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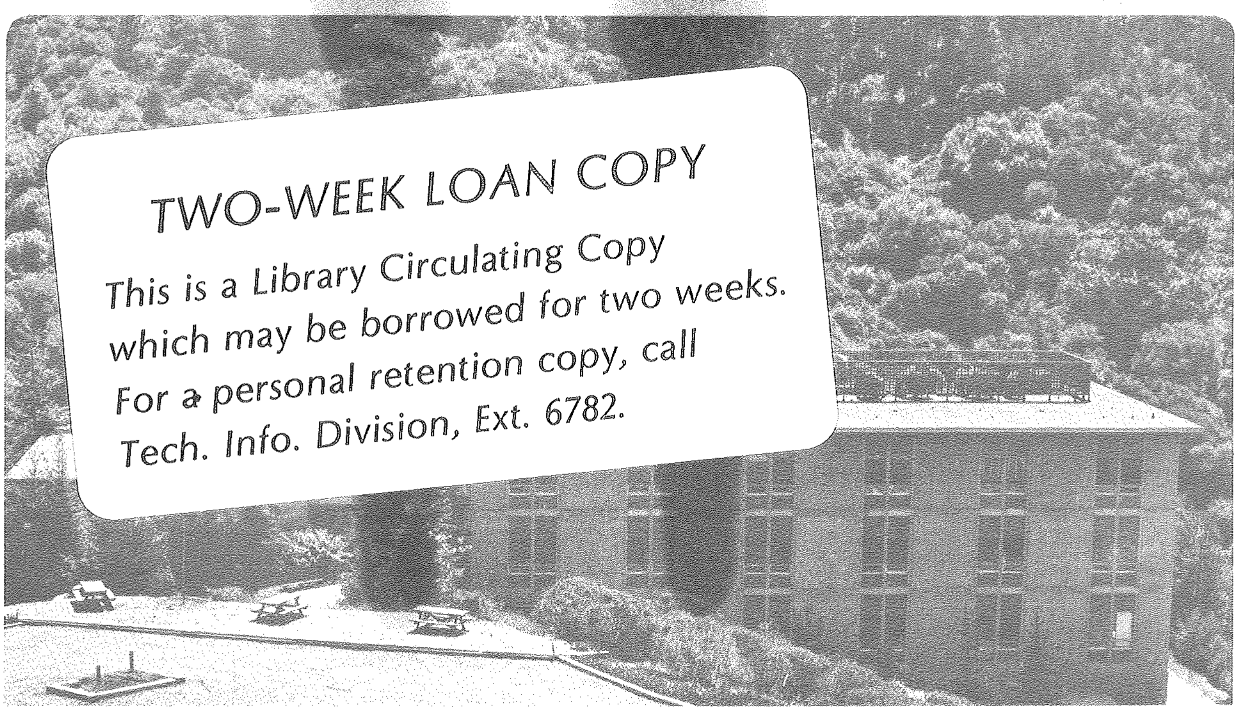

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CHARGE IMBALANCE IN SUPERCONDUCTING TIN FILMS PRODUCED BY A SUPERCURRENT IN THE PRESENCE OF A TEMPERATURE GRADIENT

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Abstract

A pair-quasiparticle potential difference V arising from a quasiparticle charge imbalance has been measured in superconducting tin and tin-indium films along which there exist both a supercurrent, I, and a temperature gradient, ∇T. The voltage is proportional to $I\nabla T$ at a given temperature, and near T_c diverges approximately as $(1-t)^{-1}$ for given values of I and ∇T. Theories by Schmid and Schön and by Clarke and Tinkham are in good agreement with the temperature dependence and magnitude of $V/I\nabla T$, while a theory by Beyer Nielsen *et al.* predicts the correct magnitude but a temperature dependence of $(1-t)^{-\frac{1}{2}}$.

1. INTRODUCTION

Pethick and Smith[1] predicted that when a supercurrent, $\vec{I}$, flows in a superconductor along which there exists a thermal gradient, $\vec{\nabla}T$, a charge imbalance[2-4], Q^*, should be created that is proportional to $\vec{I}\cdot\vec{\nabla}T$. In the usual way, this charge imbalance produces a potential difference relative to the electrochemical potential of the pairs that can be detected by a normal metal in tunneling contact with the superconductor. Clarke *et al.*[5] observed this effect in Sn films and established that the voltage scaled with $\vec{I}\cdot\vec{\nabla}T$ as predicted. However, the original theory[1] is valid only in the limit in which the inelastic quasiparticle scattering rate is much higher than the elastic scattering rate, whereas the reverse is true for the samples studied. As a result, it was found that the measured voltage was two to three orders of magnitude smaller than the theoretical prediction. Three subsequent papers, by Schmid and Schön[6], Clarke and Tinkham[7] and Beyer Nielsen *et al.*[8], then appeared in attempts to account quantitatively for the temperature dependence and magnitude of the experimental data. More recently, Heidel and Garland[9] observed the effect in Al.

