that the image possess sufficient contrast to register on a photographic plate. For comparable intensities of elastic and inelastic scattering, the former will produce a stronger image than the latter, since it is coherent with the incident beam and can interfere with it. If we assume unit magnification and unit incident intensity, the integrated intensity is found to be simply the elastic scattering cross section σ_e; with an image radius a, the contrast is approximately twice the forward scattered amplitude, or $\approx 2(\sigma_e/\pi a^2)^{\frac{1}{2}}$. Making use of [2]$\sigma_e \approx 22Z^{4/3}(\hbar/mv)^2$ and $a \approx 5\hbar^2/me^2Z^{\frac{1}{3}}$, one finds the contrast becomes $\approx 0.008Zc/v$. Since this must be at least 10 percent, the minimum atomic number for 60-kev electrons is $Z \approx 7$; this is somewhat smaller than the estimate recently obtained by Hillier[3] from a classical calculation.

The contrast limitation disappears if dark-field illumination is used. This can be obtained, for example, by forming an image of the electron source on the object, placing an annular aperture in the condenser lens, and adjusting the objective aperture so that the unscattered transmitted beam just fails to pass through it.[4] It would seem that in this case there is no simple limitation on resolving power. For suppose, as appears to be possible, that the electron source can be designed so that an electron from any part of the emitting surface could reach any part of the condenser aperture, thus making the whole condenser beam coherent. With an object in place, the objective aperture would then be illuminated about its edge by a coherently scattered beam, and this would give even greater resolution than could be obtained if the whole objective aperture were illuminated. Moreover, the problems involved in overcoming aberrations in the objective and condenser lenses would be greatly simplified if only the edges of these lenses were used.

The writer acknowledges with thanks several informative conversations on the construction and operation of the electron microscope with Drs. J. Hillier, E. G. Ramberg, and T. F. Anderson of the RCA Research Laboratory.

---

[1] V. K. Zworykin, J. Hillier, and A. W. Vance, J. App. Phys. 12, 738 (1941).

[2] L. Marton and L. I. Schiff, J. App. Phys. 12, 759 (1941).

[3] J. Hillier, Phys. Rev. 60, 743 (1941).

[4] M. von Ardenne, *Elektronen-Übermikroskopie* (Springer, 1940), p. 37.

The Observation of Crystalline Reflections in Electron Microscope Images

James Hillier and Richard F. Baker
RCA Manufacturing Company, Inc., Camden, New Jersey

April 14, 1942

Borries and Ruska[1] have shown that in the case of crystalline material the density of the electron-microscope image is not uniquely determined by the mass thickness of the specimen but is also dependent on the orientation of the crystals relative to the direction of the illuminating electron beam. This phenomenon was clearly demonstrated in micrographs of small single crystals of chromium smoke which could be made to appear either transparent or opaque by proper adjustment of the angle of incidence of the illuminating electron beam. Von Ardenne[2] extended the observations of this phenomenon to crystalline lamina which exhibited slight irregularities. In the latter case the electron image of the crystal contained dark bands, the position of which varied with the direction of the electron illumination. Von Ardenne stated that the dark bands could not be interpreted on the basis of mass-thickness variations in the crystalline lamina.

Similar observations have been made in this laboratory on a variety of materials with the result that the phenomenon has been shown to be due to Bragg reflections from those crystalline planes which are properly orientated.

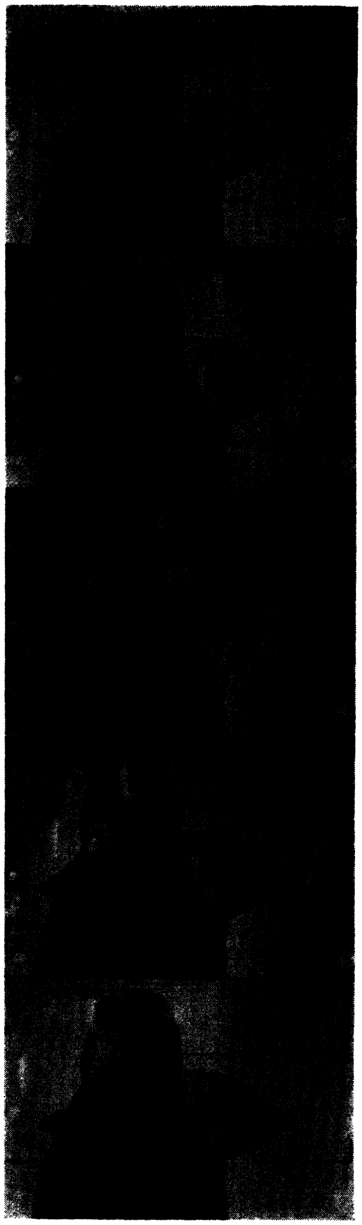

FIG. 1. A "through the focus" sequence of electron micrographs of $Al_2O_3 \cdot H_2O$ crystals demonstrating the reflection of electrons from properly orientated crystalline material. The bright regions representing the intersection of the reflected beam with the imaged plane and the corresponding anomalous darkening of those areas of the crystals in which the reflections occurred are indicated by the inked-in brackets.

