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Current-voltage characteristics of superconducting Pb films in contact with a normal metal*

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We have observed step structure in the current-voltage characteristics of single-crystal and polycrystal Pb films in parallel applied magnetic field near H_{c2} of the film. The single-crystal films are in direct contact with a normal metal which suppresses surface superconductivity on that side of the film. These films exhibit the same type of step structure in their I-V curves as do Pb films deposited directly onto glass substrates.

I. INTRODUCTION

Recently there have been reports of step structure in the current-voltage characteristic curves of superconducting Sn microbridges, Sn whiskers, and Pb films[1–3] Tinkham[1] has shown that the observed step structure in the I-V curves of both the Sn whiskers and Sn microbridges, near T_c, are due to the appearance of phase-slip centers each contributing a constant differential resistance and being offset by a time-averaged local supercurrent of $(0.5-0.65)I_c(T)$. Chen *et al.*[3] have observed step structure in the I-V curves of Pb films in the presence of a parallel applied magnetic field slightly less than H_{c2} in magnitude. In such a field the center portion of the films are normal while there is a superconducting layer on each surface. Chen *et al.*[3] have suggested the existence of bound quasiparticle states in this normal interior as the explanation for the structure they observed. We have made measurements of the current-voltage characteristics of Pb films in a parallel applied magnetic field with the films having both surfaces free (a surface in contact with an insulating substrate is considered free) and also with one film surface in direct contact with a normal metal. In both cases step structure was observed in the I-V curves. These Pb films, when held at temperatures near T_c (films with and without a normal-metal overlayer), exhibited similar step structure in their I-V curves.

II. FILM PREPARATION AND CRITICAL-FIELD MEASUREMENTS

The Pb films that were in direct contact with the normal metal were epitaxially grown single-crystal Pb films. These single-crystal films were grown by the technique of Schober.[4] In this method a polished KBr substrate[5] that has been cut so its surface lies in the desired plane was rapidly heated to 200 °C. Ag was then vapor deposited at a rate of 1000 Å/ sec directly onto the substrate surface, which resulted in the epitaxial growth of the Ag. Immediately Pb was vapor deposited, also at a rate of 1000 Å/sec, onto the single-crystal Ag film and this produced the epitaxial growth of the Pb. The Ag film thickness was typically on the order of 1000 Å. The polycrystalline films were made by simply depositing Pb directly onto a glass substrate that had been heated to 200 °C.

Before the I-V characteristics of a film were measured the parallel (H_{c3}) and perpendicular (H_{c2}) critical fields were determined by recording their resistive transition in an increasing magnetic field. We define the critical field to be the value of the applied magnetic field at which the ratio $R_F/R_R = 0.995$, where R_F is the film resistance and R_R is

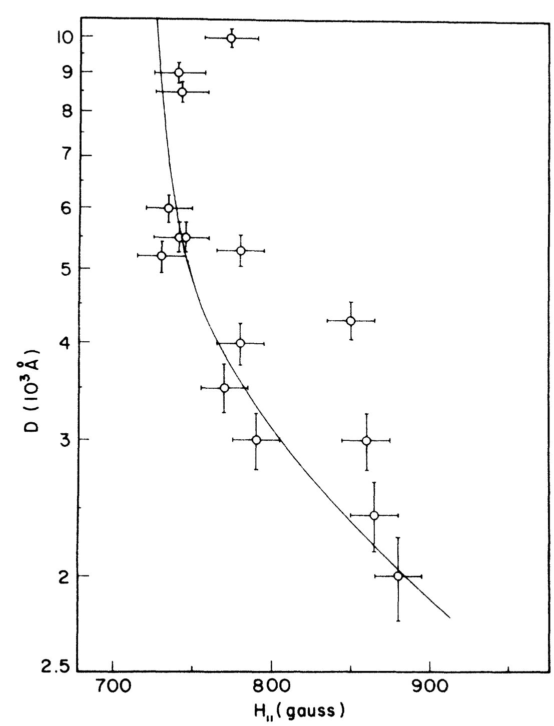

FIG. 1. Thickness dependence of parallel critical field (H_{c3}).

TABLE I. Experimentally measured properties of Pb films.

