The Philips electron microscope EM 300

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Two parallel lines of attack can be distinguished in the development of the Philips electron microscopes. Improvement of the resolving power goes hand in hand with improvement of the arrangement and design of the instrument, giving maximum efficiency of operation and ease of use. The latest Philips electron microscope, the EM 300, offers some noteworthy advances in both of these aspects.

Introduction

The range of electron microscopes put on the market by Philips in the last 20 years, the EM 100, the EM 75 and the EM 200 [1], has recently been extended by the addition of a new instrument, the EM 300. The main difference between this microscope and the others is its even better resolving power (less than 5 Å). The EM 300 is also simpler to operate than its predecessors, and in its equipment and design even more attention than before has been paid to the convenience of the user. A large number of matching accessories have been developed; so that the microscope can be used for a very wide variety of investigations without requiring major changes of the instrument. The picture can be displayed on a television monitor [2] as well as on the usual fluorescent screen. The magnification can be varied in 31 calibrated steps from 220 times to 500 000 times; the range of possible magnifications thus partly overlaps that of the optical microscope.

As can be seen from fig. 1, the microscope tube of the new instrument is vertical, as it is in the EM 200 and the EM 75. This arrangement has proved to be the best one for stability, ready accessibility of the operating controls, easy attachment of accessories and simple maintenance. The cabinet on the left-hand side contains the sensitive electronic circuits, such as the stabilizing circuit for the high voltage and the lens currents, and various auxiliary circuits. The vacuum system is accommodated in the central section, behind the space for the operator's feet. This central section, which carries the microscope tube, is very sturdily built to ensure mechanical stability, and its weight is taken directly by the floor, independently of the two side cabinets.

In the projection chamber, fitted with three viewing windows, the fluorescent screen is located at the height of the table-top. This screen can be swung aside to give the electrons access to a plate camera or to a television camera tube ("Plumbicon" [3] tube). When the camera tube is used, an image intensifier can be interposed. Facilities are also available for taking photographs with two types of roll film camera in addition to the plate camera.

The electronic circuits are all transistor circuits. Some of them are water-cooled. All circuits are contained in standard exchangeable modules. The operating controls not regularly needed are on sliding panels immediately below the table-top (fig. 2). There are no controls on the table-top itself.

One of the distinguishing features of the vacuum system is that it works automatically, and another is that the roughing pump can be switched off for hours once a sufficiently high vacuum has been reached. This eliminates a major source of vibration and noise. The vacuum is better and is reached more quickly than in the predecessors of the EM 300. A number of vacuum locks are provided, so that the filament, photographic plates or films and the specimen can be changed without having to admit air into the entire microscope tube.

Photographic exposures are also very easy to make. The film and plate transport is motor-driven, and the EM 300 is fitted with an exposure meter which is arranged so that photographs may be taken in much the same way as with a semi-automatic camera: for correct

Fig. 1. The Philips EM 300 electron microscope.
exposure the operator adjusts the shutter speed or current density on the screen until the pointer of a meter on the control panel is at the centre of the scale. To make an ordinary exposure and a diffraction exposure of the same object one after the other, it is simply necessary to turn the knob of the “function switch”.

An important feature of the new microscope is that all parts of the electron-optical system can be separately aligned. This minimizes displacement of the image in the image plane, due to variations in the strength of the lenses.

The very high resolving power of the new microscope is illustrated by fig. 3. It is so good partly because of the mechanical stability noted earlier and partly because of the excellent stabilization of lens currents and high voltage, the low sensitivity to external fields and, in particular, the extremely short focal length of the objective lens (1.6 mm). The importance of making the focal length short is explained in the next section, where the image formation and the electron-optical factors that determine the resolving power are dealt with. The other sections will be concerned with technical features of the microscope and accessories.

Electron optics and resolving power

Fig. 4a shows schematically the principal electron-optical components inside the microscope tube. Apart from various diaphragms, these components (from...

b) Path of rays in normal use (high magnifications).  The intermediate lens and the diffraction lens are both in operation.

c) Path of rays for medium magnifications.  The objective lens forms a virtual image of the object.  The intermediate lens is switched off.

d) The diffraction lens used as objective (very small magnifications, for initial investigation of a specimen).  In the case illustrated the objective lens is weakly excited.  

e) Electron diffraction.  At the object plane of Pr the diffraction lens now no longer forms an image of the object, but of the focal plane F2 of the objective.  If necessary the intermediate lens can be switched off.

d) The size of the spot projected on the specimen, and its intensity (current density) can be varied over a wide range by varying the strength of the two condenser lenses (Fig. 5).  This has considerable advantages which are not present in an illumination system using only one condenser lens [3].  In the first place, the electron...
The specimen can be illuminated in the normal way, or with oblique illumination (dark-field illumination). The maximum value that can be chosen for the angle between the axis of the beam and the optical axis of the microscope is as much as 5°.

The optical characteristics of the next component, the objective lens, which are of great importance to the quality of the image formation and the resolving power will be dealt with in more detail later. It is sufficient to note here that this lens can be varied in strength, that the coil is situated above the specimen, and that the specimen is located inside the magnetic field of this lens (immersion objective).

