Measurement of the Fermi Velocity in Single-Crystal Films of Lead by Electron Tunneling*

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(Received 22 July 1970)

The authors have successfully exploited the Tomasch effect in quasiparticle tunneling from thick, superconducting, single-crystal Pb films to measure Fermi velocities in three high-symmetry directions. Multiple gaps were observed in all of these directions which agree with those reported earlier in bulk single-crystal studies, indicating that these films behave in a fashion similar to bulk Pb.

Tomasch[1] in 1965 first observed oscillations in the derivatives of the current (as a function of voltage) in the region beyond the energy gap (interval b in Fig. 1) in aluminum-insulator-lead tunnel junctions when examined at temperatures below the superconducting transition temperature of lead. It was found that this effect depended in a systematic way on the thickness of the lead film and could be related to the Fermi velocity in lead. McMillan and Anderson[2] showed that this phenomenon could be explained as a simple quasiparticle interference effect caused by scattering from a perturbation ($\delta\Delta$) in the energy-gap function on or near the film surfaces. They found that the effect caused the quasiparticle density of states to change by

$$\delta N(\omega) \propto \frac{\omega\Delta}{\omega^2-\Delta^2}\,\delta\Delta \mathrm{Si}\left[\frac{2Z(\omega^2-\Delta^2)^{1/2}d}{\hbar v_F}\right], \qquad (1)$$

where $\mathrm{Si}(x) \equiv \int_x^\infty (\sin y/y)dy$, $Z(\omega)$ is the usual renormalization function in the Green's function theory of superconductivity, and d is the thickness of the film. The function $\mathrm{Si}(x)$ is an oscillatory function with maxima occurring when

$$Z(\omega^2-\Delta^2)^{1/2}d/\pi\hbar v_F = n, \quad n=0, 1, 2, \cdots. \qquad (2)$$

One can, by analysis of the voltage position of the extrema of these oscillations, determine the reduced Fermi velocity in the direction normal to the film surface. This phenomenon has been used by the authors to determine the reduced Fermi velocity as a function of orientation in single-crystal films of lead. It is worth noting that the present method measures v_F averaged over a small spot on the Fermi surface and not over an orbit girdling the entire surface.

It has been possible to grow single-crystal films of lead of various orientations in this laboratory using a combination of the techniques of Schober[3] and of Landry and Mitchell[4] as applied to lead. Basically, silver (0.05 to 0.15 μm thick) was first evaporated on a polished oriented crystal of KBr and this was subsequently overcoated with lead. To date single-crystal films have been grown with the following directions normal to the film surface: [100], [110], [111], and [211]. In the instance of the [100] orientation it was necessary to grow the film 5° off axis in order to get a good single-crystal film and it is this orientation that will be called [100] in this paper. These films were oxidized in dry oxygen at elevated temperatures (of the order of thirty minutes at 100°C) and overcoated with polycrystalline lead films. Orientation and quality of the films was verified using transmission electron diffraction and back-reflection x-ray diffraction. Thickness of the single-crystal Pb was determined by weighing parts of the films on a microbalance and ranged from 0.4 to 17 μm in these experiments.

Tunneling data were taken using circuitry similar to that described by Adler and Jackson.[5] The dynamic resistance (dV/dI) and its derivative (d^2V/dI^2) were recorded as a function of bias voltage (V). In addition the gap structure was studied by recording curves of dI/dV and I vs V for the junctions. In all junctions used as

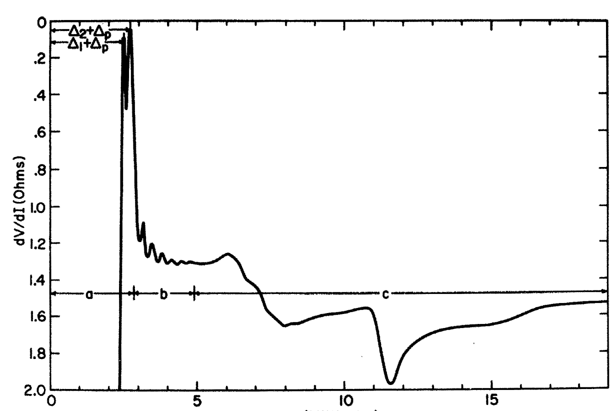

FIG. 1. Curve representing the relation between dV/dI and V in a lead-insulator-lead tunnel junction in which the bottom electrode was a 6.1-μm thick [111] single-crystal film. The data were taken at 1.1°K.

