Electric breakdown in bismuth

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Electric breakdown in a metal (bismuth) has been observed for the first time. It is concluded from the experimental results that the breakdown occurs by a Zener mechanism. It may be possible to observe this effect in other metals.

Electric breakdown consists of a sharp increase in the conductivity of a material in a sufficiently strong electric field. To the best of our knowledge, this effect has never been observed in metals. In this letter we report the first observation of an electric breakdown in a metal. The samples, clamped in special holders, are microbridges fabricated from ultrapure bismuth single crystals grown by the Czochralski method. The dimensions of the entire sample are $1 \times 1 \times 15$ mm. At the neck, the diameter of the microbridge reaches a value on the order of 1 μm (Fig. 1; similar microbridges of Cu and W are described in Ref. 1). The long axis of a sample runs along the C_2 axis. The resistance was measured at temperatures of 1.7–5 K by the standard four-contact method. The samples were in liquid helium or its vapor. Contacts were soldered to the massive banks of the microbridge (test experiments showed that the position of the contacts had essentially no effect on the resistance of the samples).

Meaurements were taken from about 20 samples. The current-voltage characteristics of the samples are essentially independent of the temperature and have the same structural feature: At a voltage $V \approx 0.1$ V across the bridge, the characteristics begin to deviate from their linear (ohmic) behavior (Fig. 2). The current through the bridge increases more rapidly than linearly as the voltage is raised. A careful analysis of the current-voltage characteristics showed that the nonlinear increment in the current, ΔI, increases in accordance with $\Delta I \sim \exp(-V_0/V)$. The value of V_0 increases with increasing bridge diameter d: from 0.5 V for a sample with $d = 1$ μm to 3 V for a sample with $d = 8$ μm. In a longitudinal magnetic field, V_0 increases (Figs. 2 and 3); the

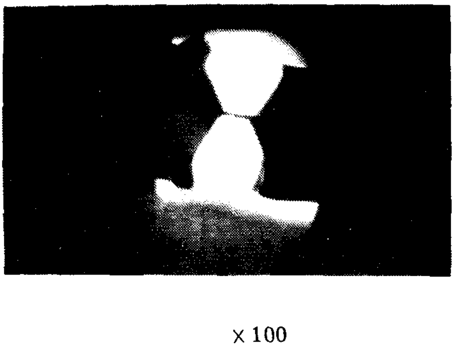

FIG. 1. Photograph of the neck region of a sample (taken wth a long-focal-length objective).

slopes of the line $V_0 \sim H^{3/2}$ are approximately the same for the various samples. We believe that the exponential increase in ΔI is caused by an exponential increase in the number of current carriers. The most probable reason for this effect might be impact ionization or interband tunneling. In the case of impact ionization, however, the conductivity σ would increase in a different way, $\sigma \sim \exp \alpha E$ or $\sigma \sim \exp \alpha \sqrt{E}$ (α is a constant), and the process itself should begin at a voltage across the bridge corresponding to the energy of the band gap: $eV \approx E_g$ (Ref. 2; in bismuth, this energy is[3] $E_g \approx 10$ meV).

In the experiments, the conductivity begins to increase at a far higher voltage, $eV \gtrsim E_f$ ($E_f \approx 30$ meV is the Fermi energy of the electrons in bismuth[3]). In this case, states at the bottom of the conduction band are partially emptied, and carriers can tunnel into these states from the edge of the valence band. The effective mass of the charge carriers at the band extremum is $m^* \approx (3–6) \times 10^{-3} m_0$ (m_0 is the mass of the free electron),[4,5] and the tunneling probability, calculated from the Zener formula,[2] is

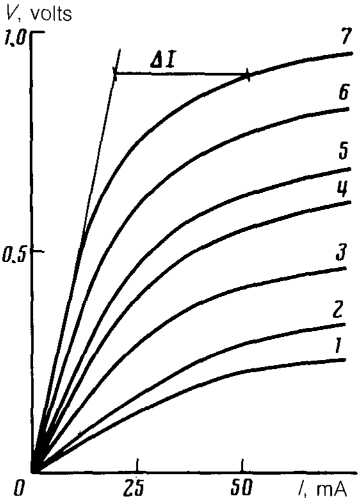

FIG. 2. Effect of a longitudinal magnetic field on the current-voltage characteristics of a microbridge. 1—$H = 0$; 2—4.5 kOe; 3—10.6 kOe; 4—14.6 kOe; 5—17.1 kOe; 6—23.1 kOe; 7—31 kOe.