The diffraction lens, which is relatively weak and has a wide bore, and the intermediate lens can also both be varied in strength. If these two lenses are used — either together or separately — as an intermediate lens, the whole range of magnifications can be covered without having to alter the strength of the projector lens. For high and very high magnifications (greater than 20,000 times) the combination shown in fig. 4b is used, for moderate magnifications (4000 to 20,000 times) the combination of fig. 4c, and for small magnifications that of fig. 4d. In the last case the diffraction lens in fact functions as a (non-immersion) objective lens; the diffraction lens could hardly be used in this way if the specimen were above the coil of the objective lens, because the distance from the specimen to the lens would then be too great.

When both the diffraction and the intermediate lenses are used, as in fig. 4b, the magnification is varied by varying the strength of the intermediate lens. (The strength of the objective lens is also varied slightly in order to keep the image in focus.) The diffraction lens is always set to maximum strength. With the arrangement of fig. 4c, the intermediate lens is switched off and the magnification is varied by means of the objective and the diffraction lenses. As can be seen, the objective here forms a virtual image of the object. This image, which moves upwards with increasing magnification, is projected by the diffraction lens on to the object plane of the projection lens. With the mode of operation shown in fig. 4d, the objective lens is usually weakly energized so as to cause the electron paths to cut the optical axis at the location of the selector diaphragm D4. This can then act as an objective diaphragm, so that good contrast is still obtained when the instrument is used in this way. If it is desired not to subject the specimen to a magnetic field, or to subject it only to a field whose strength is accurately known, the objective lens is not excited. As a result of the arrangements and modes of operation illustrated in fig. 4a-d, the distortion of the magnified image obtained with the EM 300 is low even at the weakest magnifications. Finally, fig. 4e shows the path of the rays when the microscope is used as an instrument for making electron diffraction photographs.

Resolving power

The resolving power of the EM 300 is primarily determined by the objective lens. The less fundamental factors affecting the resolving power, such as the mechanical and electrical stability, are of lesser importance in the new microscope. We shall therefore briefly review the way in which the resolving power is affected by the principal lens errors: spherical aberration, chromatic aberration and astigmatism.

Chromatic aberration cannot be neglected because an electron beam in an electron microscope can never be completely monoenergetic: there is energy dispersion immediately outside the gun since the electrons are liberated by thermionic emission, velocities are affected by space charge in regions where the paths cross one another (Boersch effect) and finally not all the electrons are subject to the same amount of energy loss in the specimen. These effects make it necessary to take account of chromatic aberration even in an electron microscope that is electrically perfectly stabilized.

Every magnetic lens with circular symmetry suffers from positive spherical aberration, that is to say the focal length is smaller for the peripheral rays than for the paraxial rays. Unfortunately, no practical method has yet been found for correcting this lens error. The spherical aberration can, however, be minimized by choosing appropriate values for the spacing and bore of the pole-pieces, and in particular for the excitation of the lens. This minimum of spherical aberration decreases as the focal length of the lens is made smaller. This is the primary reason for making the focal length of the objective lens as small as possible in order to obtain a good resolving power.

The chromatic aberration of an electron lens is also less when the focal length is smaller. The chromatic aberration constant Ce of the EM 300 (see below) is therefore only 1.3 mm. This means that the spread of the energy of the electrons will prevent the theoretical resolving power from being achieved only when the electrons pass through a relatively thick specimen. Provided the specimen is sufficiently thin (e.g. a carbon film
of 20 nm), only a small fraction of the electrons loses energy in the specimen.

If spherical aberration only were present, and if the situation in an electron microscope were entirely analogous to that in an optical microscope — in particular with respect to the illumination of the object — the theoretical resolving power found from the classical treatment due to Rayleigh would be 2.3 Å (0.23 nm) at an accelerating voltage of 100 kV.

In ordinary optics the classical treatment of resolving power has been supplemented in the last 20 years by the theory of contrast transmission, which uses contrast-transfer functions and curves. For some years now this type of treatment has also been applied to electron lenses. It will appear that the value of resolving power quoted above can be approached very closely, but also that the interpretation of the image of an object whose details are of the order of magnitude of Ångströms is a complicated matter.

We shall now consider how the transfer of contrast in the object is affected by spherical aberration, defocusing of the microscope and, through chromatic aberration, by fluctuations in the high voltage and the lens currents.

Let us consider a beam of rays emitted from the first focal point. If there were no defects in the lens, the spherical wave-front of the beam would emerge from the lens as a planar wave-front. The lens defects do however cause some deviation, known as the wave-front aberration $\Delta$, which depends on the radius vector $r_b$ in the plane under consideration and on the position of that plane. (For object points lying in the first focal plane but away from the optical axis, different values of $\Delta$ are found at a given $r_b$, but this complication may be neglected in an electron microscope since the objects are relatively small.) Taking only the spherical aberration into account, then the wave-front aberration in the second focal plane is given by $\Delta(r_b) = -Ar_b^4$. If the object point is on the axis but not at the first focal point, an extra term $Br_b^2$ enters into the equation, where $B$ depends on the distance $d_{zp}$ of both points, the “defocusing”. The total wave-front aberration is then:

$$\Delta(r_b) = -Ar_b^4 + Br_b^2.$$  \hspace{1cm} (1)

Fig. 6 gives a curve of this function for the objective lens of the EM 300, for the case $B = 0$ and also for four cases where there is a certain amount of defocusing. The wave-front aberration $\Delta$ is expressed in terms of the wavelength of electrons at 100 keV (0.037 Å). A second horizontal scale beneath the graph gives $r_b$ in terms of the line spacing (grating constant) $d$ of a sine grating that diffracts an electron beam of 100 keV through an angle $\alpha$ such that the diffracted beam is focused into the second focal plane at a distance $r_b$ from the optical axis.

