Spin relaxation of conduction electrons at an arbitrary probability of scattering from the surface of a metal

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The method of stationary paramagnetic resonance in lithium films was used to measure the probability ϵ of the spin flip of an electron on the boundary of a sample with a strong spin scatterer (Invar, niobium). A new type of surface relaxation, with characteristic size and temperature dependences, is observed, wherein the relaxation rate is determined not by the value of ϵ but by the electron diffusion rate.

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The theory of the line shape of paramagnetic resonance on conduction electrons (PRCE) with allowance for inelastic scattering of the spins by the sample surface was constructed by Dyson[1] (the theory was subsequently refined by Walker[2]). In the general case it yields for the resonance line a rather cumbersome expression that cannot be set in correspondence with a single surface relaxation time T_s. A simple analytic expression

$$T_s^{-1} = \epsilon v_F d^{-1}, \tag{1}$$

can be obtained only in the asymptotic sense of smallness of the mathematical parameter of Dyson's theory $Q=3\epsilon d/4(1-\epsilon)\lambda \ll 1$ (ϵ is the angle-averaged spin-flip orientation per collision with the surface, v_F is the Fermi velocity, λ is the electron mean free path, and d is the sample thickness). Expression (1) is valid provided the surface relaxation is weak, and is usually employed to determine ϵ from the observed line width. It is undoubtedly of interest, however, to investigate the opposite asymptotic case $Q \gg 1$, which corresponds to a strong influence of the surface on the physical properties of the sample (one such case can be, for example, the situation with a weakly magnetic metal in contact with a ferromagnet, when polarization of the conduction electrons of the weakly magnetic signal is possible on account of the natural or induced diffusion of the carriers from the ferromagnetic substrate[3,4]).

The purpose of the present paper is to describe the preliminary results of an experimental study of this question by the PRCE method on lithium films with strong spin scatterers on the boundary, namely "magnetic" (Invar) and "spin-orbit" (niobium). These metals were chosen because it is easy to observe in Li narrow spin-resonance signals with a temperature-independent line width, and Fe, Ni, and Nb are not soluble in Li. The lithium films with Invar or niobium substrates were prepared by successive evaporation in a vacuum of $\sim 5\times 10^{-6}$ Torr. In each evacuation act we sputtered five samples with different lithium-layer thicknesses but with identical scatterer sublayers (<50 Å), as well as control samples without this scatterer, so as to separate the surface contribution to the relaxation. The lithium-layer thickness was monitored with a quartz thickness meter directly during the course of the sputtering, and the thickness of the Invar (niobium) sublayer was estimated with an interference microscope. The interval of the investigated thicknesses of the lithium layer was $d = 0.7$–$4.7\ \mu$m. Measurements of the PRCE signals were made with a three-cm radiospectrometer in the temperature interval 100–400 K.

The presence of Invar on the lithium boundary has led to a strong broadening (by almost two orders of magnitude) of the PRCE line and of the size and temperature dependences of the line width, of the form $(\gamma T_s)^{-1} \sim \lambda d^{-2}$, as shown in Figs. 1 and 2.

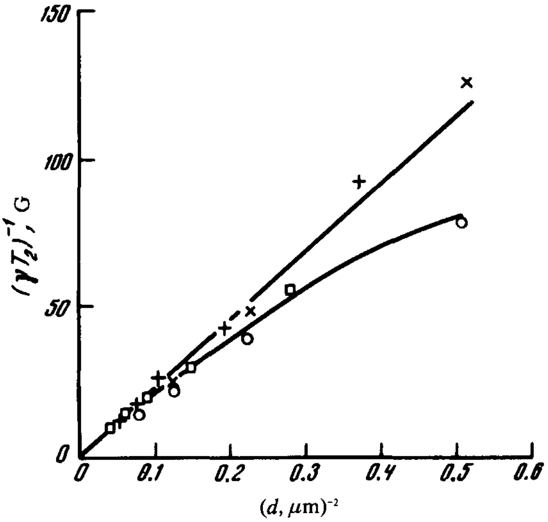

FIG. 1. Dependence of the PRCE line width on the dimension. Samples with sublayers: a) Invar—+,×, b) niobium—○,□ (for different sputtering acts).

These data represent the first unequivocal observation of temperature-dependence surface relaxation, the possible existence of which was discussed in the literature many times.[2,5–7] The results can be interpreted on the basis of simple physical arguments. The experimental conditions are such ($d \gg \lambda$) that the electron crossing the sample moves diffusely. It can be shown that in each "diffusion approach" to the scattering boundary the electron experiences on the average $\sim d/\lambda$ ballistic collisions with the sample surface (we neglect the thickness of the scatterer sublayer, since it is $< \lambda$). The Dyson parameter Q then acquires the physical meaning of a quantity proportional to the spin-flip probability in one "diffusion approach" to the boundary. At large Q, the probability of scattering at the very first approach is large, and the spin lifetime is equal to the average time needed by the electron to reach the boundary. Consequently, in this case there can exist the simple solution:

$$T_s^{-1} = a D d^{-2} \quad , \tag{2}$$

where $D = (1/3) v_F \lambda$ is the electron diffusion coefficient and α is a numerical averaging coefficient. It is important to emphasize that Eq. (2) is valid not only for $\epsilon = 1$ (see[7]),

