Observation of absolute instability of motion of relativistic electrons along axis of single crystal

B. R. Meshcherov and V. I. Tumanov
I. V. Kurchatov Institute of Atomic Energy, Moscow

(Submitted 5 February 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **51**, No. 5, 239–241 (10 March 1990)

Experiments on the redistribution of a beam of electrons moving along the axis of a single crystal indicate an intense mixing of the below-barrier and above-barrier parts of the beam over thicknesses comparable to the period of the particle oscillations in the channel.

Electrons moving along one of the principal directions in a crystal can be divided into two groups:[1,2] below-barrier particles, which have acquired less "transverse" energy and which are executing a finite motion in a potential well formed by an atomic row or plane, and the other particles, which ar moving in a random fashion and which form the so-called above-barrier group. At low energies, the scattering of electrons as the result of quantum-mechanical effects is suppressed,[3,4] and states of stable motion are observed.[5] In the limit of very high energies, the motion of the particles is classical and also relatively stable[6] because of a decrease in the ratio of the angle of the multiple scattering over an oscillation period to the Lindhard angle. In the intermediate region (some tens of MeV for an axial potential), on the other hand, the motion of the electrons is extremely unstable, as was shown in Ref. 6. The instability results from a rapid mixing of the above-barrier and below-barrier groups.

In an effort to observe this effect we have studied the yield of a process with close collisions[1)] (a nuclear reaction) for oriented and disoriented silicon targets, over thicknesses corresponding to the average mixing time within a potential well. Since this length scale is short (about 0.4 μm at an energy $\sim$50 MeV; see the discussion below), we selected a method based on the anodic oxidation of silicon,[7-9] which makes it possible to break the sample up into thin layers.

The targets we bombarded by the electron beam of the Fakel intense pulsed linear accelerator (Kurchatov Institute of Atomic Energy), with the following parameter values: a particle energy $\sim$47 MeV, a beam divergence $\sim 4\times 10^{-4}$, and an average current $\sim$13 μA. The targets were perfect single crystals $\sim$50 μm thick, made of silicon with a slight boron dopant (a substitutional dopant), which was required for the anodizing. The concentration of dopant atoms was $\sim 2\times 10^{16}$cm^{-3}, i.e., had essentially no effect on the dynamics of the passage of the electrons. The crystals were cut in the direction perpendicular to the $\langle 100\rangle$ axis within an error of 0.5°. The error of the orientation was no greater than $0.2\theta_{L'}$, where θ_L is the Lindhard angle, which is $\sim 2\times 10^{-3}$ under the specified conditions. The deviation of the electrons from the selected direction was thus no greater than $0.3\theta_L$ (the beam divergence has been taken into account here).

The procedure for breaking the bombarded sample up into layers consists of several repetitions of a two-state process of oxidation of the target surface and dissolution of the oxide film which grows as a result. Ellipsometric measurements of the thickness of th oxide layer and measurements of its reproducibility and homogeneity yielded ~470 Å and ±3%, respectively. For the Si/SiO_2 ratio we found the value ~0.37; i.e., ~170 Å of silicon was removed in each cycle. When the anodic oxidation was completed, the surface of the sample was washed and dried. The oxide was then etched away with a drop of hydrofluoric acid. The acid was then soaked up with a piece of filter paper, and the crystal was ready for a repeated oxidation.

In the bombardment of the silicon target with electrons from Si^{30}, whose natural abundance in the mixture is ~3%, in the reaction $Si^{30}(e,2pe')Mg^{28}$, with a cross section $\sim 8\times10^{-31}cm^2$, we obtained the β-active isotope Mg^{28}, with a decay half-life ~21.2 h. The activity was measured by the low-background (150–160 counts/h) UMF-m apparatus (see the description in Ref. 10). For this purpose, pieces of filter

