Electrostatic Electron Microscopy. II[1]

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This paper is a continuation of the description of problems arising in the development and design of an electrostatic electron microscope. The present article discusses depth of focus, lens and field stops, shielding, manufacturing tolerances, the choice of the number of stages of magnification, and alternative methods of viewing and recording the final image. A following paper will describe a completed instrument.

DEPTH OF FOCUS

The depth of focus of any electron-optical system, whether magnetic or electrostatic, may be computed in the same way as it is computed for ordinary light-optical systems. Having chosen a minimum resolution, it is necessary only to examine the paths of extreme rays to or from the object or image as a function of the departure of either from best focus position. Accordingly, the theory will not be further considered here. The electrostatic microscope, having common accelerating and lens potentials, is one in which the focal length of the lenses is fixed by their geometrical form and dimensions, and which, for all practical purposes, is completely independent of the voltage applied to the instrument. Focusing is thus most conveniently done in the same way as in an ordinary light microscope—namely, by the axial motion of one or more parts of the system. Simple depth of focus considerations show that it will not prove practical to focus by moving the fluorescent screen (or photographic plate); though the magnification change will be large, the correction effect to neutralize the specimen departure from best location will be very small. This scheme, if useful in focusing at all, would be so only as a very sensitive micrometer method. It follows conversely that one cannot appreciably alter magnifications by moving the specimen without losing resolution quickly. Thus, the best plan is to obtain sharp focus by axial motion of the specimen or some electrode in the electron-optical system near the specimen.

LENS AND FIELD STOPS

In an electrostatic unipotential lens, the lens stop cannot be placed at the center of the lens. It becomes necessary then to consider the relative effectiveness of various possible locations for the limiting apertures. Small apertures already exist at the entrance and exit of the lens, and in general others may be placed ahead or beyond the lens region. Every electrode in the optical system that allows some electrons to pass through it and rejects others which have too great a departure from the axis, acts partially as a field limiter and partially as an aberration limiter.

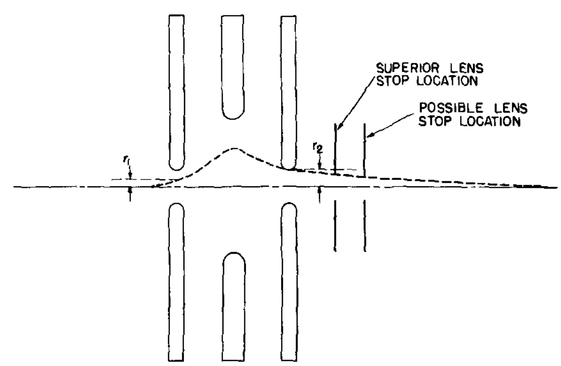


Fig. 1. Lens stop locations.

Suppose, for example, that it is desired to limit the spherical aberration of the objective lens. The electrons are assumed to originate at a point on the axis very near a focal point and to cross the axis again at some distance from the lens (Fig. 1). The electron trajectory for lens potential distributions previously discussed[1] is approximately as indicated in Fig. 1. Electrons which enter the lens region with a displacement r_1 leave the lens with a much larger displacement r_2. Approximate computations for the case of voltage drops in the lens of about one-half anode-cathode voltage indicate that r_2/r_1 may easily be as great as five and usually would be expected to be greater than two. Accordingly, in the interests of stopping the lens without having to resort to minute aperture diameters (whose rough edges may bring in field emission and image distortions), it would be best to regard the region beyond the lens exit as the best lens stop location.

The stop should be placed as close as possible to the exit since, as indicated in Fig. 1, the farther away the aperture is placed, the smaller it must be. Furthermore, it should be evident that as the stop approaches the image plane, it commences more and more to be a field limiter rather than a lens aberration limiter.