Table I. Tabulation of v_F/Z for the orientations [110], [111], and 5° off [100].

Orientation	No. of specimens	Thickness (μm)	2Δ (meV)	v_F/Z (10^8 cm/sec)
[110]	6	3.5- 7.0	2.52	0.93 ±0.05
			2.74	0.96 ±0.05
[111]	5	3.4-12.8	2.36	1.15 ±0.10
			2.78	1.20 ±0.10
[100]	2	7.2- 8.2	2.47	1.37 ±0.10
			2.75	1.43 ±0.10

data the conductance inside the gap ($|V|<\Delta_1+\Delta_p$) was at least two orders of magnitude less than outside the gap ($|V|\approx 3\Delta_1+3\Delta_p$). Gap structure, Tomasch oscillations, and phonon spectra were generally observed. Figure 1 represents a typical curve of dV/dI vs V for one of these films. Most of these data were taken at temperatures near 1.7°K.

Tomasch oscillations have been observed in all of the specimens reported here and the renormalized Fermi velocity $v_F'=(v_F/Z)$ has been calculated using the method presented by McMillan and Anderson.[2] The results are given in Table I.

Figure 2 shows an example of Tomasch oscillations in the tunneling characteristics of a 6.1-μm Pb film (oriented in the [111] direction). The index n corresponds to minima in dV/dI. Since the data reported here were taken for tunneling between the thick single-crystal film of lead and the thin overcoat of polycrystalline lead, ω in Eq. (2) is taken to be $V-\Delta_p$, where Δ_p is the energy gap associated with the polycrystalline lead.

In order for our curve to satisfy Eq. (2), we also have to correct for the dependence of Z on ω; this is done by plotting n vs $Z(\omega)(\omega^2-\Delta^2)^{1/2}/Z(\Delta)$ which is shown in the inset curve in Fig. 2 as a solid curve. There is an uncertainty as to which of the gap values, Δ_1 or Δ_2 (see Fig. 1), to use in the calculation of v_F'. The choice of Δ can change the reduced Fermi velocity by about 10%. A least-squares fit of the corrected data by Eq. (2) is not sufficiently sensitive to resolve this question (probably because the oscillations for low n are not resolved). Since the relative amplitudes of the conductance peaks are not generally the same for different films of the same orientation, the criteria used by Blackford and March[6] in their assignment of the gaps to specified zones cannot be used. If one chooses Δ_1 in the calculation of v_F' the resulting reduced Fermi velocities are in better agreement with average velocities for electrons in the third Brillouin zone derived from cyclotron-resonance and de Haas-van Alphen[7] experiments. As indicated earlier, the above method and the method