Film	d (Å)	H_{c3} (G)	H_{c2} (G)	R_R (10^{-3} Ω)	R_{0s}[a] (10^{-3} Ω)	Surface orientation	Field direction	$R_{300}/R_{4.2}$
Pb58	5500	740	540	57.5	1.25	T[b]		215
Pb65	4000	780	465	42.8	0.93	⟨110⟩	⟨100⟩	441
Pb67	4300	850	610	34.9	0.76	⟨110⟩	⟨110⟩	845
Pb68	5300	780	510	39.1	0.85	⟨110⟩	⟨100⟩	545
Pb70	10000	773	600	9.43	0.21	⟨110⟩	⟨110⟩	1600
Pb71	5200	730	600	28.5	0.62	⟨110⟩	⟨110⟩	650
Pb72	9000	740		14.9	0.33	⟨110⟩	⟨100⟩	870
Pb73	3500	1083	690	53.4	1.16	⟨111⟩	⟨110⟩	480
Pb75	3500	1087	650	232	5.05	T		
Pb76	5500	745	550	97.5	2.12	⟨111⟩	⟨110⟩	147
Pb78	6000	734	580	33.2	0.72	G[c]		
Pb79	8500	743	585	37.3	0.81	G		
Pb80	3000	860	600	222	4.82	G		
Pb82	3500	770	595	66.3	1.44	G		
Pb83	2400	865	640	217	4.71	⟨100⟩	⟨100⟩	74
Pb84	3000	790	640	143	3.10	⟨100⟩	⟨110⟩	150
Pb85	2000	880	570	262	5.7	⟨100⟩	⟨110⟩	98

[a] $R_{0s} = R_R W/L$, W is film width and L is film length.
[b] T indicates a ⟨111⟩ twin.
[c] G indicates film was deposited onto glass substrate.

the residual resistance at 4.2 °K. All measurements were made with the films submerged in liquid helium (4.2 °K).

To determine an accurate value of the parallel critical field the film surface must be aligned parallel with the applied magnetic field as accurately as possible. This alignment was accomplished by increasing the magnetic field until the film became resistive and had obtained about one-half its residual resistance. The film was then rotated until a minimum in film resistance was found; at this position the film was considered parallel to the applied field. For the single-crystal films this was a particularly sensitive method because they usually had very sharp transitions (about 90% in the residual resistance at 4.2 °K was obtained with a change of applied magnetic field of 10–20 G). The perpendicular orientation was obtained by simply rotating the film 90°. Results of these measurements are given in Table I along with the orientation of the surface (the crystallographic direction normal to the surface) and the direction along which the magnetic field is applied when the film is parallel to the field. The thickness dependence observed is consistent with that determined by Cody and Miller[6] and is shown in Fig. 1.

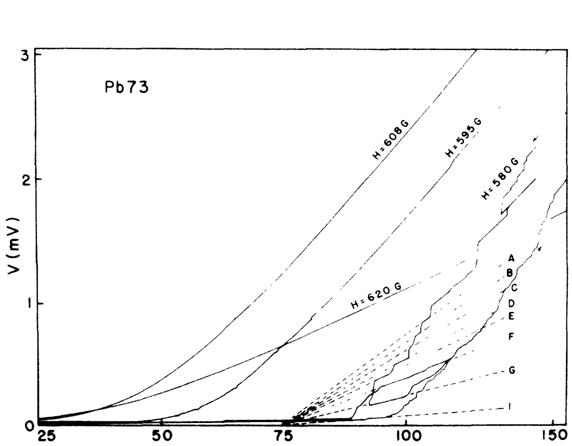

FIG. 2. Current-voltage characteristics of a single-crystal Pb film with Ag underlayer. Vertical scale for the $H = 620$ G curve is 2.5 times that shown.

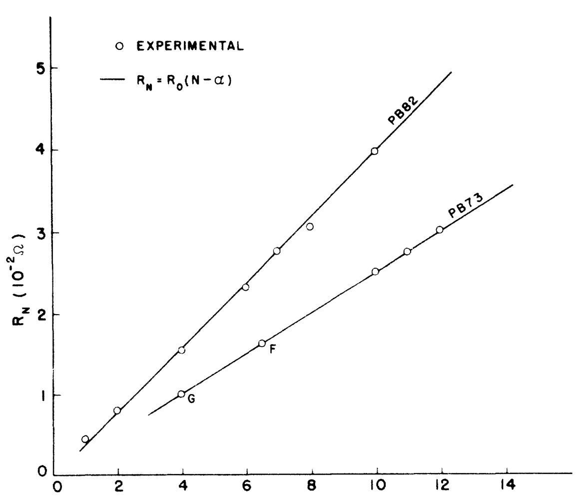

FIG. 3. Data fitted to $R_N = R_0(N - \alpha)$.