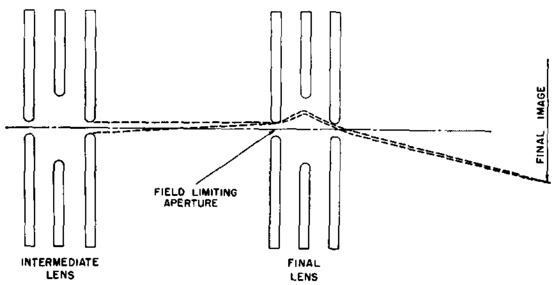


FIG. 2. Field stop location.

If possible, it is advisable to limit the rays entering the lens to as small a bundle as is conveniently accomplished by a well-rounded aperture—consistent, of course, with the ratio of r_1 to r_2. This procedure will lessen the possibility of secondary electron production on the lens side of the exit aperture. These secondaries, caused by unwanted non-axial electrons, return into the lens region where they bombard the electrode surfaces and the insulation.

To consider the location of the stops which limit the field, we must move to the last lens of the system. For this lens we may in most cases consider that the electrons arrive with very small angles of inclination to the axis since they will be coming from a rather small opening at the exit of the previous lens which is relatively far away (Fig. 2). If the lens is so designed that the focal points are near the entrance and exit of the lens, then an initially, nearly parallel ray will, of course, be found to cross the axis rather close to the exit plane (Fig. 2). Thus the exit aperture of the last lens may be smaller than the entrance aperture before it begins to limit the field.

To summarize, the exit of the objective lens limits the aberrations of the system while the entrance of the last lens limits the field whenever the entrance and exit apertures of each lens are of equal diameters.

SHIELDING

The electron beam, from the source to the screen or photographic plate, must be shielded both from stray electrostatic and stray electromagnetic effects. The electron gun itself must not be overlooked since, if the shielding problem is well taken care of there, it becomes possible to design the gun so that it may be permanently aligned with the remainder of the electron-optical system in manufacture and will not require re-alignment by the operator even when the filament is changed.

Electrostatic shielding is easily taken care of in the gun by the use of shielding cylinders (Fig. 3), every part of the instrument being at ground potential but the cathode and the interior portions of the focusing lenses. The authors have developed a lens assembly which is exceedingly compact and which uses a single rod inside the vacuum envelope to connect the negative potential electrodes of the lenses to the cathode. The stray electrostatic field of this connector may again be shielded from the beam in the region between lenses by the use of further cylindrical shields (Fig. 3). However, inside the lens itself, the center electrode is energized asymmetrically by it, so it becomes necessary to choose the distance of the connector to the axis to be large compared to the spacing between lens electrodes. The detrimental effect due to this source can be detected in the image resolution since it will vary with azimuthal angle about the axis. This disturbing effect in the symmetry of the electric field of the lenses constitutes one limit to the reduction in diameter of the microscope body for any given lens design.

There are two classes of magnetic shielding problems. The field due to the gun's filament current must be attenuated highly before it reaches the region of the specimen. The entire electron path must, in addition, be shielded from external magnetic fields. The former problem is, of course, simplified if high frequency is used for heating of the filament. For the use of low frequencies, such as 60 cycles, shielding has been obtained by adding sufficient mu metal in the gun components (Fig. 3) so that the magnetic field of the filament can reach the specimen only through the small vacuum pumping holes or the holes that must exist in the gun anode and defining apertures.

By arranging the microscope to be of minimum diameter and by using a multiple lens imaging system it is possible to reduce the over-all size of the entire instrument so that one single magnetic shield may enclose the entire structure for general shielding from external magnetic effects. The amplitude a transverse a.c. stray magnetic field may be permitted to reach before interfering with resolving power down to below 100A has been computed to be of the order of 10^{-6} gauss, averaged over the electron beam's length.[2] For a given length of path and electron velocity, the resolution (as limited by a stray a.c. field) will increase with the magnification; this, because the ultimate deflection of the electrons at the image is divided by the magnification to obtain resolution referred to the object plane. With everything else fixed, the resolution will vary inversely with electron velocity (or the square root of anode-cathode voltage).

The chief difficulty in predesigning a suitable magnetic shield for an electron microscope is that the permeability of the shielding material is not known in the range of the exceedingly small field strength to which the inner layers of the shielding will be subjected. One has no better choice then than to try experimentally various amounts of turns of a given thickness of shielding until the required amont of shielding is obtained. Possibly the electron microscope itself will serve eventually as a means for obtaining such data.

