ELECTRON OPTICS
AND THE
ELECTRON MICROSCOPE

BY

V. K. ZWORYKIN, E.E., Ph.D.
RCA Laboratories
Princeton, N. J.

G. A. MORTON, Ph.D.
RCA Laboratories
Princeton, N. J.

E. G. RAMBERG, Ph.D.
RCA Laboratories
Princeton, N. J.

J. HILLIER, Ph.D.
RCA Laboratories
Princeton, N. J.

A. W. VANCE, E.E.
RCA Laboratories
Princeton, N. J.

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PREFACE

Electron microscopy, which, within the past ten years, has developed from a subject of purely academic interest into one of great practical importance, is engaging the attention of men in all branches of science. Recognizing this, the authors have for some time felt that there was a real need for a comprehensive text covering the electron microscope in all its phases.

The material for the book was chosen to fulfil a twofold purpose. The first is to aid the present or prospective electron microscopist in understanding his instrument and in using it to greatest advantage; the second, to present systematically the practical and theoretical knowledge which must form the basis for further progress in electron microscope design. To this end the book has been divided into two parts. The first part contains descriptions of various types of electron microscopes together with a non-mathematical discussion of the electron optical theories on which the electron microscope is based and the practical information necessary for its effective operation. The second part presents a survey of theoretical electron optics and employs mathematics as liberally as a methodical development of the subject matter warrants. This treatment is intended to supplement the practical information of the first part and may serve as a guide in the electron optical design of improved instruments.

The first part of the book opens with a qualitative introduction to the principles of electron optics and a survey of its applications. These sections are succeeded by a description of the different types of electron microscopes, stressing instruments other than the magnetic electron microscope. Next the design principles of the several components of the magnetic electron microscope are outlined, the most successful instruments are described in detail, and the operation tolerances of the magnetic electron microscope are given. A chapter is devoted to the construction of suitable electric power supplies for the microscope. The first part closes with a chapter on the techniques of electron microscopy and a general survey of the research accomplishments of the new instrument.

The second part of the book begins with a discussion of the theoretical basis of electron optics. Chapters dealing with the measurement and calculation of electrostatic fields, the tracing of electron rays through such fields, and the properties of various types of electrostatic lenses (and mirrors) follow in sequence. They are succeeded by analogous treatments of magnetic fields and magnetic lenses. The aberrations of electron lenses are derived in systematic fashion and discussed quantitatively, possible ways of correcting them being pointed out. The modifications introduced by the variation of the electron mass with its velocity at high accelerating potentials, as well as those due to the greater mass of ions in ion optics, are treated in a later chapter. The final chapter attempts to summarize our present knowledge of the process of image formation in the electron microscope. A brief discussion of noise problems arising in connection with electron multipliers and with the scanning microscope, as well as a few useful tables, form an appendix to the book.

Throughout the preparation of this book the authors have benefited from the assistance and helpful criticism of their associates in the RCA organization, to whom they gratefully acknowledge their indebtedness.

V. K. ZWORYKIN
G. A. MORTON
E. G. RAMBERG
J. HILLIER
A. W. VANCE

Princeton, New Jersey
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NOTE

The metric centimeter-gram-second system of units has been adopted throughout. Electrical quantities (charge, current, voltage, resistance) are expressed in electrostatic units (e.s.u.), magnetic quantities (magnetic potential and magnetic field) in electromagnetic units (e.m.u.). Practical units are employed for these quantities in all equations in which constant factors have been reduced to numerical coefficients.