III. CURRENT-VOLTAGE CHARACTERISTICS

The single-crystal Pb films were in direct contact with a normal metal, Ag, which suppressed surface superconductivity[7] on the surface making contact with the normal metal. Therefore, when such a film is in a parallel applied magnetic field above H_{c2}, superconductivity is limited to one surface sheath on the free surface of the film. In contrast to this, the films deposited directly on glass substrates when in a parallel applied magnetic field above H_{c2} have a normal center portion with superconducting layers on each surface. With this type of film there is the possibility of the existence of bound quasiparticle states.[2] However, we believe that the appearance of phase-slip centers may be a better explanation for our results.

The steps we observed in I-V curves are similar to those previously reported for Pb films[2]; however, the steps do not seem to be as stable. Figure 2 shows the I-V curve of a 3500-Å single-crystal Pb film with a Ag underlayer. The data were taken with the film in a parallel magnetic field of 580 G, which is 0.84 of the measured H_{c2}. These steps can be fitted to the expression[2]

$$R_N = R_0(N-\alpha), \quad (1)$$

if we assume the first step was observed and that α is a small number. We further assume that the series A through E (see Fig. 2) has no missing steps. Therefore $R_N = R_0 N$ and $R_0 = (dV/dI)_A - (dV/dI)_B = 0.25\times10^{-2}\,\Omega$. These data are plotted, assuming that the point A in Fig. 2 does correspond to $N=12$. The point G can easily be located at $N=4$ (Fig. 3) indicating that steps for $N=2$ and $N=3$ are not distinct. Point F falls between $N=6$ and $N=7$.

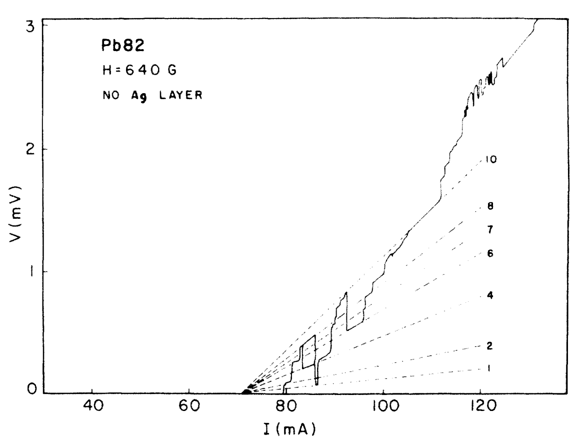

FIG. 4. Current-voltage characteristics of a Pb film deposited directly onto glass substrate.

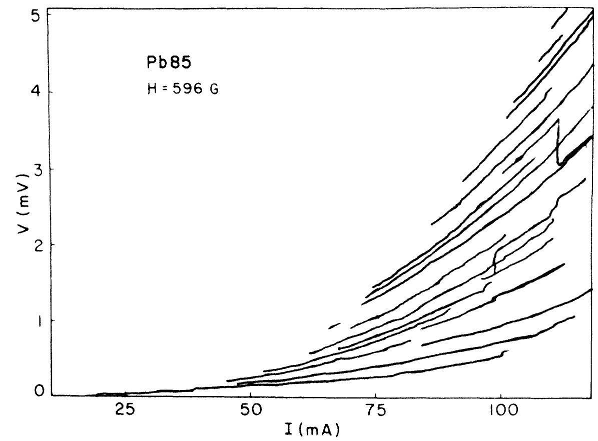

FIG. 5. Current-voltage characteristics of thin single-crystal Pb film. Low-current branches can be seen between 25 and 50 mA.

Data taken on a Pb film deposited directly onto a glass substrate is shown in Fig. 4. The fitting of the data was similar to that discussed above with $R_0 = 4\times10^{-2}\,\Omega$ and $\alpha = 0.05$.

The magnetic-field dependence of the resistance steps was not studied in detail, but we can describe their general behavior. Steps seemed to be most stable and largest at a magnetic field of $1.05H_{c2}$ and disappeared rather rapidly with increasing field. The steps were usually not detected above $1.2H_{c2}$. Observation of low-field behavior of the steps was hampered by the current limitation of our dc current supply.

Figure 5 shows data taken on another single-crystal Pb film with Ag underlayer in an applied parallel field of $1.06H_{c2}$. This I-V curve exhibits stable current branches extending over large current ranges. The film was one of the thinnest on which data were taken, and had a thickness about equal to the superconducting coherence length $\xi(T)$.

Tinkham[1] has observed step structure in I-V curves of Sn microbridges and attributed their origin, along with that of similar structure in the I-V curves of Sn whiskers, to quantum phase-slip centers. These measurements were made within a few millidegrees of T_c and the localized voltage units occurred at local critical currents determined primarily by variations in T_c along the bridge. Our measurements were made near H_{c2}, which restricted superconductivity to a surface layer about one coherence-length thick. The phase-slip centers in our case could occur at local critical currents determined by variations in critical field. The geometry of our films is such that when a normal static region occurs in the surface sheath it is shunted by the normal lamina below; this will cause the height of the step to be smaller and pro-

TABLE II. Quasiparticle diffusion lengths and film parameters.