The first-order effect of a d.c. field is to deflect the whole image bodily. If there were truly no relative motion of the various electron beams which yield the image, resolution would be unaffected; the only effect would be a disturbance in the alignment of the system. Such a condition would call for absolute constancy of the disturbing field and the electron velocity. Now, quite apart from resolving power, to keep a 25,000- to 50,000-volt electron beam centered, say within one-hundredth of a centimeter over a distance of the order of 50 centimeters, requires that the transverse d.c. field be no higher than about 10^{-3} gauss. Obviously this degree of refinement in centering the beam along the axis may be relaxed with distance from the objective lens since the later lenses can tolerate greater departure of the beam from the axis. This factor is important in designing an instrument which is permanently aligned in manufacture. Magnetic shielding sufficient to protect the beam from transverse a.c. stray fields will at the same time protect against this disturbance in alignment due to stray d.c. fields of somewhat greater strength. If the a.c. 60-cycle and d.c. fields are of comparable strength and the a.c. fields have been sufficiently well attenuated by shielding, then a generous ripple in the voltage supply may be permitted before there is a limiting of resolution by the d.c. field.

The foregoing statements apply to all electron microscopes. An additional factor which comes up in the electrostatic instrument is that in the central region of the lens the electrons are traveling at reduced velocity and thus are more susceptible to deflection. The most serious effect here is that electrons on the axis are slowed down less than electrons at the beam edge, since the potential varies over the lens cross section. This is another way, in other words, in which even a d.c. transverse magnetic field would work to destroy resolution because electrons at different distances from the axis will receive different deflections from the same strength of stray field. It is possible to estimate the difference in deflection of electrons passing through the lens on the

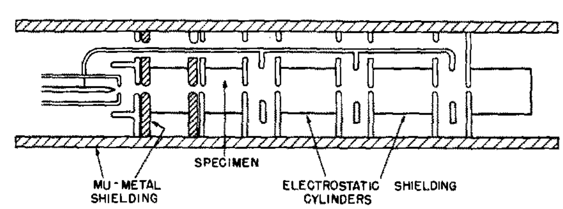


FIG. 3. Shielding of electrostatic microscope.

axis and a few mils away from the axis by the aid of approximate potential distribution functions. For lenses in which the lens drop[1] does not exceed one-half of the anode-cathode voltage, this effect will not limit the resolution if the shielding is already adequate from the standpoint of alignment accuracy. In a design, however, which seeks to use a very high voltage drop at the center of the lens compared to the cathode-anode voltage, the effect must not be overlooked.

A stray magnetic field that is axial, since it acts symmetrically, may be regarded as an additional electron lens which, if it failed to pulsate at all in focal length, would not be at all objectionable. An a.c. magnetic field or even a d.c. magnetic field along the axis may prove troublesome in this respect for the desired simple electrostatic microscope in which an appreciably greater voltage ripple might otherwise be allowed. It is possible to compute the order of magnitude of this effect for a given magnetic field strength by simply adding to the focusing action of the electrostatic lens system a small oscillating magnetic lens whose focal length may be related to the magnetic field strength from the simple theory of magnetic lenses. Such a simple analysis leads to the conclusion that if the shielding is adequate to protect the electron path against transverse fields and it is allowed to protrude beyond the electron path an amount equal approximately to the radius of the shielding tube, the axial magnetic field will die off rapidly enough so that there will be insufficient strength at the specimen to affect the resolving power. This statement assumes that the axial field is of magnitude comparable to the cross magnetic field. Particularly strong axial fields should probably best be regarded as an unfortunate choice of location for the instrument and remedied in a manner more straightforward than the addition of axial shields.