BOOKS ARE WEAPONS IN THE WAR OF IDEAS

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PART I. PRACTICAL ELECTRON OPTICS AND ELECTRON MICROSCOPY

CHAPTER 1

ELECTRON OPTICS

1·1. Electrons and Electron Emission. The electron is one of the basic constituents of matter. For many purposes it may be thought of as a small electrically charged sphere with a diameter of the order of 10^{-12} cm, a charge of $1.60 \cdot 10^{-19}$ coulomb, and a mass of $9 \cdot 10^{-28}$ gram. Every atomic nucleus is surrounded by an atmosphere of these minute charged particles coursing about it in planetary orbits, the individual electrons being prevented from escaping by the strong attracting electric field of the positively charged nucleus. This attractive force is least for the electrons traveling in the outer fringe of the atmosphere, being here in large part balanced by the repulsive forces exerted by the remaining electrons. These outer, or valence, electrons are hence more readily detached from the atom than the rest. An idea of the relative dimensions of an electron and an atom, as well as of the distribution of electrons in the atmosphere surrounding an atomic nucleus, is given by Fig. 1·1.

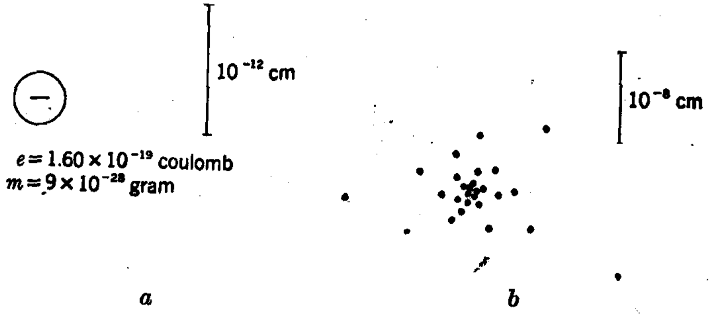

FIG. 1·1. Relative Dimensions of an Electron and an Atom. (*a*) The Electron. (*b*) Electron Atmosphere of an Atom (Copper).

When a large number of atoms of the so-called metallic elements —

for which the binding of the outermost electrons is especially loose — aggregate and form solid substance, that is, a block of metal, the attracting force exerted on these valence electrons by neighboring atomic cores or *ions* becomes comparable to that of the parent core, so that these valence electrons pass readily from the domain of one to the next. They become so-called *free electrons* within the metal, free to move through the entire block (Fig. 1·2). If the block is subjected to an electric field, they will drift in the direction of the force exerted on them by the field and thus give rise to an electric current in the metal, while the heavier atomic ions remain fixed in the regular crystalline framework of the metal. Collisions between these moving electrons and the ions will cause part of the kinetic energy of the electrons to be converted into heat, that is, energy of vibration of the ions. This gives rise to the *resistance heating* of a wire carrying current.

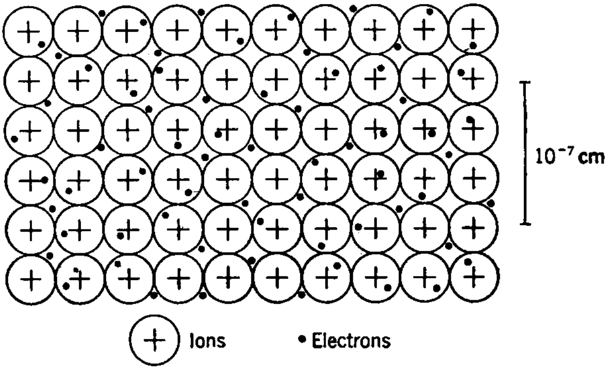

FIG. 1·2. Positive Ions and Free Electrons Composing a Metal (for Example, Copper).

Under normal circumstances the free electrons cannot leave the metal; the attractive force of the positively charged atom cores or ions near the surface prevents their escape. Normally their velocity within the metal is too small to overcome this attraction. There are, however, a number of ways of getting electrons out of metals into free space. Perhaps the most important of these consists in heating the metal to a high temperature, that is, setting the ions of the metal into strong vibrations. Collisions between free electrons and ions, as well as of the former among themselves, give some of the electrons sufficient energy to escape through the surface.