From the curves of fig. 6 we can immediately find the effect of the spherical aberration and the defocusing on the diffracted image obtained from a given grating in the second focal plane, and thus at the same time obtain some idea of the imperfections that the magnified image on the screen will have. This comes about since an object can be regarded as a superposition of a variety of phase and amplitude gratings with different constants. (An object is a phase object when the emergent wave has the same amplitude and thus the same intensity at all points, but differs locally in phase.) For example, at zero defocusing the beam diffracted by an amplitude grating with $d = 5.3$ Å has a wave-front aberration of $-\frac{1}{2}\lambda$. This means that the image of this grating looks like that of a phase grating, i.e. the grating structure is completely imperceptible on the screen. On the other hand, if the object is a phase grating, its image will have maximum contrast. Because of the spherical aberration the structure of the phase grating, which in the ideal case would be imperceptible, can now be observed.

If we determine the contrast with which amplitude and phase gratings with a different grating constant are reproduced, and we plot the result in a graph, we obtain what are known as contrast-transfer curves. The

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(1) The advantage of using a third magnifying lens, in addition to the objective and the projector lens, was first pointed out by J. B. Le Poole in Philips tech. Rev. 9, 33, 1947/48.


(3) See the second article quoted in reference (1).

(4) See for example K.-J. Hanszen, Naturwiss. 54, 125, 1967 (No. 6).
curves for the EM 300 are shown in fig. 7. It can be seen from this figure even more clearly than from the previous one that there is no setting at which the finest grating structures ($d < 10 \text{ Å}$) can all be seen at the same time. For instance, with a defocusing of 120 nm amplitude gratings with $d = 3 \text{ Å}$ and $3.5 < d < 6.5 \text{ Å}$ are reproduced with good contrast, but those where $d$ is in the region of 3.25 and 9 Å are not. The best setting in this respect is the one with a defocusing of 40 nm. The corresponding defocusing for phase structures is 80 nm. We should add that there are many specimens (particularly biological ones) that yield only very weak amplitude contrasts. In the investigation of such specimens the presence of phase contrasts can be a help instead of an interfering effect.

From the foregoing we can find the stability requirements which the accelerating voltage $V_0$ and the excitation current $I$ of the objective lens should meet in order to minimize the effect of fluctuations in $I$ and $V_0$ on the resolving power. The displacement $\delta z_F$ of the focal point caused by variations $\delta V_0$ and $\delta I$ is given by:

$$\delta z_F = C_0 (\delta V_0/V_0 - 2 \delta I/I).$$  

(2)

The quantity $C_0$ is the chromatic aberration constant mentioned previously. We can now calculate that the contrast decreases to 90% if, in the period of observation (one minute at the most), the wave-front aberration $A$ varies between $\pm \frac{1}{2} \lambda$ and $-\frac{1}{4} \lambda$, and all values are equally likely. Taking this as the criterion, we find from the wave-front aberration curves what variation in defocusing is permissible, and then from equation (2) what relative variation of $V_0$ and $I$ this corresponds to at a given value of $d$ (Table I). For the EM 300 the relative drift of $V_0$ is less than $5 \times 10^{-6}$ per minute, and that of $I$ less than $2.5 \times 10^{-6}$ per minute. It is evident from this that the drift of $I$ and $V_0$ in the EM 300 does not prevent the theoretical resolving power from being reached.

**Table I. Maximum deviation in the accelerating voltage $V_0$ and the lens current $I$ at which a phase object with a periodic structure (phase grating) of line spacing $d$, still gives an image with good contrast.**

<table>
<thead>
<tr>
<th>$d$ (Å)</th>
<th>$\delta V_0/V_0 - 2 \delta I/I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$110 \times 10^{-6}$</td>
</tr>
<tr>
<td>5</td>
<td>$26 \times 10^{-6}$</td>
</tr>
<tr>
<td>4</td>
<td>$17 \times 10^{-6}$</td>
</tr>
<tr>
<td>3</td>
<td>$9.7 \times 10^{-6}$</td>
</tr>
<tr>
<td>2.3</td>
<td>$5.7 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

If the same is to apply for the effect of the astigmatism of the objective lens, then there should be virtually no change in the contrast-transfer curves when the plane in which the diffracted beam lies changes position. If this plane is rotated one full turn around the optical axis, the defocusing range must not be greater than about 10 nm. This means that the requirements for the circular symmetry of the pole-pieces are very exacting. These requirements cannot be met using normal machining methods and tools. The pole-pieces of the EM 300 are therefore made on a specially designed ultra-high precision machine equipped with hydrostatic bearings [8]. Before the pole-pieces are mounted in the microscope they are checked with a precision instrument, one of whose special features is that its own mechanical deviations do not affect the measurement [9]. Even with these special devices and provisions the astigmatism still cannot be reduced to a sufficiently small value. The residual astigmatism is compensated by means of a stigmator, which in principle is simply a combination of two cylindrical magnetic lenses whose strength can be varied. In the EM 300 the stigmator is a set of eight small coils mounted directly under the objective lens.

