instruments?

Author: This type of instrument (it should be regarded as a single instrument since the mirror mode is also a retarding field mode) offers excellent sensitivity for the mapping of surface microfields; allows the examination of insulating surfaces because of low impact voltages; and avoids specimen damage and contamination in the mirror mode. It should, therefore, have considerable potential for research and possibly inspection in the general field of electronics. There may also be applications in the field of biology, although these are somewhat speculative at the present time. The resolution obtainable is not as high as for conventional scanning microscopy, and image interpretation is not as straightforward. All things considered, it should be an extremely useful method of microscopy but possibly only to a limited number of users.

Conversion of the standard SEM to operate in the retarding field mode requires a relatively simple attachment which should be within the financial means of most laboratories. There should, therefore, be no lack of experimentation with the method, and it would indeed be surprising if some significant, useful and possibly unexpected results, were not forthcoming.

Reviewer III: In view of the energy spread reported for electron beams by Pfeiffer, (11th IEEE Symposium on Electron, Ion and Laser Beams, Boulder, Colorado, 1971, and p. 113, these Proceedings), could you please comment on when neglect of chromatic aberration is justified.

Author: The large energy spreads reported by Pfeiffer imply that under most conditions encountered in the SEM chromatic aberration should be taken into consideration and may, indeed, be dominant. In the latter case an alternative expression, analogous to equation (1), may be derived which takes into account only chromatic aberration and diffraction,

$$dc_{min} = B(C_c \frac{\delta V}{V} \lambda)^{\frac{1}{2}} (1.52 \times 10^{-6} \frac{N^2}{c^2 T_S} \frac{T}{J} + 1)^{\frac{1}{4}}$$

where B is a coefficient whose value lies in the range 1.1 - 1.56 (the precise values of both the coefficients A and B depend on the definition of the diameter of the diffraction disk). C_c (cm) is the chromatic aberration coefficient, $\frac{\delta V}{V}$ is the fractional energy spread. The quantity $(C_c \frac{\delta V}{V} \lambda)^{\frac{1}{2}}$ may be termed the "chromatic resolution parameter" by analogy with the resolution parameter derived when considering spherical aberration and diffraction only.

Putting into this equation the same values for the various parameters as before, and assuming $B = 1.1$, one obtains

$dc_{min} = 4.7 \times$ (chromatic resolution parameter) for the tungsten hairpin

$dc_{min} = 2 \times$ (chromatic resolution parameter) for the LaB_6 cathode

Comparing the ratio of these diameters with that obtained previously, the gain obtained with the LaB_6 cathode is not as great. However, in this case the two cathodes do not have identical resolution parameters since the energy spreads are different. Using Pfeiffer's values for the energy spreads of 5 volts for the tungsten hairpin and 3 volts for the LaB_6 cathode, gives a further gain for the latter by a factor 1.3. Thus, irrespective of whether spherical or chromatic aberration is predominant, the LaB_6 cathode will give an improvement in the probe diameter of a factor of between 3 and 4 under typical operating conditions.

In general both aberrations need to be taken into account in which case the full expressions quoted by Broers in SEM/1970, page 2, will be found useful. These, however, are rather cumbersome and do not afford such a convenient basis of comparison as the restricted expressions above.

For the field emission cathode the Boersch effect is negligible at the small currents used in guns at the present time, and the energy spread associated with this type of cathode is rather less than 1/2 volt. Consequently, except when operating at very low beam voltages, chromatic aberration could be safely neglected in most systems employing a field emission gun.