The heating itself may conveniently be accomplished by passing a current through the metal, as shown in Fig. 1·3. Here the electron-emitting metal has been shaped into a thin filament so as to achieve a high current concentration and consequently a high temperature with a moderate current. If, now, this filament were isolated within a glass bulb, the escape of electrons would soon cease, since the filament would become more and more charged up positively, exerting a greater attractive force on the escaping electrons and causing their return to the filament. Hence it is necessary to place in the bulb another piece of metal, connected to the filament (for example, through a battery as shown) so as to create an electric field which draws off the electrons from the filament to the plate or *anode.*

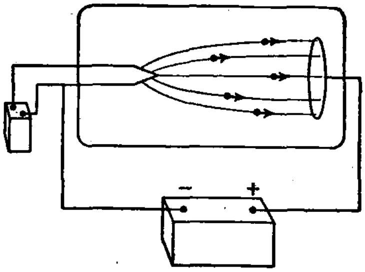

Fig. 1·3. Thermionic Emission of Electrons.

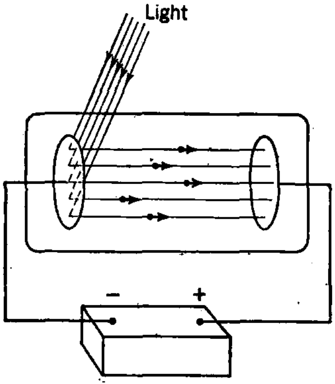

Fig. 1·4. Photoemission of Electrons.

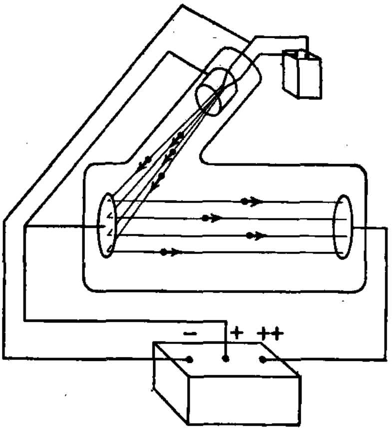

Fig. 1·5. Secondary Emission of Electrons.

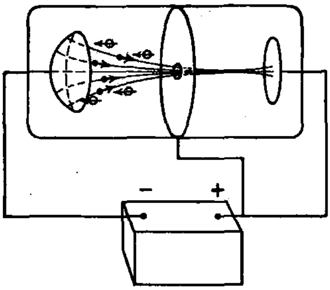

Fig. 1·6. Emission of Electrons in Gas Discharge.

Electrons within the metal may also be given sufficient velocity to leave the metal by illuminating the surface of the metal with light (Fig. 1·4). The energy of the light absorbed by the metal, being concentrated in individual energy packets, light quanta or *photons*, is transferred to some of the metallic electrons, which thus can leave the metal and eventually be collected by an anode. Quite similarly (Fig. 1·5), a stream of fast (primary) electrons impinging on a metal plate can give the metal electrons sufficient energy to escape, giving rise to the emission of *secondary electrons.* The electrons may also obtain the required energy from positive ions, or positively charged gas atoms or molecules, striking the metal as shown in Fig. 1·6. For this purpose a slight amount of gas is left in the region between the anode and the electron emitter or *cathode*; the former may be provided with a small hole to permit the escape of the electrons into a more highly evacuated region. The positive ions are initially produced by the removal of the most loosely bound electrons from gas atoms or molecules in impacts with rapidly moving electrons or other ions, the latter being accelerated by a strong electric field between the cathode and the anode. A sufficient number of charged particles is always present in a gas to start off the *discharge.*

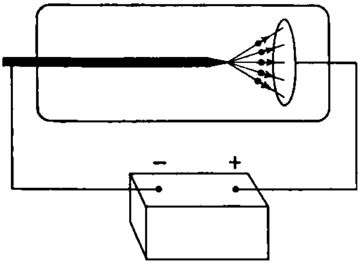

FIG. 1·7. Field Emission of Electrons.