Apart from the above-mentioned characteristics of the objective lens and the more trivial factors referred to in the introduction, like the mechanical stability and sensitivity to stray magnetic fields, other factors affecting the resolving power are the quality of the specimen stage and the brightness of the electron source.

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[9] This instrument was built by the Central National Organisation for Applied Scientific Research in the Netherlands (TNO), Technical University of Delft, and was described by J. Kramer, J. B. Le Poole and A. B. Bok in TNO-Nieuws 20, 297, 1965 (in Dutch, with English summary).
The specimen stage must be capable of holding the specimen in position to within a few ångströms during the period of an exposure. The specimen stage in the EM 300 is the same as the one used in the EM 200, which meets these requirements.

The brightness of the electron source comes into the picture in the following way. We have just seen that in order to make the very finest details visible, it is often necessary to make use of phase contrasts. This calls for highly coherent illumination, and this condition is most easily met with a small illuminating aperture. (The condenser system of the EM 300 does in fact permit operation with a small illuminating aperture, as we noted earlier.) In order to obtain a sufficient current density at the fluorescent screen when using a small illuminating aperture and the maximum magnification of the instrument, it is necessary to have an extremely bright electron source.

The microscope tube

In this section we shall consider the principal design features of the components contained in the microscope tube. A simplified cross-sectional drawing of the tube is shown in fig. 8. In addition to the components in fig. 4, the drawing shows

Fig. 8. Cross-section of the microscope tube. G gun. An anode. C1 and C3 condenser lenses. O objective lens. St specimen stage. Di diffraction lens. I intermediate lens. Pr projector lens. G gimbal ring. 2 knob for diaphragm D1 (fig. 4). 3 knob for diaphragm D2. 4 coils for oblique illumination and focusing. 5 knob for objective diaphragm D0. 6 knob for selector diaphragm Ds. 7 alignment controls for lenses and pole pieces. 8 vacuum valves. 9 shutter. 10 camera (35 mm). 11 binocular microscope. 12 plate camera. 13 vacuum line. 14 rapid coupling device. The camera 10 can be replaced by an electron-diffraction device (i.e. a specimen holder for large specimens).
the specimen stage, the stigmator, the coils for oblique illumination, the photographic shutter and a number of vacuum valves and locks, as well as a number of controls for operating the various diaphragms and for the alignment of lenses, pole-pieces, etc.

**Electron-optical section**

The electron gun is of the conventional type, comprising a filament, a Wehnelt cylinder and an anode. It can be aligned by displacing the cathode (here taken to be the combination of filament and Wehnelt cylinder) with respect to the anode and rotating it about two axes perpendicular to the centre-line of the microscope tube and passing through the emitting tip of the filament. The mounting of the cathode in a gimbal bearing ensures that it moves smoothly and can be accurately aligned. The height of the anode can be adjusted while the gun is in operation. This is important in order to achieve maximum brightness from the electron gun at voltages lower than 100 kV. Facilities such as the rapid coupling arrangement and the vacuum lock situated immediately below the electron gun enable a filament to be replaced in less than a minute.

Each of the condenser lenses is fitted with a diaphragm holder containing three interchangeable diaphragms. Fitted against the lower pole-piece of C2 is a disc which contains the stigmator. This compensates for departures from circularity of the illuminating beam caused by astigmatism in the condenser system. (If the beam is not of circular cross-section, the specimen may receive more thermal energy from the beam than necessary, and there may be unwanted charging effects at the edges of diaphragms, etc.)

In addition to the above-mentioned facilities for displacing and tilting the gun, the illumination system has a variety of other correction and alignment facilities which cannot all be mentioned here.

The design of the objective lens is illustrated in fig. 9. This lens, together with the specimen stage (shown shaded), forms a single assembly, which however can easily be removed in order to change from one type of specimen stage (see below) to another.

The upper pole-piece of the objective lens cannot be displaced and constitutes one of the fixed points used for alignment (the other is the centre of the fluorescent screen). The lower pole-piece can be aligned. When the current in the coil is at its maximum value (5 A), the magnetic field between the pole-pieces is about 1.5 Wb/m². Situated immediately under the lower pole-piece is the stigmator of the objective lens.

Fitted in the bore of the magnet coil, above the lens field, are the deflection coils for oblique illumination. These operate on the same principle as Le Poole's focusing device [10], and they can also be used for this purpose. Here, however, there are two pairs of coils instead of one. These pairs are arranged at right angles to one another, so that the azimuth of the plane in which the deflection takes place can be chosen as required.

The deflection coils of the focusing device are wound in such a way that the magnetic field they produce is highly uniform. There are also a few correction coils to compensate for any difference in orientation that may exist between the upper and the lower coils. With these facilities the angle between the beam and the optical axis can be increased to the high value of 5° mentioned earlier, with no noticeable change in the location at which the beam meets the specimen. When a set of these coils is used for focusing, very sharp images can be obtained even at quite high magnifications.