In the above-mentioned published work small limiting apertures were used in the objective (angular aperture of the order of 3×10^{-3} radian) and these prevented the reflected electrons from reaching the image. In the present work comparatively large limiting apertures have been used which has made possible the demonstration of the existence of a strongly reflected electron beam. Figure 1 is a sequence of electron micrographs of $Al_2O_3\cdot H_2O$. The electron beam which illuminated the specimen had an angular aperture of 10^{-4} radian and an energy of 78 kilovolts. The maximum angular aperture of the objective system was 0.6 radian. The individual micrographs, *a* to *e*, of the sequence in Fig. 1 were obtained with the objective current set at values about that required for the best focus and are thus reproductions of the electron distribution, passing through those planes of the object space conjugate to the plane of the viewing screen. The micrographs are arranged *a* to *e* in order of increasing objective current, i.e., they correspond to planes of the object space situated successively closer to the objective lens.

In those regions of the crystal lamina where the crystal planes have the proper orientation the electron beam appears to be almost totally reflected. The dark and bright regions caused by this reflection are quite evident in the micrographs. Corresponding pairs can be identified by their similarity in shape and size. The dark region in the crystal and the corresponding bright region represent the position of the intersection of the image-forming and reflected rays, respectively, with the plane imaged. Thus, the change in separation of the corresponding dark and bright regions in the successive images is a measure of the angle through which the incident beam is reflected. It should be pointed out that the lens aberrrations prevent the bright regions, due to the reflected rays, from coinciding with the corresponding dark areas when the instrument is in best focus.

As a final check on the nature of the phenomenon the following experiment was carried out. A large crystal, which, viewed at the high magnification of the final image screen, gave a strong reflection, was identified on the intermediate image screen and the bright spot due to the same reflection observed. The objective lens current was then slowly reduced to zero. As this was done the bright spot was seen to move out from the crystal and the axis of the lens system until in the limit it took up a position on one ring of the diffraction pattern of the material. In the limit (objective lens current zero) the arrangement of the apparatus is the same as a diffraction camera (a small area of the specimen illuminated by a narrow pencil of electrons) so that a diffraction pattern of the specimen is visible and the final position of the bright spot can be identified.

The authors wish to thank Dr. V. K. Zworykin for his many suggestions.

[1] B. von Borries and E. Ruska, Naturwiss. **28**, 366–367 (1940).

[2] M. von Ardenne, Zeits. f. Physik **116**, 736–738 (1940).

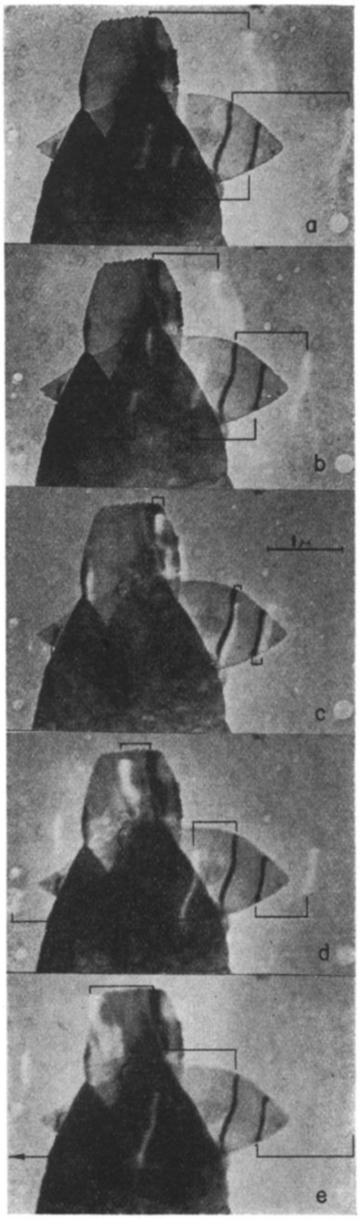

FIG. 1. A "through the focus" sequence of electron micrographs of $Al_2O_3 \cdot H_2O$ crystals demonstrating the reflection of electrons from properly orientated crystalline material. The bright regions representing the intersection of the reflected beam with the imaged plane and the corresponding anomalous darkening of those areas of the crystals in which the reflections occurred are indicated by the inked-in brackets.