Film	ρ ($\mu\Omega$ cm)	Length (mm)	Width (mm)	dV/dI (10^{-3} Ω)	L_n (μm)
Pb85	0.114	8.3	0.15	2.16	68.4
Pb82	0.050	8.3	0.15	0.67	84.0
Pb73	0.041	8.3	0.15	0.57	89.0
Pb86	0.50	8.3	0.15	10.0	39.5
Pb88	1.00	7.77	0.26	8.0	22.0

duce a smaller slope in the I-V curve. We suggest that the rapid disappearance of the step structure with increasing magnetic field is due to the eventual dominance of resistive normal sections. These normal sections are caused by variations in H_{c3} and, most probably, by a normal component of the magnetic field introduced by irregularities in the film surface.

In order to suggest feasibility we can show that Tinkham's quasiparticle diffusion length calculated from our data also has the proper dependence on the electron mean free path l. The product ρl for a given metal at a constant temperature should be a constant. Therefore, using the expression for the quasiparticle diffusion length

$$L_N = 2\left(\tfrac{1}{3}v_F\tau_2\right)^{1/2} l^{1/2} \quad (2)$$

from Tinkham,[1] we can write

$$L_N = B\rho^{-1/2} \quad (3)$$

and

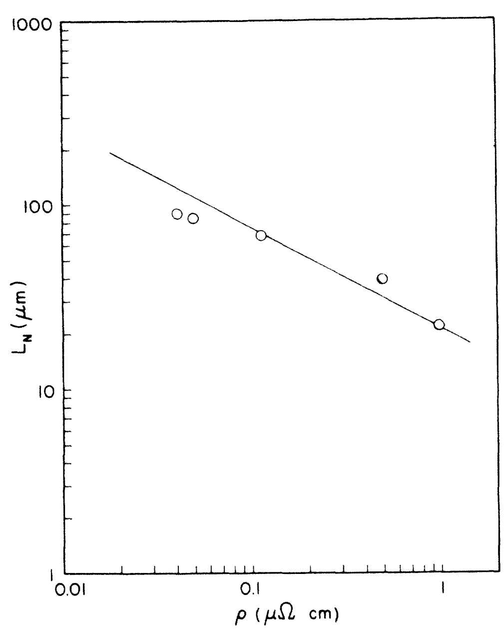

FIG. 6. Dependence of the quasiparticle diffusion length on resistivity determined from our data.

$$B = \left(\tfrac{4}{3}v_F\tau_2 C\right)^{1/2}, \quad (4)$$

where $\rho l = C$, v_F is the Fermi velocity, and τ_2 is the quasiparticle relaxation time. In Fig. 6 we show a log-log plot of L_N and ρ (the line has a slope of $-\frac{1}{2}$), and Table II gives the data for these films. A calculation of the quasiparticle relaxation time from the plot in Fig. 6 gave $\tau_2 = 1.2\times10^{-10}$ sec, where we have used $v_F = 1.56\times10^8$ cm/sec and $\rho l = 1.5\times10^{-11}$ Ωcm^2.[6] Perhaps this is only fortuitous but this is the same order of magnitude Tinkham[1] has calculated for Sn.

IV. CONCLUSION

The fitting of our data for Pb films deposited directly on glass substrates to expression (1) indicates that the steps in dV/dI are approximately constant in size, including the first (small α). Data of the same type were obtained on films that were in direct contact with a normal metal in a magnetic field smaller than H_{c3}. These films exhibited the same type of step structure in their I-V curves. The bound states suggested by Chen *et al.* require the existence of the two superconducting sheaths since these bound states are due to the coherent reflections of quasiparticles (holes) into quasiholes (particles) by the pair-potential boundaries separating the normal-center portion of the film from the two superconducting surface sheaths.[2] Thus it is hard to understand our observations in terms of bound states.

The resolution of our data in the low-current regime is only fair; however, quasiparticle diffusion lengths calculated from these data do apparently have the proper electron mean free path dependence. At large currents we observe an increase in the slope of the I–V curves together with some hysteresis. This type of behavior of step structure in I–V curves of Pb films is not dependent on the fact that the films are in a parallel applied magnetic field near H_{c2}. Preliminary measurements on similar Pb films held at temperatures near T_c also exhibited step structure in their I–V curves. Therefore we believe that our data are best described by the phenomenological model proposed by Tinkham.[1]

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