BAND EDGE AT THE (111) SURFACE OF COPPER MEASURED BY THE TOTAL ENERGY DISTRIBUTION OF FIELD-EMITTED ELECTRONS

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The upper limit of the conduction band was found to be 0.4 ± 0.05 eV below the Fermi level in the ⟨111⟩ direction of a copper crystal, in good agreement with theoretical predictions. The crystal was grown on the end of a tungsten field-emission tip and exhibited a central dark (111) region about 1000 Å in diameter. With the maximum permissible total emission, a current of 300 electrons/sec was observed from a region about 30 Å in diameter positioned on the ⟨111⟩ pole.

Hörl[1] has suggested that the anisotropy of field-emission patterns should depend partly on the shape of the Fermi surface in addition to the well-known dependence on the work function and electric field strength at the emitting surface.[2] More recently Itskovich[3] has shown that where the emission direction interesects the Fermi surface only the pre-exponential factor in the Fowler-Nordheim equation[2] is affected. However, he went on to show that when the emission direction does not intersect the Fermi surface (i.e., where there is a band gap) the measured work function should be larger than the true work function of that surface. This follows from the highly directional nature of the field-emission process: The maximum energy of the emitted electrons in such a case would no longer be the Fermi energy, but the upper limit of the conduction band in that direction in k space. This Letter reports a direct experimental observation of such a shift in the total energy distribution of electrons emitted through the (111) surface of copper.

Figure 1 is a diagram of the analyzer used in this experiment. It is similar to the design of van Oostrom[4] except that it selects those electrons moving nearly paraxially via a 2-mm aperture in the spherical section. The electrons are energy analyzed in a plane-parallel retarding field and collected by a channel multiplier. Any desired range of tangential momenta can be passed through the analyzer simply by adjusting the focus of the electron lens adjacent to the fluorescent screen.

In addition the whole assembly, including the screen, was mounted on gimbals and could therefore be adjusted to accept electrons with initial momenta normal to the emitting surface.

Copper crystals were grown on the (110) region of a tungsten field emitter by deposition from the metallic vapor in a vacuum of less than 4×10^{-10} Torr. Many energy spectra were obtained from (111) dark regions of about 300 Å diam, but in all cases a large peak appeared at the Fermi energy. However, when a crystal was grown with a central (111) region of about 1000 Å diam, the energy spectra differed markedly at the edge

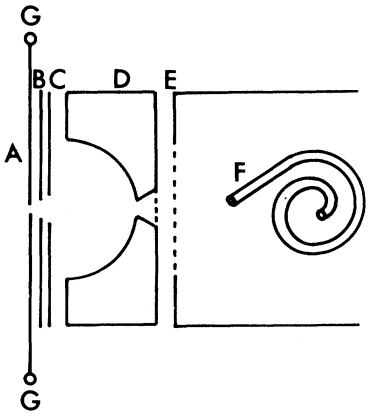

FIG. 1. Diagram of total-energy analyzer. (A) Fluorescent screen; (B) and (C) lens electrodes; (D) van Oostrom shpere; (E) parallel-plate retarding-field analyzer; (F) channel multiplier; (G) gimbals mounting.

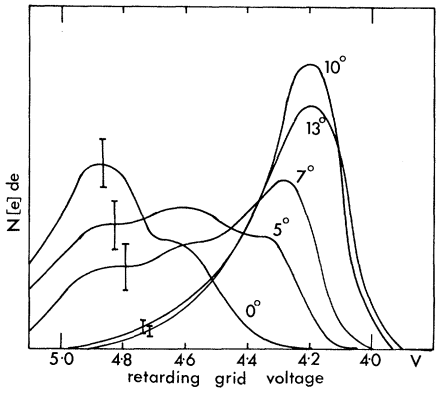

FIG. 2. Total energy distribution of electrons emitted from a copper (111) plane. The projection of the probe hole at the tip was about 30 Å diam. The position of the probe hole is defined by the apparent crystallographic angle away from the ⟨111⟩ pole.

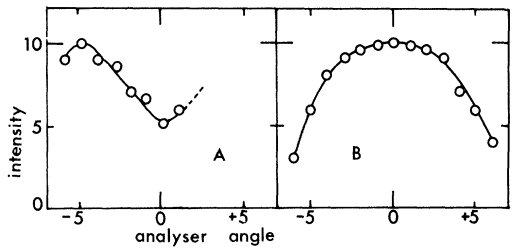

FIG. 3. The emission current plotted as a function of rotation of the analyzer. The scales are proportional to intensity and angle but have not been calibrated. (a) Copper ⟨111⟩; (b) tungsten ⟨110⟩.

and center of the dark area as shown in Fig. 2. (The projected diameter of the probe hole, in this case, was 30 Å.) These five plots are the averages of four separate runs in which a smooth curve was drawn through any variations which could be attributed to random noise. However, no significance is attached to the structure in the curves. The emission current for the 10° and 13° plots was adjusted to 10^4 counts/sec while for the other three it was maintained at 300 counts/sec. This latter figure represented the maximum total current it was possible to draw without danger of rupturing the tip. The associated large shot noise was augmented by thermal migration of the prominent surface atoms since the tip was held at room temperature. The random noise is shown in Fig. 2 for the two count rates used. Figure 3 shows the effect of varying the alignment of the analyzer. The scales have not been calibrated in angle or intensity. In the case of the copper ⟨111⟩ direction, as the analyzer was rotated away from the straight-through direction the threshold in the energy distribution plots approached the Fermi energy.

These results show that the upper limit of the conduction band in the ⟨111⟩ direction of copper is 0.4 ± 0.05 eV below the Fermi level. This is in good agreement with the calculations of Burdick.[5] It also appears that an insignificant amount of diffuse electron scattering was caused by the thermally migrating surface, and that the band structure of the bulk copper persists to the surface monolayer. It is further concluded that the alignment of the analyzer is of great importance to the observation of these effects.

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KBr:Tl EMISSION IN AN ELECTRIC FIELD

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The influence of an electric field ($\sim 10^4$ V_{rms}/cm) on the luminescence of KBr:Tl for excitation in the *A* band has been investigated. The measured spectrum points out beyond any doubt that there are two different centers responsible for the emission.

The emission spectra of thallium-doped alkali-halide phosphors have been investigated at different temperatures by several authors.[1-4] In general, emission bands can be ascribed to the optical transitions between localized electronic states and their shapes will be due to the interaction with the ions neighboring the impurities. The theoretical analysis of these bands becomes extremely difficult when electronic degenerate states are involved because the electron-lattice interaction will yield a coupling between different levels. This is just the case of the alkali-halide crystals activated by thallium. Particularly we have investigated the luminescence of KBr:Tl at 80 and 300°K on the entire *A*-band excitation as shown in Fig. 1.

At 300°K the emission consists of two bands centered at 3.99 and 3.54 eV, while at 80°K the bands are shifted to 4.06 and 3.46 eV, respectively. In the latter case both bands show approximately Gaussian shape. At 300°K the area of the lower energy emission band (E_2) is 1.6 times greater than the area of the higher energy emission band (E_1). At 80°K the E_2 band area is 3 times greater than the E_1 band area. On comparing the areas of the bands at the two temperatures it was noted that the E_1 area is reduced to half when the temperature changes from 300 to