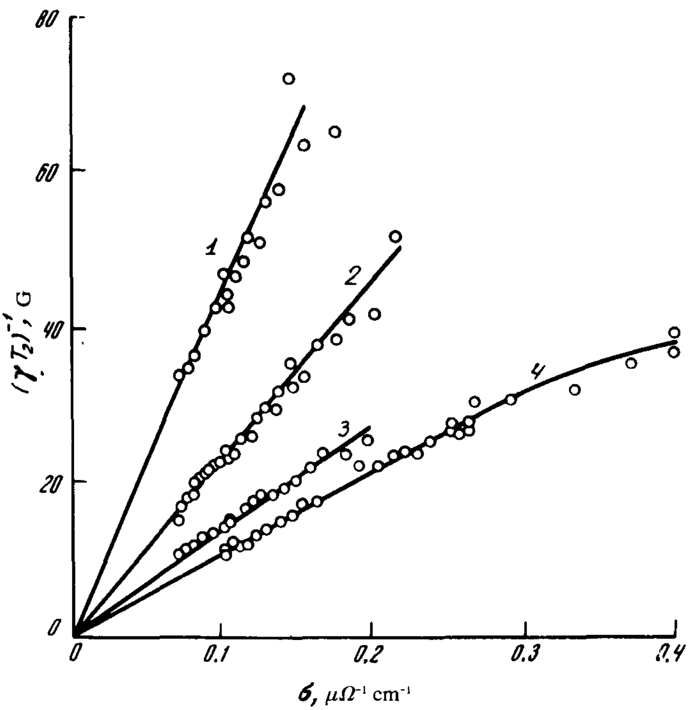

FIG. 2. Dependence of the line width on the electric conductivity for samples with Invar sublayer and with lithium-layer thickness (microns) $d=2.1(1)$; $2.8(2)$; $3.5(3)$; $4.2(4)$.

but also under the weaker condition $Q \gg 1$ in a wide range of ϵ. In fact, a computer calculation of Dyson's equations has shown that at $Q > 4$ the line width $(\gamma T_s)^{-1}$ does not depend[1)] on ϵ and is described by expression (2) with $\alpha \approx 2.5$. From the slope of the size dependence (Fig. 1) we obtain with the aid of (2) the value of the electron diffusion coefficient at room temperature, $D=16\pm3$ cm^2/sec, which agrees with earlier measurements by the spin-echo method.[8]

The value of ϵ for the boundary with Invar is large, so that deviations from the conditions of strong relaxation are observed only at the very lowest temperatures (Fig. 2). We succeeded in effecting a continuous transition between both types of relaxation for a weaker "spin-orbit" scatterer (niobium). The size dependence of the PRCE line width for samples with niobium is shown in Fig. 1, while Fig. 3 shows the temperature dependence plotted in coordinates that are convenient for the analysis of the type of surface relaxation, namely the reduced line width $(\gamma T_s)^{-1}d^2$ and the conductivity σ. It is seen from Figs. 1 and 3 that the experimental results are described by expression (2) at high temperatures and large d, and by expression (1) at low temperatures and small d. This has made it possible to determine the spin-flip probability of the conduction electron on the boundary with niobium $\epsilon(\mathrm{Nb})=(5\pm1)\times10^{-3}$. From the change of the observed line shape we estimated $\epsilon(\mathrm{Invar})\approx10^{-2}$. We did not observe in the investigated samples the possible change of the g factor, or the increase of the resonance-signal intensity as a result of the polarization of the conduction electrons in the lithium.

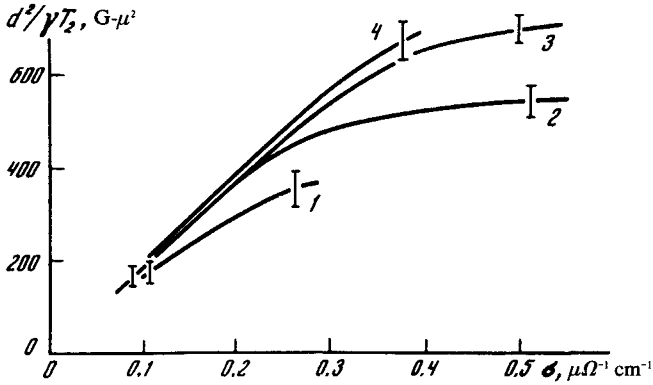

FIG. 3. Temperature dependence of the "reduced" line width: 1, 2, 3—for samples with niobium sublayer and lithium thicknesses 2.8, 3.3, and 4.0 μm, respectively; 4—for samples with Invar sublayer (averaged over all the measurements).

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[1)]It was noted, however, that the shape of the observed PRCE line depends on ϵ in this case if the sample thickness exceeds the skin-layer depth.

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