MANUFACTURING TOLERANCES

Glass lenses used in high-grade light optical instruments are known to require the most exacting precision in manufacture. Fortunately, the electrons in electron optical lenses do not cross electrode surfaces, but only equipotential surfaces whose forms are indirectly determined by the adjacent conductors and impossible tolerances are not called for in order to produce higher than light microscope resolving power. One approach to the precision manufacturing problem is simply to have every part of the microscope made with as high a precision as possible. Such a criterion is not very practical, however, for commercial production. Here it is desirable, if not essential, to know where the high tolerances may be relaxed and to what precision one must necessarily build certain parts of the instrument. Naturally, it is difficult to obtain very precise specifications at this stage of the art. However, it is possible to obtain some idea of the orders of magnitude of permissible distortions by a few simple attacks. These methods and chief results will next be described.

A complete electrostatic lens may be thought of as consisting of many thin lenses in series. Misalignment of any one of the lens electrodes (so that the three electrodes do not have a common axis) may be thought of as a misalignment of some of the thin lenses which are mainly in the immediate vicinity of that misaligned electrode. The electron beam when passing through these thin lenses will appear to these misaligned lenses as a non-axial beam. Aberrations will result which can be computed as due to the failure of all electrons to be completely axial. With such information as has been described previously[1] as to the size of aberrations for a given electron path departure from the axis, and with some approximate distribution of the lens action among the regions near the various electrodes, the order of magnitude of this effect may be estimated.

Another type of aberration might be caused by placing even perfectly formed electrodes in planes which are not all parallel to each other; or in other words, not perpendicular to the axis. Here one can think of such a lens as consisting of many lens sections in parallel (Fig. 4) around the axis so that with electrode spacing differing around the axis the focal lengths of these elements will differ accordingly. Now the variation of focal length that can be permitted in a lens, i.e., the tolerable spread of focal length that will just allow the desired resolution has been previously

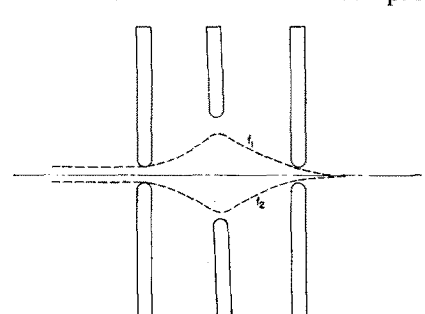


FIG. 4. Focal length variation around the axis.

computed.[1] Also approximate relations between focal length and the various inter-electrode spacings are known. From such information one can estimate the focal length spread and consequently the resolution limit due to the variation of inter-electrode spacing with azimuthal angle around the axis.

A third manifestation of insufficiently close manufacturing tolerances is the lack of concentricity of any one electrode. For example, a hole in the central electrode may not be a perfect circle. This is similar to the two preceding distortions, especially the case of variation of focal length with angle around the axis due to non-parallel lens elements. The difference, however, is that in the case of lack of concentricity, one may expect an averaging effect. If, say, one part of what should be a circle protrudes toward the axis slightly, then the rest of the circle tends to shield and diminish the effect of that single disturbance (Fig. 5a). Though this particular case has not been examined theoretically, closely related cases have been treated. Figure 5b shows the case of a hemispherical hub on one of two parallel plate conductors. This case has been worked out[3] and it is shown that the disturbing effect of the hub dies off very rapidly with distance from the plane—rapidly, that is as compared to the case of a spherical hub alone (without the benefit of the "averaging out" or shielding of the plane). From such analyses, one may make a reasonable guess as to the averaging factor to be expected when small distortions occur on the face of electrodes. The remainder of the estimation of the effect on resolution is as in the previous example.

The results of these rough analyses indicated first of all that only the objective lens needs to be given careful attention, since the magnification which is usually designed into this stage sufficiently reduces the tolerances required for the second and third stages so that there should be no problem in manufacture. As to the objective lens, approximate computations called for tolerances of a little better than one-thousandth of an inch in axial alignment, concentricity of individual electrodes, and inter-electrode spacing variation around the axis in order that resolving powers superior to 100A be possible.