One more method for releasing electrons from metals relies on reducing the effectiveness of the attractive force of the metal ions near the surface by the application of a strong external opposing field (Fig. 1·7). The opposing field must, for this purpose, be of the order of several million volts per centimeter and can best be attained by shaping the cathode into an extremely sharp point. The electron emission so obtained is usually referred to as *field emission* or *cold emission.*

1·2. Analogy of Electrons and Light. Electron optics deals with the propagation of electrons as light optics deals with that of light. Just as a light beam may be conceived of as a wave motion guiding minute packets of energy or mass, that is, light quanta or photons, an electron beam may be represented as a wave guiding the individual electrons. As will be seen in greater detail later, the laws governing light optics and electron optics show a close resemblance. Apart from this, deep-seated, qualitative differences characterize the behavior of electrons and of light.

The distinction which has made electrons particularly useful in *microscopy,* the examination of very small objects, is quantitative rather than qualitative: The wave length of an electron wave (for electrons traveling at the velocity attained when accelerated through a difference of potential of about 50 kilovolts) is only about 1/100,000 as long as that of a wave of visible light. The significance of this is appreciated when light waves and sound waves are compared, the latter having wave lengths of the order of a million times as long as the former.

In the absence of external influences sound waves, light waves, and electron waves are all propagated in straight lines. However, if an obstacle is placed in their path, they will, to some extent, bend around the obstacle, into the latter's shadow. The degree of bending depends upon the wave length, decreasing as the latter is decreased. Thus, a man standing behind the wall at *B* in Fig. 1·8 can hear sound from the source placed at *A*, but cannot see light from a similarly placed light source. This is a familiar phenomenon: Sound does not cast sharp shadows, as does light. In fact, to achieve a bending of light waves about an obstacle similar to that of the sound waves, all dimensions would have to be reduced by a factor of a million. With electrons, having a much smaller wave length, the bending, or *diffraction*, of the waves plays a still smaller role. To imitate the condition obtaining for light the obstacle would have to be reduced by a factor of a hundred thousand! The propagation of electrons, and hence the degree of dif-

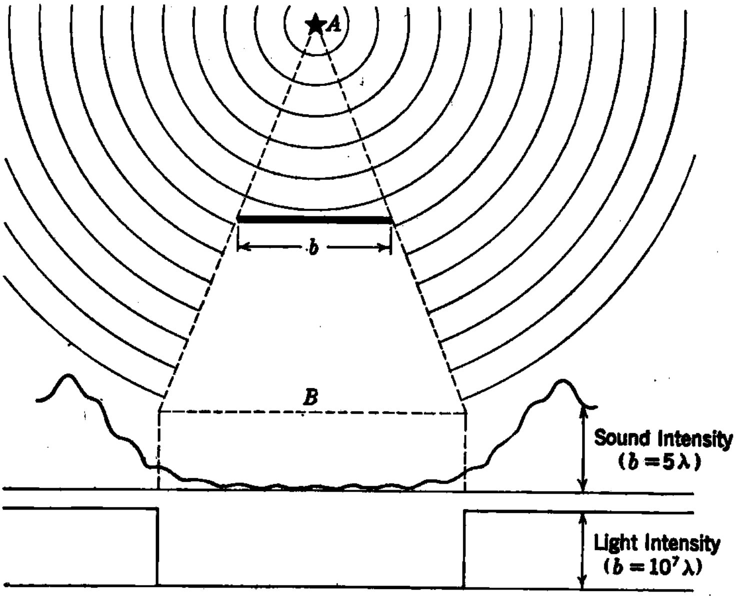

FIG. 1·8. Diffraction of Sound and Light Waves by a 20-Foot Wall.

fraction, is, for velocities small compared to that of light, inversely proportional to their velocity or the square root of the accelerating voltage.

Now, in the design of ordinary light-optical instruments, such as telescopes and microscopes, light is not treated as a wave motion, but as consisting of a set of mutually independent light *rays*, which in the wave picture correspond to the normals of the wave fronts (Fig. 1·9).