![Fig. 9. Schematic cross-section of the objective lens and specimen stage (shaded). The pole-pieces are shown black. When the upper part (including the coil) is detached from the ring W, the specimen stage can easily be removed. The lower pole-piece can be aligned.](image)

**Fig. 10a** shows how the specimen stage is mounted in the microscope tube. **Fig. 10b** shows the central section, which contains a cross-slide system. This system is driven by a system of pushrods and two levers, each driven in turn by micrometer screws, operated from the control panel. Exceptionally smooth and accurate movement of the specimen is obtained by proper balancing of frictional forces, spring forces and masses and by the appropriate choice of material. As in the previous Philips microscopes, the specimen is introduced through a vacuum lock by means of an injector.

The diffraction lens, the intermediate lens and the projector lens are relatively simple in design. The diffraction and intermediate lenses can be fully aligned, i.e. the lens can be displaced as a whole and in addition one of the two pole-pieces can be displaced with respect to the other. The projector lens can only be dis-
placed as a whole, which is sufficient because this lens is not varied in strength and no further magnification takes place after it.

Projection chamber and aids for viewing and recording

The aperture of the beam that converges at one point of the image formed in the projection chamber of an electron microscope is very much smaller than the aperture of the projector lens itself, and therefore the depth of focus is very great. This gives the designer considerable freedom in the positioning of the various viewing aids. A 35 mm camera is accommodated directly under the projector lens, and a plate camera just below the screen. Below this there is room for a camera for 70 mm film or for a television camera tube, which may if necessary be used in conjunction with an image intensifier. When the image intensifier is used, exposures can be made at a very low current density, permitting the investigation of specimens that would be damaged at the normal current density. In addition to the ordinary fluorescent screen there is a small screen with a very fine grain; the image formed on this can be viewed with a binocular microscope at a magnification of 10 times.

The arrangement of the plate camera is illustrated schematically in fig. 11. The main component is a rotating disc situated eccentrically with respect to the axis of the microscope tube. At every revolution this disc picks up a plate from a magazine, carries it into position under the microscope tube and, after the exposure is made, lets it drop into a box. The disc also carries the vacuum valve which shuts off the projection chamber from underneath. This is done by turning the disc until the vacuum valve is immediately under the tube opening and then raising it until it closes the opening.

Between the projector lens and the 35 mm camera there is a rotating shutter, which can be used for all photographic exposures. A rotating shutter has constructional advantages in view of the requirement that opening and closing must cause the least possible vibration.

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[10] See the first article quoted in reference [1].
Vacuum system and electrical equipment

The vacuum system of the EM 300 (fig. 12) is basically conventional — comprising a roughing pump, vacuum reservoir, mercury ejector pump and oil diffusion pump — but differs in some significant details from the system used in the earlier Philips microscopes.

In the first place facilities are provided which make the entire pumping process completely automatic. Besides making the instrument very simple to operate, automation has the advantage that the pumping process is optimized and human errors in operation are excluded, thus reducing the risk of breakdown. In the first phase only the roughing pump is in operation and all the valves, apart from $V_3$, are closed. When the pressure at the location of the Pirani gauge $M_1$ has dropped to about 0.1 torr and the two diffusion pumps are hot enough, $V_1$ closes and $V_2$ opens. If the pressure at $M_1$ again has dropped to 0.1 torr, $V_3$ closes and $V_1$ and $V_3$ open. The buffer vessel, the mercury ejector pump and the oil diffusion pump are then in series between the roughing pump and the tube. Once the pressure above the oil diffusion pump at the location of the Penning gauge $M_2$ has dropped to $10^{-8}$ torr, valve $V_1$ closes, the roughing pump stops and $V_4$ opens. Since after the second phase the roughing pump is isolated from the microscope tube by the closing of $V_2$, contamination of the vacuum system by oil from the roughing pump is minimal; there is no back diffusion of oil vapour above about 0.1 torr. Another favourable feature here is that the roughing pump normally operates for so short a time that it barely gets warm.

There are of course various safety devices in the automatic system which protect the microscope from damage if the water-cooling should fail, if there should be a serious vacuum leak, if a heating element should break down, and so on. The high-vacuum valve $V_3$, for example, is arranged so that the valve closes immediately if there is a mains failure.

Other differences between the equipment of this and the earlier Philips microscopes are the incorporation of a pump unit with a very much higher pumping speed and the provision of a number of vacuum valves in the microscope tube and in the viewing chamber. As we noted earlier, there is no need to let air into the entire microscope tube of the EM 300 when changing a filament or loading the plate camera.
The *electrical equipment* of the EM 300 is rather different from that of the earlier Philips microscopes. The most conspicuous difference is the use of transistors instead of valves; in the whole of the electrical equipment there are only two valves, in the high-voltage stabilizing circuit. The advantage of transistor circuits is that they are more reliable and develop less heat. It is also much easier to use printed wiring with transistor circuits than with valve circuits. The changeover to transistors made it necessary to develop new circuits for most sections of the electrical equipment.