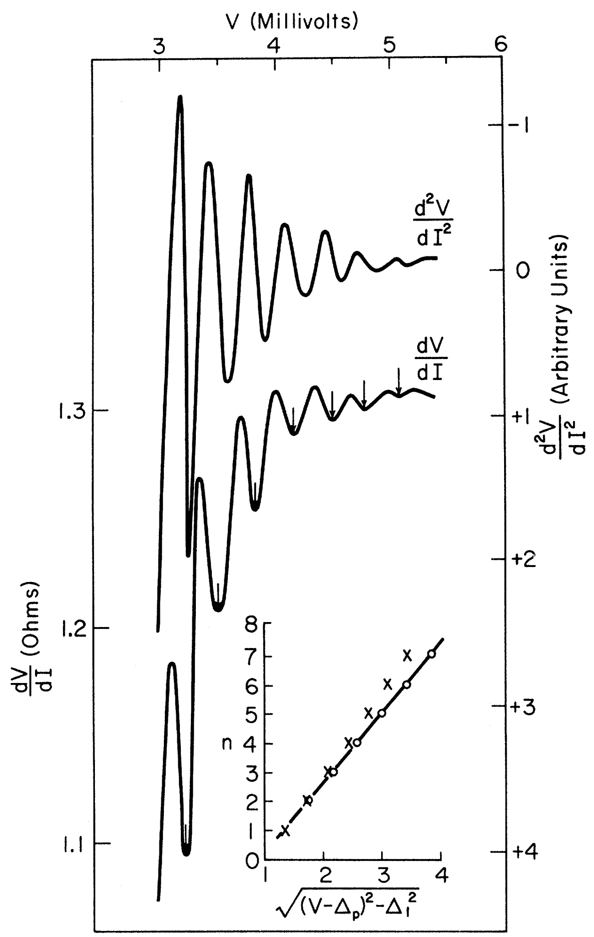

FIG. 2. Presentation of the relation between Tomasch oscillations and the applied voltage for film of Fig. 1. Upper curve: d^2V/dI^2 vs V; scales top and right. Lower curve: dV/dI vs V; scales top and left. Inset curve: oscillation minima (n) vs $[(V-\Delta_p)^2-\Delta_1^2]^{1/2}$; crosses are original data while circles have been corrected for $Z(V)$ dependence.

used here do not average v_F' in the same way; hence this criterion is suspect. Work is in progress in this laboratory to calculate v_F' from accepted Fermi-surface models[7] so that a more direct comparison may be made. The values of v_F' reported here were calculated using both gaps in each of the directions for purposes of comparison.

The only other experimental datum with which to compare these results is the value of the $v_F/Z = 0.98\times10^8$ cm/sec for Tomasch's[2] results on polycrystalline lead and $v_F/Z = 0.5\times10^8$ cm/sec from anomalous skin-effect measurements.[8] Tomasch's[9] result should probably be compared with the results reported here for the [111] orientation since Tomasch tentatively reported his films as having a [111] texture axis normal to the surface of the film. It should be noted that the results calculated from anomalous skin-effect data represent an average over all orientations and that the number has an inherent uncertainty of at least 30% due to the uncertainty in the penetration depth[10] used in the calculation.

In some instances the observed oscillations could not be interpreted in terms of a single set of oscillations, though this was not the case for any of the results shown in Table I. Tentative analysis of such data indicates that they can be interpreted in terms of a superposition of two sets of oscillations which represent two different reduced Fermi velocities. A preliminary comparison of these results with Fermi velocities calculated from a knowledge of the Fermi surface in lead indicates that the second set of velocities are due to electrons from a different zone. Analysis of these more complex data is continuing.

An effort is being made to grow single crystals oriented with the [100] axis normal to the film plane. The growth of this orientation is complicated by the tendency to grow [111] twins on the (100) face of KBr. Preliminary information on the best of these crystals indicates that v_F/Z in this direction will be considerably (the order of 25%) below that reported here for 5° off [100].

Well-resolved double gaps (interval a in Fig. 1) have been observed in nearly all junctions studied with single-crystal lead electrodes of thickness between 0.4 and 17 μm. These gaps are believed to be due to contributions to the tunneling from two different Brillouin zones. The positions of the double gaps agree with those reported by Blackford and March[6] though the relative amplitudes are not always the same as those reported by them.

As can be seen in Fig. 1 (interval c), considerable structure is evident in these data at voltages greater than those for the Tomasch oscillations which presumably contain information on the phonon density of states in lead. This has not been analyzed but measurements on single-crystal films in which the top metal is normal (as opposed to superconducting) are under way. This may make possible the determination of the phonon spectra as a function of orientation.

The authors wish to acknowledge the very helpful discussions concerning the interpretation of these data with K. Dy and C. V. Briscoe of this department.

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*Work supported by the U. S. Air Force Office of Scientific Research under Grant No. AF-AFOSR-1241-7, and by the Advanced Research Projects Agency of the Department of Defense to the University of North Carolina Materials Research Center under Contract No. SD-100.

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