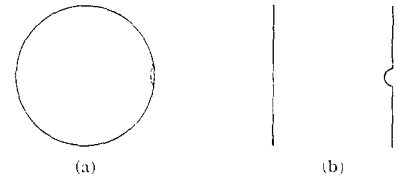


FIG. 5. Electrodes with imperfections in manufacture.

Since these computations are admittedly of questionable accuracy, it appears excusable at this time to attempt to manufacture the objective lens with tolerances considerably better than one mil or the tolerances may well be expected to set the limit to resolution.

CHOICE OF THE NUMBER OF STAGES OF MAGNIFICATION

In an electrostatic microscope having disk-type electrodes, all capable of fitting into one cylindrical enclosure, it becomes inviting to consider radically shortening the electron microscope structure by the use of more than two stages of magnification. This shortening of the structure, in addition to the obvious advantages in vacuum pumping operations and the saving of material and over-all weight, yields a system which is much more easily shielded and aligned.

It is well worth knowing beforehand, however, whether or not the choice of the number of stages and the spacing between lenses will materially affect the resolving power, the brightness of the final image for a given current density at the specimen, and other over-all performance and design characteristics. Let us reconsider then the various design conditions that have been previously discussed to determine how these matters will depend upon the number of lenses.

Expressions were derived in the previous paper[1] for resolution as limited respectively by spherical and chromatic aberrations:

$$\delta_{\text{spher}} = (pS/2f^3)r^3; \tag{1}$$

$$\delta_{\text{chrom}} = (p/f)(\Delta V/V)r. \tag{2}$$

S is a characteristic constant of the lens type, f is the lens focal length, r is the radius of the lens stop (evaluated at the lens exit), p is the object distance, and ΔV and V are electron voltage spread and average voltage, respectively. When the number of stages is varied for a fixed f and fixed over-all magnification, the magnification per stage and the object distance p will also vary. With an increase in the number of stages, p increases.

Since the resolution as limited by spherical aberration [Eq. (1)] varies with the cube of the stop radius, a small percentage change in the latter will make up for a larger change in p. We can assume, therefore, that only a negligible decrease in lens stop need be made if the number of stages is increased say from two to three or four, if the resolution is to be held constant.

TABLE I.

No of Stages	p (cm)
1	1.00
2	1.01
3	1.05
4	1.10
5	1.15

If the resolution is limited by chromatic aberration [Eq. (2)], then the stop radius must be reduced in the same proportion as p is increased to hold constant resolution. Table I gives the variation in p with number of stages for a fixed over-all magnification of 10,000× and a fixed focal length for all stages of one centimeter.

When taking account only of spherical and chromatic aberrations, there is little need for considering any but the first stage. Regardless of what number of stages is selected, the magnification per stage will always be greater than unity, so that the angle of rays entering the second lens coming originally from an axial point on the specimen or its image will be less than that entering the first lens. Also the object for the second lens need not be imaged with so good a resolving power (referred of course to the second lens magnification scale).

Let us consider next the brightness of the final image for a given electron density passing through the specimen as a function of the number of stages. A limit in one direction may be obtained by assuming that each point of the object appears as a source of electrons spread uniformly over an angle of 2π solid radians (Fig. 6). The brightness is then determined by the opening solid angle θ of the objective lens. For a given stop diameter θ is seen to decrease according to $1/p^2$. If the diameter of the aperture is decreased to preserve resolution as the number of stages is increased, then the brightness is further decreased. When chromatic aberration is the limit to resolution (a case much more pessimistic as regards brightness than if spherical aberration is assumed as the limit), the brightness would decrease with the fourth power of object distance. Thus a two-stage instrument will have around 16 percent more intensity in the image than a three-stage instrument for constant focal length lenses, constant over-all magnification, and constant resolution as limited by chromatic aberration.