In the following parts of this section we shall deal at somewhat greater length with some important circuits.

*The universal control amplifier*

In order to be able to stabilize the lens currents and high voltage to such a degree that their fluctuations do not prevent the theoretical resolving power from being achieved, fluctuations of about $1 \times 10^{-6}$ have to be detected. Since low voltages are used in transistor circuits, the control voltage derived from a lens current is also low, only a few volts. Variations of a few microvolts in the control voltage must therefore still be readily detectable. This calls for a highly sensitive amplifier with a carefully designed wiring layout: there must be no risk of interference from magnetic or electric fields or from coupling with other circuits. To offset these difficulties, there is the advantage that in transistor circuits the resistances across which the control voltages appear are small, so that the amplifier does not need to have a high input impedance.

The preamplifier which we have developed for the control circuits required in the EM 300, and which meets the above-mentioned requirements, is a special...
type of chopper amplifier. Its principle of operation is illustrated in fig. 14, and the main features are summarized in the caption. The d.c. input voltage is converted by the transistor circuit on the left (the chopper) into an alternating voltage with a frequency of 1200 Hz and then passed by a transformer to an a.c. amplifier. The output signal from this amplifier is converted into a d.c. voltage again by the circuit on the right.

The distinguishing feature of the universal control amplifier is that the conversion from d.c. into a.c. voltage is not effected mechanically, but by means of a transistor circuit. This arrangement was chosen for maximum reliability and long life. As can be seen, the input circuit is separated by a transformer from the a.c. amplifier; this gives considerable freedom from interference, and permits the unit containing the sampling resistor and the input circuit to be earthed separately. The output signal from the a.c. amplifier is not rectified by an ordinary rectifier but by a circuit which is more or less the counterpart of the chopper circuit, connected to the same oscillator (synchronous detection).

The chopper circuit in fig. 14, like any other chopper, causes interference signals, mainly during switching. Various measures have been taken to minimize these, but they can still reach a peak value of about 200 μV, which is far in excess of the variations of the control signal. Nevertheless, the new amplifier will give faithful amplification of control signals of 1 μV. This is due to the fact that the amplification has not been made unduly high, so that input signals may be as high as 200 μV without blocking occurring in the later stages of the amplifier.

Finally, some remarks on the chopper circuit. As can be seen, it consists of a symmetrical arrangement of four transistors. These are germanium transistors, selected in matched pairs for identical collector-emitter voltage at zero collector current. Germanium transistors are preferable here to silicon transistors, because in the transition from "completely" off to "completely" on (and vice versa) they require a much smaller signal on the base (70 mV r.m.s.). The use of germanium transistors therefore means that there is much less inter-
rack-mounted module of the kind already mentioned (fig. 15). The electrical equipment of the EM 300 contains altogether nine such modular units. They are used for the lens-current and high-voltage stabilizers, for the monitoring circuit and also for the circuit that supplies the reference voltage with which the control signal is compared in each stabilizing circuit.

The central reference voltage

For stabilizing the high voltage and the lens current a reference voltage is needed that meets at least the same requirements of stability. A simple and very effective solution is to derive the reference voltage from a battery, but in that case the battery must not deliver any current. In the EM 300 this is not practicable for the following reason. As the power for the lenses comes from transistor circuits, the currents used are relatively high. The sampling resistors must therefore be small (of the order of 1 \( \Omega \)). This means that the current cannot be varied by varying the sampling resistance, because in a resistance of about 1 \( \Omega \) the variations in the contact resistance would be too large compared with the total value. The lens current can therefore be varied only by varying the reference voltage, that is to say by connecting a potentiometer circuit across the source supplying this voltage. This rules out the use of a battery. For the EM 300 a reference-voltage source has therefore been developed that can deliver a current and meets the appropriate stability requirements. Its output voltage is about 10 V and varies less than 1 in 10^6 per minute and less than 3 in 10^5 in 24 hours. The circuit can deliver 50 mA and is short-circuit proof. The temperature coefficient averages 10^{-6} per \( ^\circ\text{C} \) and is never more than 3 \( \times 10^{-6} \) per \( ^\circ\text{C} \). All stabilizing circuits derive their reference voltage from this single voltage source.

Fig. 16 shows a block diagram of the reference voltage source. The main units are the amplifiers discussed above (fig. 15) and a bridge circuit consisting of three resistors \((R_1, R_2, R_3)\) and a Zener diode selected for low noise. The bridge circuit is housed in a small thermostat. The principle of operation is very simple. As soon as the part of the output voltage determined by \( R_2 \) and \( R_3 \) differs from the operating voltage of the Zener diode, the chopper amplifier receives an input signal and the output voltage is returned to the correct value. Variations too fast to pass the chopper amplifier are fed via capacitor \( C \) straight to the input of the difference amplifier.

