tial may also explain the absence of intrinsic localized states on ideal oxide-coated silicon surfaces.[14] In tunneling experiments, oxide and vacuum behave quite similarly and it is perhaps paradoxical that they should have such different interface state distributions. In a one-dimensional model, a band gap may be denoted as "S" or "n-S" according to whether or not it gives Shockley states. Matching arguments indicate that no localized states will exist at the boundary between two S-type materials. The absence of intrinsic states on oxides and ionic crystals has formerly been interpreted as resulting from an n-S gap, in which case surface states should exist at an oxide-semiconductor interface. However, the present results and the recent extension of the pseudopotential scheme to MgO[15] suggest that the gap in the oxide may be basically S-type, giving no surface states for oxide-coated silicon or germanium, but with the bands on the oxide-vacuum interface so separated that they are near the edges of the bulk band gap and produce no detectable consequences.

The results described here will not necessarily be identical to those obtained for other crystallographic faces. The (110) face is of particular importance, however, since the semiconducting compounds generally cleave at this face. Calculations on other faces are in progress.

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RECOMBINATION TIME OF QUASIPARTICLES IN SUPERCONDUCTING ALUMINUM

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The quasiparticle recombination time τ_γ, has been measured in superconducting aluminum films. The temperature dependence of τ_γ at low temperatures was found to be in good agreement with theoretical expectations.

We have measured the recombination time of quasiparticles in superconducting aluminum by a method similar to that of Miller and Dayem (MD).[1] In contrast to their results, but in agreement with theoretical expectations,[2,3] the recombination time τ_γ was found to be nearly proportional to $\exp(\Delta/kT)$ at low temperatures. Here, Δ is the (temperature-dependent) energy gap and T the temperature. MD found a much weaker temperature dependence of the form $\exp(\approx 0.3\Delta/kT)$.

As the general experimental technique was adequately described by MD, we give only a brief description here. The measurements were made with a double tunnel junction, shown in Fig. 1(a). Care was taken to prevent direct contact between the indium film and the bottom (400 Å) aluminum film. Excitations (essentially unpaired electrons) are made at a steady rate in both aluminum films by biasing the aluminum-oxide-aluminum tunnel junction (generator) at a bias voltage $V \gtrsim 2\Delta_{Al}/e$, where Δ_{Al} is the energy gap in the aluminum. This increases the quasiparticle density above the thermal equilibrium

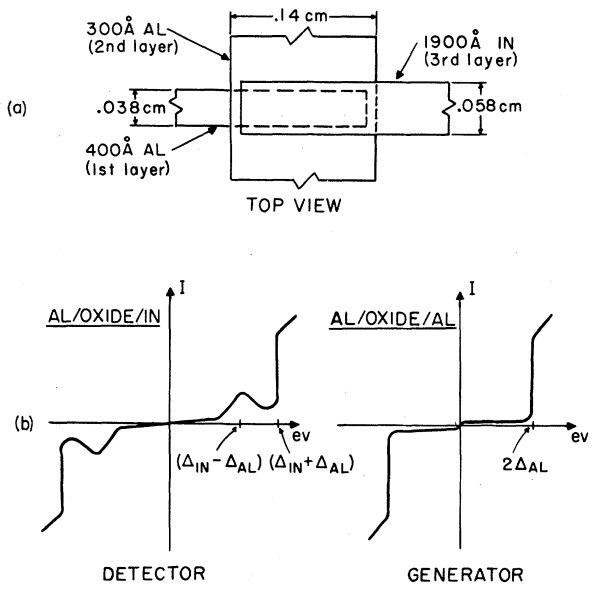

FIG. 1. (a) Geometry of double tunnel junction (not to scale). The films are separated by thin oxide layers. (b) Schematic representation of I-V curves for detector and generator junctions.

value by an amount proportional to τ_γ. The increase in density in the center film is obtained from measurements made on the current-voltage (I-V) relation of the aluminum-oxide-indium junction (detector) allowing a determination of the lifetime.

In Fig. 1(b), we indicate schematically the I-V relations for each junction in order to illustrate the salient features. The generator was operated on the nearly vertical portion of its characteristic, so that excitations were created only slightly above the gap edge in the aluminum films. Part of the detector current arises because of the presence of excitations in the center aluminum film; consequently, an increase in detector current proportional to the excess quasiparticle density occurs when the generator is turned on. The most sensitive region of the detector characteristic is at the peak at voltage $(\Delta_{In}-\Delta_{Al})/e$. Here, Δ_{In} is the indium energy gap. The measurements were made by sweeping out the detector I-V characteristic twice in rapid succession, with the generator current set at different values for the two sweeps. The traces were converted to digital form and stored in adjacent halves of a 1024-channel memory.[4] Additional sweeps were added coherently until an acceptable signal-to-noise ratio was obtained. This technique was effective in suppressing the effects of slow drifts in the amplifiers and in the sample temperature.