For a wide range of specimens, it certainly will not be true always that the opening angle determines the brightness as assumed in the previous pessimistic reasoning. The true situation on the average will probably be somewhere between the above assumption that each point of the object is a source, and the following picture: The specimen is generally transparent and thus allows electrons to pass through practically undisturbed in angle of inclination to the axis, which angle is set by the gun to be small regardless of the number of stages. The denser portions of the sample deflect or absorb electrons and produce correspondingly less brilliant spots on the final screen. With the assumption that the gun sends electrons through the specimen at an angle that is smaller than the opening angle of the objective

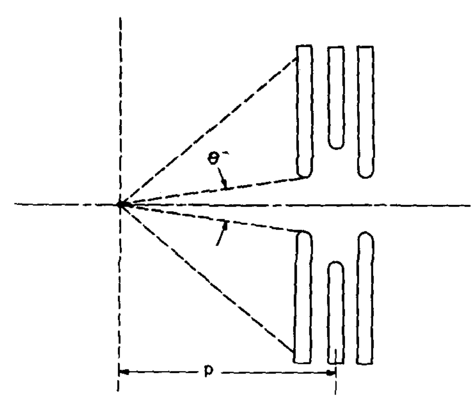


FIG. 6. Point source in front of lens.

lens, the brightness is hardly then dependent upon the number of stages.

These two extreme pictures: (1) The specimen acts as a source of electrons which completely and

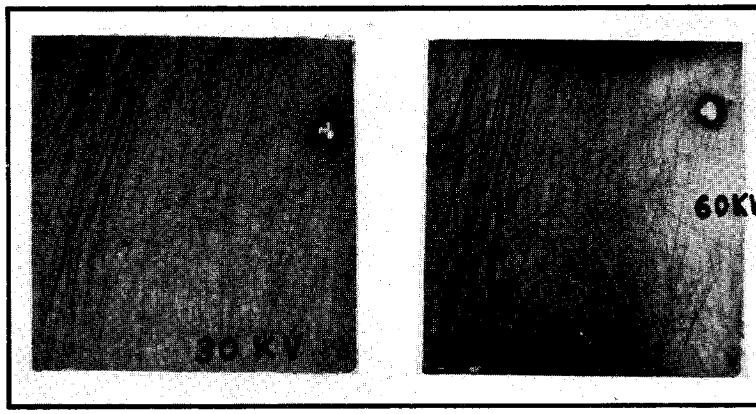


FIG. 7. Vanadium pentoxide at two different accelerating voltages.

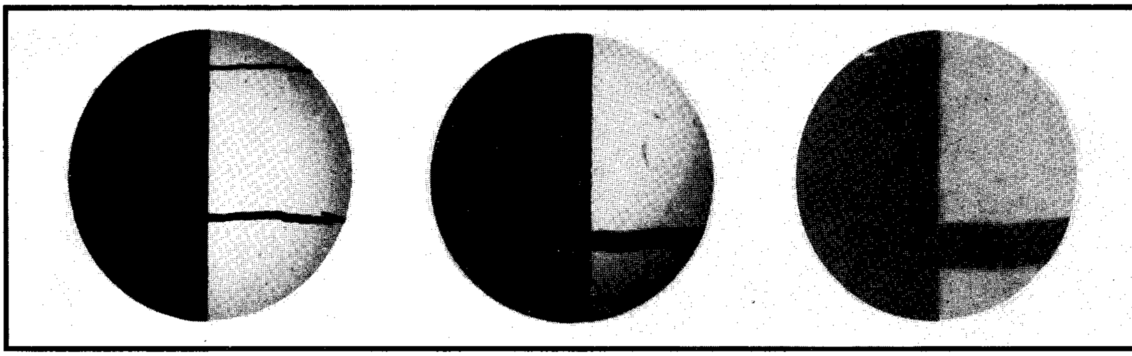
uniformly fills the opening angle of the lens; (2) the specimen allows the electrons to pass through undisturbed in angle from their initial paths after leaving the gun—may be used also to see how depth of focus referred to the object plane is dependent upon the choice of the number of stages of magnification. For a specified resolution, it can easily be shown from elementary optics that the depth of focus in the object plane decreases as the object position approaches the lens; this, assuming that the opening angle of the objective is completely filled by the rays which are assumed to come from a point on the axis. If, on the other hand, the electrons are assumed to pass through the specimen parallel to the axis, and to retain approximately their initial angle after passing through the specimen, then obviously the depth of focus is very long no matter what number of stages is selected. Furthermore, we have already granted the possible reduction of stop diameter as the number of stages is increased to maintain a given resolution. The depth of focus will be further increased by any such stop decrease. The depth of focus will thus always increase with an increase in the number of stages for a given over-all magnification, regardless of which of these assumptions is made.