Generation and stabilization of lens current and high tension

Fig. 17 gives a block diagram of the power supply system for the lenses and shows how the lens currents are stabilized. All the lenses are fed from a single rectifier which can supply a current of 20 A. The output voltage is 42 V unstabilized and 33 V stabilized. From the output of the voltage stabilizer the current is distributed to the six lens circuits, each of which is a series configuration of a current regulator \( T_p \), a sampling resistor \( R_m \) and the lens coil with a polarity reversal unit \( RU \). A power transistor, or a number of power transistors in parallel, act as the current regulator which, to-
together with the sampling resistor, forms part of the current stabilizing circuit; these transistors are mounted on a water-cooled plate. All stabilizing circuits are short-circuit proof — if there is a short-circuit or overload, the current is reduced to a safe value. In addition, the stabilizer for the objective-lens current contains a cut-out which switches off the lens current if one of the parallel transistors becomes overloaded or fails. (With a parallel arrangement of five transistors this is not immediately noticed, but it is with one or two.) The sampling resistors are resistance-alloy coils, housed in a water-cooled oil bath to ensure stability.

The current is reversed by means of mercury-wetted reed relays. The entire operation is completely automatic and its sequence is as follows. First the lens coil is short-circuited and almost simultaneously cut off from the current source. After about half a second, which is sufficient for the dissipation of the field energy stored in the coil, the coil connections are reversed, the short-circuit is removed and the current again switched on. These relays are extremely reliable, and they are also bounce-free and have a very low and stable contact resistance.

Slow variations in the lens current are suppressed by applying the difference between the voltage across the sampling resistor and the reference voltage as an input signal to the control amplifier described above (fig. 15). The output signal from this amplifier drives the power transistor \( T_p \). This control does not respond to fast fluctuations, as the chopper amplifier cannot handle them. The output of \( T_p \) is therefore directly connected to the input of the difference amplifier through a capacitor \( C \) (cf. fig. 16).

As explained above, changing over to another lens current entails altering the reference voltage. This is done by means of a potentiometer circuit (on far left in fig. 17) consisting of a fixed resistor \( R_1 \), a resistor with tap \( R_2 \) and a variable resistor \( R_3 \). The form of \( R_2 \) differs for each lens, varying from a very simple to a highly complicated arrangement. The objective-lens current can be varied by means of a divider in very small steps over a large range (the smallest steps are 4 in \( 10^6 \)).

More than one potentiometer is provided for three lenses. This makes it possible for the user to switch from normal magnification to very low magnification, or to electron diffraction, by merely turning the function switch mentioned previously.

There is a similar facility, as in previous Philips microscopes, for changing over to another high voltage. The resistor \( R_3 \), which controls the magnitude of the current in the potentiometer circuits, is coupled to the high-voltage switch and controls the current in such a way that when the high voltage is changed to another value the illumination, magnification and focusing remain practically unchanged.

A low-frequency alternating current (1.5 Hz) can be applied to the input of the chopper amplifier. In this case the lens current is modulated approximately 7%, which is necessary for alignment. (Changing the strength of a lens causes a rotation of the image, so that the point where the optical axis cuts the image plane can be found.)

The recording shown in fig. 18 gives a good idea of the stability achieved. There is little variation in current even over periods much longer than the one minute mentioned earlier.

The high voltage is stabilized by means of two control circuits, which have some sections in common. The first is completely analogous with the circuit of fig. 17; the correction signal produced in this circuit is added to the output voltage of the high-voltage generator. This circuit has a limited control range, however (about 1200 V on either side), which would rapidly be exceeded if no further provision were made. This difficulty is avoided by arranging that the output voltage also controls the stabilizing circuit that holds the primary voltage for the high-voltage transformer constant. In this way only slow variations can be smoothed out,
but the control range is very wide (0 to 100 kV). Together, the two circuits are capable of keeping the high voltage constant to the extent required. For interfering signals at a frequency lower than about 10 Hz the control is principally achieved through the supply voltage. As a result of the control method described, the loop gain is very high at low frequencies (more than $10^5$ below 1 Hz).

The accessories

The accessories for an electron microscope are almost as important as the microscope itself, since they often determine whether or not an investigation can be carried out. Besides the accessories we have already mentioned, like the cameras, the television camera tube and the image intensifier, the EM 300 has many others: we shall just mention a few of them here. One important accessory is a cooling element (below 120 °K), which can be brought close to the specimen in the tube to reduce contamination of the specimen by carbon formed by the breakdown of hydrocarbon molecules (see fig. 10b). There are also a large number of specimen holders enabling the specimen to be put under tension, cooled (to below 120 °K), heated (to 1250 °K) and so on. A special type of specimen stage, called a goniometer stage, enables the user to put the specimen into any required orientation (fig. 19). This is arranged so that the specimen can be tilted about an axis that

![Fig. 19. Horizontal cross-section of the microscope tube with goniometer specimen stage.](image)
cuts the microscope axis, and so that any given detail of the specimen under investigation can be made to coincide with this point of intersection. A change in the position of the specimen thus causes no change in focus or magnification, nor any change in effective camera length for diffraction exposures.

Among the many specimen holders that can be fitted in the goniometer stage there is one that permits the specimen to be rotated 360° in its own plane about an axis through its centre. This facility allows a free choice of the azimuth of the tilt we have just mentioned.

When the goniometer stage is used, the pole-pieces of the objective lens illustrated in fig. 9 have to be replaced by others with a wider gap since otherwise there will not be enough room for the tilting of the specimen. This has the result of giving the objective a greater focal length (4.1 mm). In order to concentrate the field as much as possible in the space below the specimen, the pole-pieces are unequal. When the goniometer stage is used with the objective lens modified in this way a resolving power better than 15 Å can be achieved.

