Radio-frequency size effect in the scattering of electrons by the boundary of a diffuse layer of impurities

S. V. Gudenko and I. P. Krylov

Insitute of Physics Problems, USSR Academy of Sciences

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A new type of radio-frequency size effect was observed experimentally, due to "cutoff" of the trajectories of the effective electrons on the boundary of a layer of impurity atoms that have diffused into the interior of a metallic single crystal. The coefficient of diffusion of lead in single-crystal indium was measured on the basis of this effect.

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In experiments performed at liquid-helium temperatures, we investigated the radio-frequency size effect in single-crystal disks of 18 mm diameter and $d=0.3$ mm thickness, made of high-purity indium containing less than $10^{-4}\%$ impurities and with an electron mean free path exceeding 1 mm. On one of the flat surfaces of the indium surface was deposited by evaporation in vacuum a lead film 10^{-5}–10^{-4} cm thick. Clamped to the opposite surface of the sample was a flat coil of the tank circuit of an RF generator. The changes of the imaginary part X of the surface impedance of the sample with changing external homogeneous magnetic field H led to changes in the oscillation frequency and were registered with an x-y recorder by a standard modulation technique.[1]

Prior to depositing the lead film, one of the flat surfaces of the sample, prepared in a dismountable polished quartz mold by a well known method,[2] was cleaned by cathode sputtering in a glow discharge. To this end, the sample, the lead evaporator, and the aluminum anode were placed in a glass cell, which was immersed during the time of the discharge in liquid nitrogen and was filled with pure argon. After completing the discharge, the cell was evacuated to a residual-gas pressure 10^{-5} Torr, at which the lead was evaporated. After depositing the lead film, the sample was placed in the helium unit. Control plots of the radio-frequency size effect lines were obtained for all the employed samples immediately after their preparation in the quartz mold and prior to the start of the manipulations with the surface.

Figure 1 shows typical plots of the most intense radio-frequency size effect line in indium, due to electrons of the external section of the Fermi surface in the second energy band,[3] in a magnetic field parallel to the flat surface of the sample. It is known (see, e.g., Ref. 1) that the appearance of impedance singularities—radio-frequency size-effect lines—in a certain field $H=H_0$ is due to the fact that the effective electrons of the external section, which make the largest contribution to the high-frequency current in the skin layer, collide at $H<H_0$ with the opposite surface of the sample. Obviously, for a given Fermi-surface section, the value of the field is $H_0 \propto d^{-1}$, and the shape of the radio-frequency size-effect line is determined by the distribution of the alternating field in the skin layer and by the character of the scattering of the electrons

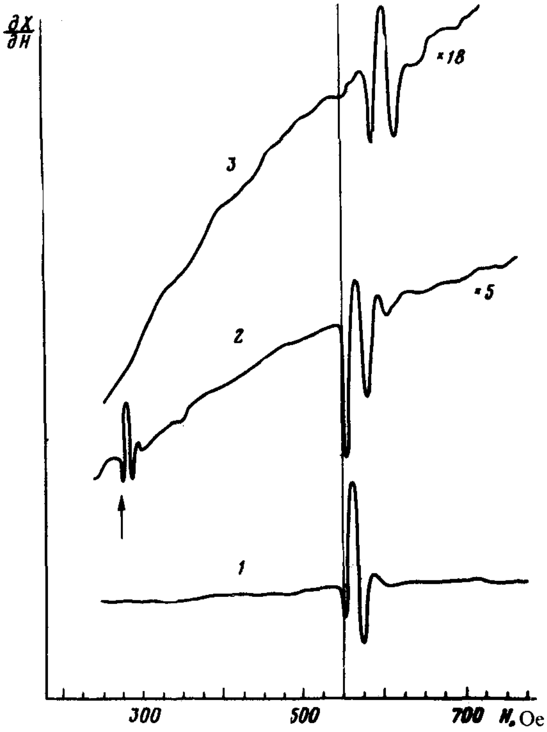

FIG. 1. Plots of the derivative $\partial X/\partial H$ in relative units, obtained under the following conditions: 1—prior to deposition of the lead film; 2—after deposition of the lead film; 3—after diffusion annealing at 22 °C for 10.5 days and 120 °C for 40 min. The thin vertical line corresponds to the field $H=H_0$ for plots 1 and 2, the arrow marks the field $H_0/2$. The orientation of the normal to the plane of the surface of the sample is $\mathbf{n} \| [100]$, the field $\mathbf{H} \| [001]$, $T=1.5$ K, the frequency is 2.4 MHz, sample 1.

from the surface of the metal. Comparison of plots 1 and 2 allows us to conclude that the presence of a superconducting lead film changed the character of the scattering of the electrons from the surface of the indium single crystal. First, a change took place in the shape of the line at $H = H_0$. Second a radio-frequency size-effect line of comparable amplitude appeared in a field $H = H_0/2$, due to the "Andreev" character of the reflection of the electrons from the boundary of the normal metal with the superconductor.[4] A qualitative comparison of the amplitudes of the two lines on the curve 2 allows us to conclude that the probability of the "Andreev" reflection of the electrons was noticably less than unity. In other words, the greater part of the electrons on the In–Pb interface was diffusely scattered, apparently because of the different inhomogeneities of the boundary between the single crystal and the sputtered film. The high sensitivity of the "Andreev" lines to the quality of the In–Pb boundary explains also why in experiments with six samples the line in the field $H = H_0/2$ was observed only on two samples after depositing the lead film.