Various shielding problems may be said in general to be reduced when the number of stages is increased—largely because of the tremendous gain in simplicity of shielding that the shortened electronic chamber makes possible. Quite apart from this practical consideration of shield design is the fact that a short path allows less possibility for the cumulative action of stray fields along the entire electron path to become excessive.

METHOD OF PHOTOGRAPHY

There are two well-known methods for producing a photographic record of an electronic image. Either the film is placed in the vacuum or else a picture is produced on a fluorescent screen and a photograph of the screen is then taken from outside of the vacuum with an ordinary camera. Both methods have been used for many years in the cathode-ray oscillograph[4] art, and both methods were described in an early electron microscope patent.[5] It is quite evident that there are many advantages to be gained from the use of external photography of the image. For example, the necessity for a pre-exhausting chamber to enable photographic film to be brought into the high vacuum without unduly long delays in re-evacuating the entire chamber is entirely eliminated.

There are other considerations in the choice between external and internal photography which require considerable experimentation to evaluate. There is, for example, the question of exposure time. If the image is to be magnified electronically to the desired degree for observation and the fluorescent screen then photographed at unity magnification, the numerical aperture of available cameras is then such that the exposure time will be very long. The time duration in itself is probably not a serious objection, since the operator will lose no more time in waiting for the exposures than would ordinarily be required for insertion of photographic film. Vibration problems and stray light may, however, easily become troublesome. Of greater importance (unless one risks destroying the specimen) is that



10× 25× 50×

FIG. 8. Photographs of an electron image on a fluorescent screen at various magnifications.

it is exceedingly difficult to obtain at high electronic magnification a sufficiently intense image on the fluorescent screen to make possible easy visual observation in a well-lighted room—let alone short exposure time photographs of near unity magnification.

Since the numerical aperture of a practical microscope camera increases with its magnification and, since it is highly desirable to improve radically the ease of visual observation, it is especially attractive to consider a system in which some of the magnification takes place in ordinary glass optics. Thus, as an example, for an over-all magnification of the order of 10,000×, the fluorescent screen picture might possess about 1000× magnification and the light microscope or camera might magnify another tenfold. By use of this technique, it is possible to look at the images on the fluorescent screen directly; then to view it under various magnifications easily adjusted at will from outside the instrument in the conventional light microscope manner; and finally to photograph the same fluorescent screen image which has been studied visually.

For visual observation, this scheme has an additional advantage in that glass optics have been developed to the point where very considerably greater light efficiency can be had than in the system in which the completely magnified electronic image is viewed on the fluorescent screen at about a foot's distance, as is required in the more conventional electron microscope. The improved over-all brightness in the image makes possible easy observation even at low voltages where for a goodly portion of specimens which it is desired to study in such a microscope exceedingly good contrast may be obtained. Figure 7 shows pictures of vanadium pentoxide recorded by the direct action of the beam on photographic film at two different voltages. These pictures were taken with a conventional electron microscope[6] at 4000 times magnification. As will easily be seen by noting the photographs, the lower voltage picture compares quite favorably in contrast and resolution.

All of these advantages encourage development of a fluorescent screen which will be capable of producing an image whose resolving power will stand the required light-optical magnification. Such screens have been prepared by the authors and tested for resolving power and ease of visual observation with a light microscope. It is fairly easy to obtain a fluorescent screen whose grain size will not show under 200× magnification. However, the chief problem is that electrons, even if they converge at a true point on the surface of the fluorescent screen, will not result in a point source of light. The disperson of the electrons and the resulting light sources throughout the thickness of the screen material limits the practical magnification of an image on a fluorescent screen earlier than does the grain size. Photographs of electronic images of sharp edges on the fluorescent screen are shown in Fig. 8. These indicate the feasibility of this method for a practical electron microscope design. (It should be noted, of course, that similar dispersion of light and electrons occurs in varying degrees whether the beam falls on photographic emulsion or is viewed either directly or by transmission through a fluorescent screen.)