The very extensive range of accessories and the good resolving power make the Philips EM 300 electron microscope particularly suitable for many widely divergent types of investigation.

Summary. The Philips electron microscope type EM 300 differs from its predecessors in that it has an even better resolving power. In normal use this is always better than 5 Å and in favourable circumstances the theoretical resolving power can be closely approached. Operation has also been further simplified by including various vacuum locks, a semi-automatic exposure meter and a "function switch", etc., and also by the design of the instrument as a whole. The image can be displayed on a television screen as well as on the usual fluorescent screen. The magnification can be varied from 220 times to 500 000 times. Nearly all of the electron-optical sections can be aligned. The electrical circuits are all transistorized. The vacuum system is fully automatic in operation and has a high pumping speed. The excellent resolving power is attributable to the very short focal length of the objective lens (1.6 mm), to good mechanical stability and to the careful stabilization of lens current and high voltage (the relative variations are less than 2.5 \times 10^{-6} and 5 \times 10^{-6} per minute respectively). There is a wide range of accessories, including a goniometer specimen stage, a cryogenic anti-contamination device and a variety of specimen holders.
Recent scientific publications

These publications are contributed by staff of laboratories and plants which form part of or co-operate with enterprises of the Philips group of companies, particularly by staff of the following research laboratories:

- Philips Research Laboratories, Eindhoven, Netherlands
- Mullard Research Laboratories, Redhill (Surrey), England
- Laboratoires d'Electronique et de Physique Appliquée, Limeil-Brévannes (Val-de-Marne), France
- Philips Zentrallaboratorium GmbH, Aachen laboratory, Weisshauserstrasse, 51 Aachen, Germany
- Philips Zentrallaboratorium GmbH, Hamburg laboratory, Vogt-Kölln-Strasse 30, 2 Hamburg-Stellingen, Germany
- MBBLE Laboratoire de Recherches, 2 avenue Van Becelaere, Brussels 17 (Boitsfort), Belgium.

Reprints of most of these publications will be available in the near future. Requests for reprints should be addressed to the respective laboratories (see the code letter) or to Philips Research Laboratories, Eindhoven, Netherlands.

G. A. Acket: The influence of doping fluctuations on limited space-charge accumulation in n-type gallium arsenide.

Int. J. Electronics 24, 1-9, 1968 (No. 1).

J. R. A. Beale: Modern developments in semiconductor devices.

P. Billard & C. Hily: Les systèmes optiques à champ étendu utilisables dans l'infrarouge.
Acta electronica 11, 237-325, 1968 (No. 3).

G. Blasse: Fluorescence of uranium-activated compounds with rocksalt lattice.

G. Blasse: Crystal structure and fluorescence of compounds LnMe₄⁺Me₆⁺O₈⁻.
J. inorg. nucl. Chem. 30, 2091-2099, 1968 (No. 8).

G. Blasse: Fluorescence of compounds with fresnoite (Ba₂Ti₂SigO₉₂) structure.
J. inorg. nucl. Chem. 30, 2283-2284, 1968 (No. 8).


G. Bouwhuis: Interferometrie met gaslasers.
Ned. T. Natuurk. 34, 225-232, 1968 (No. 8).

A. Bril, W. L. Wanmaker (Philips Lighting Division, Eindhoven) & J. W. ter Vrugt (Philips L.D.): Sr₃(PO₄)₃-Tb, a bluish-white emitting cathode-ray phosphor with a long decay time.

K. Bulthuis: Anomalous penetration of Ga and In implanted in silicon.

K. H. J. Buschow: Crystal structures, magnetic properties and phase relations of erbium-nickel intermetallic compounds.
J. less-common Met. 16, 45-53, 1968 (No. 1).


A. Cohen (Institute for Perception Research, Eindhoven): Errors of speech and their implication for understanding the strategy of language users.
Z. Phonetik, Sprachwiss. & Komm.f. 21, 177-181, 1968 (No. 1/2).


Y. Genin: A note on linear minimum variance estimation problems.
IEEE Trans. AC-13, 103, 1968 (No. 1).


J. Tillack: Gravimetric analysis of halogenides and oxidohalogenides with the „H-Rohr-Methode“. Z. anal. Chemie 239, 81-87, 1968 (No. 2). A


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Contents of Electronic Applications 28, No. 3, 1968:

J. Rozenboom: Diac triggering of thyristors and triacs (p. 85-94).


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Contents of Mullard Technical Communications 10, No. 94, 1968:

T. H. Oxley: Germanium microwave diodes for broadband mixer and low level detector applications (p. 122-132).

H. F. Dittrich: Advanced techniques in radio frequency heating generator design (p. 133-134).

H. F. Dittrich: Dielectric heater using half-wave line at 30 MHz (p. 135-145).

D. E. Nightingale: A 400 kHz induction heater of advanced design for powers up to 60 kW (p. 146-149).

D. E. Nightingale: A 300 kHz induction heater of advanced design for powers up to 120 kW/240 kW (p. 150-156).