Curve 2, obtained in experiments with one of these samples, was reproduced in repeated experiments, provided the sample was kept at liquid-nitrogen temperature between the helium experiments. However, after annealing the sample at room temperature for several hours, the "Andreev" line vanished, and the field H_0 increased. The increase of the field H_0 means a decrease in the diameter of the electron trajectory at which the "cutoff" effect takes place, and is in turn explained by the fact that the scattering of the electrons is now by the lead atoms that have diffused into the interior of the indium single crystal. Annealing the sample for several hours at a temperature 120 °C led to a considerable increase of the field H_0 (curve 3).

The probability that the effective electrons with a trajectory diameter $2R < d$, will penetrate into the metal and will return again to the skin layer is given by the formula $A = \exp(-\int w ds)$, where w is the probability of electron scattering per unit length, and the integral is taken along the trajectory.[1] If it is assumed that $w \approx C/a$, where C is the concentration of the lead impurity and a is the interatomic distance (we neglect the concentration of the uniformly distributed residual impurities), and if it is assumed furthermore that the distribution of the lead atoms is described by the solutions of the equation for the nonstationary diffusion with a constant diffusion coefficient D and a duration of the process t, when applied to the conditions of our experiment we can obtain the following estimate:

$$A \approx \exp[-10^5 \exp(-x^2/4Dt)].$$

In this formula, x stands for the minimum distance between the electron moving on a circular trajectory and that plate surface on which the lead was deposited. In view of the presence of exponential functions and of the large numerical factor, A changes from $A \approx 0$ to $A \approx 1$ in a narrow interval of values of x, of width $\sim\sqrt{Dt}$ near the value $x = 7\sqrt{Dt}$, and the numerical coefficient depends very little on the scattering cross section. If the skin-layer depth is $\delta \gtrsim \sqrt{Dt}$, then the presence of a diffuse layer of impurities near the opposite surface of the sample should lead to a certain increase of the line width of the "cutoff" effect and to a more substantial shift of the position of the radio-frequency size-effect line, corresponding to a decrease of the effective thickness of the sample by an amount $\Delta d = x = 7\sqrt{Dt}$.

The experimental results on the measurement of H_0, obtained with sample 2 for different radio-frequency size-effect lines, depending on the duration of the diffusion annealing, are shown in Fig. 2. We note that in this sample, following a shift to stronger fields, the shape and amplitude of the line changed insignificantly. From the slope of the straight line that passes within the limits of errors through the experimental points, we can determine the value of the diffusion coefficient.

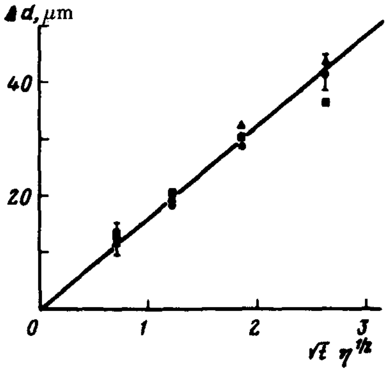

FIG. 2. Dependence of the shift of the radio-frequency size-effect line on the duration of the diffusion annealing at 120 °C, recalculated in terms of the effective change of the sample thickness. The different symbols corresponds to different field orientations: ▲—H‖[001]; ○—∡(H,[001]) = 13°, ■—∡ (H,[010] = 23°; sample 2:**n**‖[100].

Diffusion annealing at 120 °C was carried out on two samples of identical crystal orientation. We obtained $D = (1.8 \pm 0.4) \times 10^{-11}$ and $D = (1.5 \pm 0.2) \times 10^{-11}$ cm^2/sec for samples 1 and 2, respectively. Sample 1 was subjected to a sufficient long diffusion annealing also at room temperature (22 °C). The resultant value was then $D = (2.8 \pm 0.8) \times 10^{-14}$ cm^2/sec. Assuming that $D \propto \exp(-\epsilon/kT)$ (Ref. 5), where ϵ is the activation energy per atom and k is Boltzmann's constant, we obtain for the diffusion of lead in an indium single crystal along the [100] direction a value $\epsilon = 0.65 \pm 0.05$ eV/atom.

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