The change in quasiparticle density δn corresponding to the change in generator current δI_g was obtained from the corresponding difference in peak height δI_p. Apart from some differences in instrumentation, the major difference between our measurement and that of MD was the procedure used to obtain the change in density δn from the change in detector current. The desired quantity is dn/dI_p. Because the two methods yield different results, we will describe them in some detail. MD measure the current at a bias corresponding to the flat region above the peak [see Fig. 1(b)] and calculate the sensitivity from an approximation based on the standard expression for the tunnel current.[5] However, it is possible to obtain this factor more directly by measuring the peak current I_p as a function of temperature. One then has

$$dn/dI_p = (dn/dT)/(dI_p/dT). \tag{1}$$

Here, $n(T)$ is obtained from the standard BCS[6] expression:

$$n(T) = \text{const}\int_{\Delta_{Al}}^{\infty}[E/(E^2-\Delta_{Al}^2)^{\frac{1}{2}}] \times (e^{E/kT}+1)^{-1}dE. \tag{2}$$

This has the advantage of canceling out most of the potential errors associated with the measurement, as both I_p and δI_p are measured simultaneously, with the same equipment. In addition, the result is less sensitive to departures of the density of states from the BCS form caused by anisotropy, inhomogeniety, and other effects which tend to broaden the gap edge. The final expression for calculating the recombination time is

$$\tau_\gamma = A\Omega e(dn/dI_p)(\delta I_p/\delta I_g), \tag{3}$$

where A is a geometrical factor related to the overlaps of the junctions, and Ω is the volume of the center film.

Rothwarf and Taylor[7] have pointed out that the experimental lifetime may appear longer than the actual recombination time because the phonons emitted during the recombination process have a high probability of creating new quasiparticles before leaving the film. According to their analysis, this will introduce a proportionality factor between the experimental and true lifetimes of approximately 3 for our geometry. Because of uncertainties in calculating this ef-

fect, we give only the experimental lifetime. This is shown in Fig. 2 plotted as a function of Δ_{Al}/kT. A least-squares fit to the low temperature data gives a temperature dependence of the form $\exp(\mu\Delta_{Al}/kT)$ with $\mu = 1.19 \pm 0.20$. The error estimate given above includes the error in the determination of Δ_{Al}, which may be as large as 10% because of the finite width of the energy gap in the aluminum and indium films. Theoretically, it is expected that $\mu = 1$. The recombination process requires the presence of a second (thermal) quasiparticle; from Eq. (3), the density of such quasiparticles at low temperature and hence the recombination rate (τ_γ^{-1}) are seen to vary as $\exp(-\Delta_{Al}/kT)$. If our data are analyzed by the method of MD, we find $\mu \cong 0.8$, so that only part of the difference between our results and theirs ($\mu \cong 0.3$) is accounted for by the difference in analysis. At higher temperatures, τ_γ appears to level off and perhaps increase, as noted also by MD. Recent calculations by Scalapino[8] predict a similar increase in recombination time near the transition temperature T_c. Near T_c, the energy gap and hence the energy of the emitted phonons drop rapidly with increasing temperature, leading to a decrease in the amount of phase space available for phonon emission, and thus to a decrease in the recombination rate. Unfortunately, the combination of short lifetime and a large thermal detector current make the measurements difficult in this region.

We have also studied the effects of magnetic fields on the recombination rate. Fields up to several hundred oersteds applied in the plane of the films appeared to have little effect on τ_γ, apart from small changes caused by the small reduction of energy gap. In contrast, fields applied normal to the film surface caused a marked reduction in τ_γ at low temperatures. Thus, a 3-Oe field reduced τ_γ at the lowest temperatures ($\Delta_{Al}/kt \approx 6$) to approximately $\frac{1}{3}$ of the zero-field value, while a 5-Oe field reduced τ_γ nearly to the normal-state value, almost independently of temperature. Despite these large changes in recombination rate, the I-V characteristics of the junctions were only slightly changed. We believe recombination in vortex cores to be responsible for this effect. Because of the large ratio of film width to film thickness, flux enters the film at very low fields, presumably in the form of quantized vortices having cores with properties similar to the normal state. Because of the very rapid diffusion of the quasiparticles, which travel at nearly the Fermi velocity, the lifetime