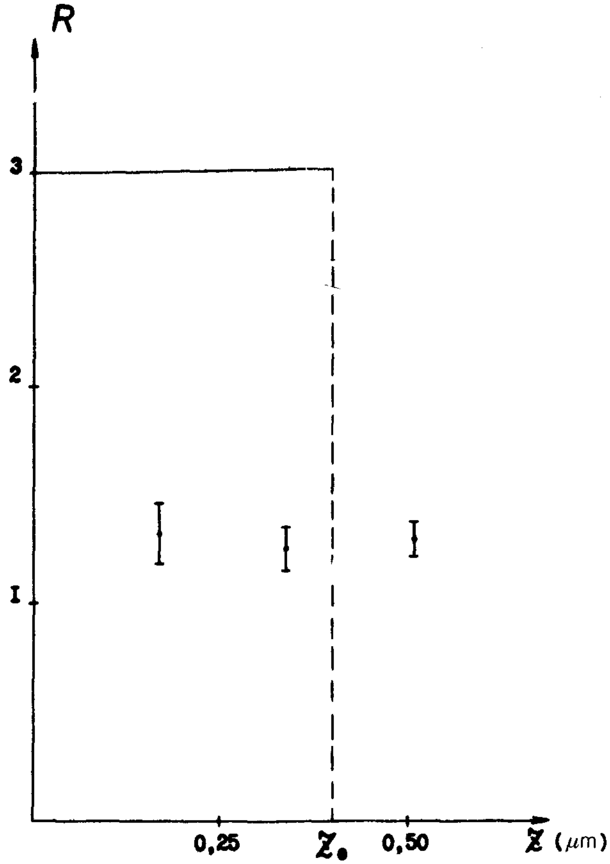

FIG. 1. Ratio of specific activities, R, versus the thickness z.

paper containing radioactive atoms, in a special cassette, were in turn placed in a flow-through proportional β counter which was part of the apparatus. The efficiency of this detection in terms of magnesium was ~ 0.5. In order to build up a sufficient statistical base (a sufficient number of counts), we selected the following parameter values for the experimental procedure: a target bombardment time ~ 7 h, a thickness ~ 0.17 μm of the silicon layer in each activity measurement, and a measurement time of 3000 s.

A quantum-mechanical calculation method, distinguished by its thoroughness and the reliability with which it reproduces experimental data on the channeling of low-energy electrons, was developed in Refs. 11 and 12. Using the set of quantities generated by that method, we can easily calculate the length scale and the magnitude of the effect in our experiments.[2)] The horizontal line in Fig. 1 shows the value expected if there is no mixing of the above-barrier and below-barrier groups. The points show the ratio of the experimental specific activities of a target oriented with its ⟨100⟩ axis along the beam and of a disoriented target. The striking discrepancy, of nearly an order of magnitude, is convincing evidence for an absolute instability of the motion, in our opinion.

We wish to thank V. A. Bazylev and V. V. Goloviznin for useful discussions.

[1)] The yield of processes with close collisions is known to differ for the below-barrier and above-barrier groups (Ref. 1, for example).

[2)] We wish to thank S. A. Mikheev for graciously furnishing data.

[1]V. A. Bazylev and N. K. Zhevago, *Radiation by Fast Particles in Matter and in External Fields*, Nauka, Moscow, 1987.

[2]A. I. Akhiezer and N. F. Shul'ga, Usp. Fiz. Nauk **137**, 561 (1982) [Sov. Phys. Usp. **25**, 541 (1982)]

[3]V. A. Bazylev and V. V. Goloviznin, Zh. Eksp. Teor. Fiz. **82**, 1204 (1982) [Sov. Phys. JETP **55**, 700 (1982)].

[4]V. A. Bazylev and V. V. Goloviznin, Radiat. Eff. **69**, 159 (1982).

[5]J. U. Andersen *et al.*, Nucl. Instrum. Meth. **194**, 209 (1982).

[6]V. A. Bazylev *et al.*, Dokl. Akad. Nauk SSSR **288**, 105 (1986) [Sov. Phys. Dokl. **31**, 410 (1986)].

[7]A. Manara *et al.*, Thin Solid Films **8**, 359 (1971).

[8]H. D. Barber *et al.*, J. Electrochem. Soc. **123**, 1404 (1976).

[9]G. Dearneley *et al.*, Can. J. Phys. **46**, 587 (1968).

[10]D. A. Simonenko *et al.*, *Practical Guidelines on Monitoring Anthropogenic Radioactivity in the Biosphere*, IAE, Moscow, 1964.

[11]S. A. Mikheev and A. V. Tulupov, Fiz. Tverd. Tela (Leningrad) **27**, 1307 (1985) [Sov. Phys. Solid State **27**, 791 (1985)].

[12]S. A. Mikheev and A. V. Tulupov, Fiz. Tverd. Tela (Leningrad) **28**, 2447 (1986) [Sov. Phys. Solid State **28**, 1368 (1986)].

Translated by Dave Parsons