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New Books

A Laboratory Manual of Electricity and Magnetism

By Leonard B. Loeb. Revised edition. Pp. 121+xii, Figs. 34, $15\times22\frac{1}{2}$ cm. Stanford University Press, Stanford, 1941. Price $1.90 (paper covered).

This laboratory manual was written to accompany *Fundamentals of Electricity and Magnetism*, by Leonard B. Loeb, the text for the third quarter of a two-year course in general physics for engineers at the University of California. It contains twelve experiments. The aims of the book are stated in the preface as follows:

1. Every experiment should have a clearly defined objective.

2. This objective should be closely coordinated with the textbook used, and should be designed to emphasize *only the most basic principles and phenomena* dealt with in the text.

3. The experiments shall at all costs be quantitative.

4. They should give the student the standard methods and techniques of making the common electrical measurements.

5. In addition to the experimental procedure, the student should be told the principles involved, the methods of achieving absolute evaluation in the c.g.s. system, precision methods available, and the reason for choosing the method of the text.

6. In order to overcome the difficulties of students who have not had the principles of the experiment in the lectures, when four experiments are run simultaneously, a complete theoretical development is given with each experiment. This does not refer to any other material and assumes that the student knows only the prerequisites of the course. If the student does not read this material before coming to the laboratory, he cannot finish the experiment in the allotted time and must postpone the experiment. This forces the student to come with some understanding of the experiment.

7. The procedure is illustrated both with schematic diagrams and perspective drawings of the apparatus and connections to make clear to the student the actual situation that confronts him on the laboratory table.

8. A form is given for the student to tabulate his results. There are five complete sets of these forms, four of which have perforations for tearing them out. A tabular report is justified on the ground that "by devising a form adequate for recording in a logical and orderly fashion the results of the measurements one not only guides the effective and orderly performance of the experiment, but also trains the student in processes of logical thinking, recording and computation." This avoids "needless copying of the text or manual or of some ancient experiment dog-eared in fraternity files." "Furthermore, the grading of problems becomes simpler, thereby reducing the assistant's load and permitting a much more uniform system of grading on the basis of accuracy tolerance."

The aims thus set forth seem to have been admirably achieved in the text. With most of the aims, one can heartily agree. The experiments are well chosen and coordinated. The results of one experiment are used in other experiments and the limitations of the method are clearly stated. Other interesting experiments not done in the text, which the student might wish to do later, are suggested.

In the complete theoretical treatment, as is to be expected, the derivation of the more complicated formulas is referred to the text. This was not supposed to be done according to aim (6). Although in a large course it is probably necessary to report the experiment by filling in a form, as in aim (8), this tends to make the experiment routine and discourages independent thinking on the part of the student. In writing up laboratory experiments, the student has his only opportunity to present material in his own words. The ability to write a good report is sadly lacking in most students. The reports do not have to be long, and they certainly should not be copied, but a statement by the student of what the experiment is all about will give him much needed practice in scientific expression. The student is often required by other instructors to write the report before leaving the laboratory.

With elementary apparatus, grades on the basis of an accuracy tolerance are somewhat a matter of chance. Tolerances could be set up suitable to the apparatus, and the student held to these limits with grading on an all or none basis. One is not going to reproduce the results of the Bureau of Standards in the elementary laboratory. What the student should learn is the principles, why the results are not more accurate, and what to do if he wants to make them more accurate. He should be expected to get results only within the limits of his apparatus by exercising proper care and technique. The statements and derivations in some cases might be made clearer to the students. For example, in the middle of page 36, it is not clear how one obtains the resistance by letting an e.m.f. flow in a coil. These and other minor errors in the text can be rectified as they are brought out by the students.

The author apologizes for the drawings. This seems unnecessary as the connections are clear and should enable