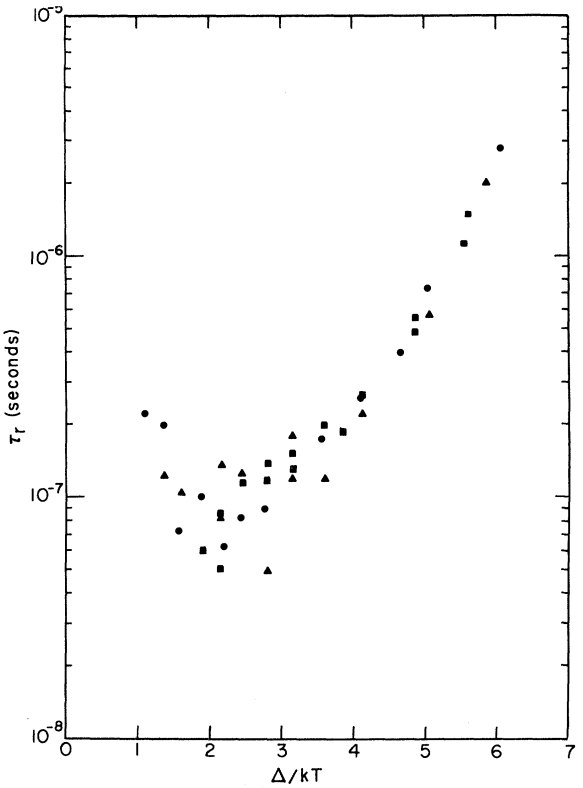

FIG. 2. Quasiparticle recombination time τ_γ as a function of Δ_{Al}/kT. The different symbols correspond to separate runs with the same sample. Error bars have been omitted for clarity.

will be reduced very rapidly by the addition of a relatively small number of vortices. While we have not made a detailed calculation, a simple estimate indicates that a field of a few oersteds could produce the observed results. In support of the above hypothesis, the field effects were found to be highly irreversible as normally observed for flux trapping effects, and appeared to be controlled by the indium film.

We have observed an additional effect which may be related to the phonon reabsorption discussed by Rothwarf and Taylor. As pointed out by MD, a part, $I_0(T)$, of the generator current arises from the transfer of thermal excitations and should not lead to an increase in the number of excitations in either aluminum film. Experimentally, we find that the portion of the generator current which is actually ineffective in creating excitations is substantially smaller than expected. We believe the reason to be the following: The thermal quasiparticles lie close to the gap edge prior to tunneling, and will be raised above it by an amount slightly in excess of $2\Delta_{Al}$ because of the applied voltage. The results of

MD and others[9] indicate that the quasiparticles will first relax to the gap edge, giving up their excess energy in the form of phonons of energy $\approx 2\Delta_{Al}$ before recombination takes place. Since the phonons appear capable of creating new quasiparticles, one would expect that only a portion of $I_0(T)$ is actually ineffective in creating quasiparticles, as observed. It should be possible to obtain information on the phonon reabsorption process from detailed measurements of this effect.

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EXPERIMENTAL STUDIES OF POLARIZATION EFFECTS IN SPIN-WAVE SCATTERING OF NEUTRONS*

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We have studied polarization effects in spin-wave scattering of thermal neutrons. In the case of a ferromagnet we have studied the polarization created along the scattering vector when an initially unpolarized beam is scattered. We have also observed the partial or complete rotation of the polarization vector when an initially polarized beam is scattered by spin waves in a ferromagnet and in an antiferromagnet.

The instrument used in these experiments was a triple-axis polarized-beam neutron spectrometer[1] at the research reactor, HFIR (high-flux isotope reactor), shown schematically in Fig. 1. The first axis holds a Co-Fe polarizer and monochromator, the second axis holds the sample under investigation, and on the third axis is a Co-Fe crystal which serves as an analyzer for both neutron polarization and energy. All three axes also hold magnets, in the gaps of which the crystals are mounted. Flipper rf coils for reversing the neutron polarization are mounted both before and after the sample. The fields on the polarizer and analyzer are always kept vertical. The sample magnet together with guide fields 2 and 3 can be rotated so that the polarization vector and field on the sample can be either vertical or horizontal, i.e., either perpendicular to or along the scattering vector. The incident beam may be depolarized by inserting an iron shim in front of the sample. Without a shim the flipping ratio measured in elastic scattering is ~100.

Polarization creation was studied in a sample of lithium ferrite, $Li_{0.5}Fe_{2.5}O_4$. Low-energy ferrimagnetic spin waves are known to obey a quadratic dispersion law[2] and thus behave like ferromagnetic spin waves. By confining the observation to positions close to the (111) reciprocal lattice point, the contribution of nonmagnetic, nuclear scattering components is negligible. Figures 2(a) and 2(b) give the number of neutrons counted when the rf between the sample and analyzer is on or off and the incident beam is depolarized. The sample crystal has been turned out of its position for elastic reflection and only neutrons scattered by spin waves of ~3 meV are reflected, in one case by spin-wave annihilation and in the other case by spin-wave creation. The curves show that neutrons scattered by spin waves are spin polarized along the scattering vector, and that neutrons scattered by creation and by annihilation of spin waves are polarized in opposite senses.

The rotation of the polarization vector of an initially polarized beam was studied on the sample, and it was found that complete reversal takes place regardless of whether the initial beam polarization is along or perpendicular to the scattering vector. Polarization rotation was also studied by spin waves from antiferromagnetic α-Fe_2O_3. Observations were made close to the rhombohedral (111) reciprocal lattice point, which is known to allow observation on spin