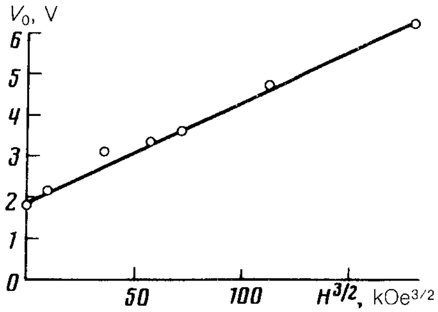

FIG. 3. V_0 as a function of the longitudinal magnetic field.

significant:

$$P = \exp(-\pi m^{*1/2} E_g^{3/2} / 2^{3/2} \hbar F) \sim 0.1,$$

where $\hbar$ is Planck's constant, and $F = eV/r_0$ is the effective electric field, in units of electron volts per centimeter.

The tunnel current density j_t, estimated from Kane's formula,[6] can reach a level on the order of the current density of the majority carriers:

$$Jj_t = \frac{e^2 m^* E_g}{72\lambda\hbar^3} VP \sim 10^6\ \text{A/cm}^2 \quad (\lambda \approx 1).$$

The Zener breakdown mechanism is also supported in a qualitative way by measurements in a magnetic field. The imposition of a magnetic field usually increases in the gap by $\hbar\omega_c$, where ω_c is the cyclotron frequency. In bismuth, however, this does not occur; i.e., the distance between the nearest levels is essentially unaffected by the imposition of a field.[7] On the other hand, transitions between these levels are forbidden by the selection rules, and the distance between nearest levels with allowed transitions—this distance plays the role of a gap—increases linearly with the field (in strong magnetic fields, $\hbar\omega_c \gg E_g$, the dependence becomes nonlinear[3]).

We can explain the experimentally observed dependence $V_0 \sim H^{3/2}$ only on the basis that the Zener formula predicts $V_0 \sim E_g^{3/2}$, and the relation $E_g \sim H$ holds. From the slope of the line $V_0 \sim H^{3/2}$ in this case it follows that the cyclotron mass of an electron at the band extremum is about $10^{-2}\ m_0$ (this result correlates with previous estimates[5]).

Unfortunately, it is not possible to make a precise quantitative comparison of the experimental values of V_0 and the theoretical predictions of the Zener formula,

$$V_0 = \frac{\pi m^{*1/2} E_g^{3/2} r_0}{2^{3/2} \hbar e}.$$

The primary difficulty is the uncertainty regarding the parameter r_0: the effective distance over which the voltage drops. If the electrons are moving in a ballistic regime, the electric field would be concentrated at the narrowest part of the bridge, and we would have $r_0 \approx d$ and $V_0 \approx 0.07$–0.6 V. In a diffusion regime we would instead have $r_0 = L$ (the length of the bridge; 50–70 μm for the various samples) and $V_0 \approx 3.5$–5 V.

In order to carry out experiments manifestly in the diffusion regime, we deliberately introduced defects in a bridge by deforming or rapidly cooling the samples. When we took this approach, however, we changed the current-voltage characteristics in a qualitative way: The conductivity of the sample no longer increased, and instead decreased, as the electric field was increased.

The experimental situation appears to correspond better to the ballistic regime and the absence of any significant structural damage in the bridges (we did not observe several anomalies—superconductivity, a negative temperature dependence, or a weak effect of a magnetic field on the resistance—which have ordinarily been observed in heavily damaged bismuth microbridges[8]). In the ballistic regime, V_0 should not depend on L, and it should increase with increasing d, as observed experimentally.

It may be that the breakdown observed in bismuth might also occur in other metals having small band gaps and light charge carriers, e.g., An, Mg, and Be.

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