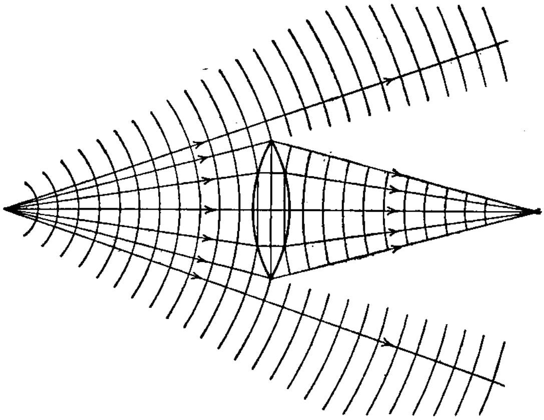

FIG. 1·9. Refraction of Light Waves and Light Rays by a Lens.

The paths of these rays depend only on their point of origin and initial direction and on the variation of the index of refraction along their path. In regions of uniform index they are straight lines, whereas at boundaries between different regions they are reflected, the reflected ray making the same angle with the normal to the boundary surface as the incident ray, or refracted, the ratio of the sines of the angles of incidence and refraction being given by the inverse ratio of the corresponding indices of refraction in the two media, as is required by Snell's law, or both (Fig. 1·10). W. R. Hamilton, over a century ago, noted that the course of these light rays was controlled by the same laws as the paths of material particles acted on by conservative forces (derivable from a potential). Examples of such forces are those exerted by a gravitational field,

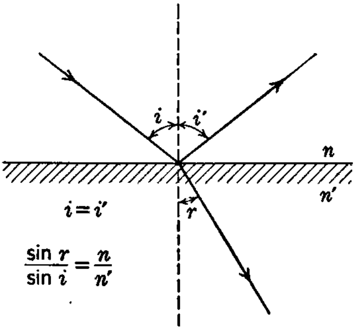

FIG. 1·10. Reflection and Refraction of a Light Ray.

or by an electric field if the particle is charged. The possible paths of the light rays and the particles will be identical if, all through space, the index of refraction in the former case is proportional to the velocity of the particle in the latter. It is generally convenient to represent the velocity of the electron by the square root of the potential ϕ, the latter being measured from a point where the electron velocity vanishes. This emphasizes the fact that, for any given electron, this velocity is, like the index of refraction for a particular light ray, a function of position only. There is thus an exact correspondence between the *ray optics* or *geometrical optics* of the light-optical designer and the Newtonian particle mechanics. It is to be expected, however, that, in view of the much shorter electron wave length, *electron-optical* instruments designed on the basis of ordinary particle mechanics will function in accord with their design even when dealing with objects of such small dimensions that light-optical instruments have become inapplicable.

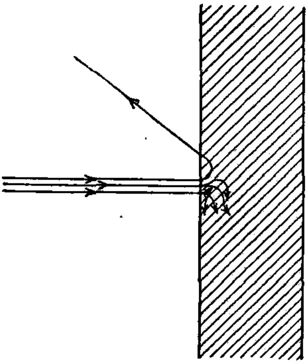

FIG. 1·11. Stopping an Electron Beam by Matter.

Among the qualitative differences, the most important deviation in the behavior of electrons from that of light consists in the fact that electrons can be deflected by electric and magnetic fields, whereas light, under normal circumstances, is not influenced by either.

The circumstance that matter is quite generally opaque to electrons may be regarded as a consequence of their being deflected by an electric field. The strong local fields of the positively and negatively charged elementary particles making up matter deflect electrons passing at close range and may cause them, eventually, to give up part of their kinetic energy (Fig. 1·11). Some of the original electrons may ultimately be scattered backwards out of the surface with a velocity comparable with the original velocity. Most of them, however, gradually lose their velocity in collisions with the constituents of the material and come to form part of the negative charge of the substance. Although relatively thick layers of matter are needed to stop a high-speed electron beam completely (for 50-kilovolt electrons 0.1 millimeter of aluminum or about 20 centimeters of air are required for this purpose), even one ten-thousandth of a millimeter of aluminum or a fifth of a millimeter of atmospheric air will cause an originally parallel electron beam to spread out into one with a mean aperture angle of 10 degrees (Fig. 1·12). Thus all vessels in which electrons are to travel must be carefully