The purpose of this paper is to report extensions of the previous experimental work to include another sample in the clean limit ($\ell > \xi_0$) and two samples doped with In in the dirty limit ($\ell < \xi_0$), where ℓ and ξ_0 are the electronic mean free path and coherence length.

The data from both clean limit and dirty limit samples are compared with the three available theories.

Section 2 describes the experimental details, Sec. 3 presents the results, and Sec. 4 compares the results with the theories. Section 5 contains a concluding summary.

2. EXPERIMENTAL PROCEDURES

Our experimental configuration is shown in Fig. 1. First, a Sn film typically 300nm thick and 0.1mm wide in the middle region was evaporated onto a $32\times7\times1\,mm^3$ soda glass or silicon substrate maintained at either liquid nitrogen or room temperature. For samples 7 and 8 in Table 1, 3 wt. % In was added to the Sn and the alloy deposited by evaporating small pellets to completion one by one. The Sn was oxidized in air for 5 to 15 min., and three Cu(+ 3% Al) disks 0.8 to 1.3 μm thick and 2 mm in diameter were deposited. Finally three Pb strips 1 mm wide and about 200 nm thick were evaporated. The thickness and mean free path, ℓ , of the Sn strips and the junction resistance at T_c, $R_{jn}(T_c)$, are listed in Table I for eight samples. In a given experimental run one of the three $Sn\text{-}SnO_x\text{-}Cu$ tunnel junctions was used to detect the quasiparticle potential in the superconducting Sn film relative to the pair potential. The Pb strips eliminated nearly all the resistance of the Cu that would otherwise generate both an excessive Johnson noise and spurious thermoelectric effects. The Cu was sufficiently thick and dirty to eliminate pair tunneling between the two superconductors in the temperature range where we made measurements. Thin PbSn solder leads were attached to the films with In pellets, and connected to Nb wires to make superconducting current (I) and voltage (V) leads. The use of superconducting current leads enabled us to apply a current without heating the substrate [except above the In transition (~ 3.4 K) where a negligible heating occurred], while the use of superconducting voltage leads eliminated spurious thermoelectric voltages. The superconducting voltage lead was attached to a region of the Sn where $I = 0$. If $I \neq 0$ and $\nabla T \neq 0$ at the point of attachment, this lead would still measure the pair potential at temperatures below the In transition, but not above it.

The sample was mounted in a vacuum can. Each end of the substrate was clamped to a Cu block, connected to the top of the can via a suitable thermal conductance. A heater was wound non-inductively around each of the Cu blocks. Two Allen-Bradley carbon thermometers were attached to the rear side of the substrate with G.E. varnish. None of the leads connected to the substrate perturbed its temperature distribution significantly. Outside the can the voltage leads were connected in series with a resistor of $\sim 3 \times 10^{-5}\ \Omega$ and the superconducting input coil of a S.H.E.

SQUID operated as a null-balancing voltmeter. (However, a small offset in the null-balance did not affect the results measureably, as we verified by deliberately introducing a rather large offset.) Thus the quasi-particle potential was measured at (nearly) zero current with a resolution limited by the Johnson noise in the resistor and the junction. The can was immersed in superfluid helium, and the cryostat was surrounded by a double Mumetal shield.

To make a measurement, we applied current to one or both heaters until the substrate attained the desired temperature gradient. This procedure invariably generated a small voltage, for one of several reasons. Since the resistance of the junction was temperature dependent and the creation of a temperature gradient almost inevitably changed the temperature of the junction, an off-set current in the voltmeter circuit produced a voltage change across the junction. Thermoelectric effects in the CuAl film, or in the In contacts above their transition temperature, 3.4K, could also contribute to this voltage. Finally, a small voltage is expected from the superconductor even for zero supercurrent, as observed by Falco[10] and discussed by Tinkham[11], although we suspect this mechanism produces a voltage that is too small to be observable in our experiment. Whatever its origin, this voltage, at most 1pV, was small compared with the voltages generated when we applied a supercurrent. When a steady temperature gradient had been established, we defined the voltage to be zero when the applied supercurrent, I, was zero. We increased I in steps, and measured the voltage V at each step, as indicated in Fig. 2. While I was being changed, we always observed an inductive signal that was sometimes larger than the steady state signal at constant current.

During the course of the experiment, we took account of a number of possible problems:

(i) We took great care to ensure that the Sn was not driven normal. For example, after taking data at a given gradient, we could raise the temperature of the colder end of the sample until $\nabla T = 0$, and check that $V = 0$ at the highest current used. In fact, the formation of any normal region would have introduced such a large resistance that we could not have mistaken its origin. If we assume that a phase-slip center were to be formed at one point in the Sn strip, the normal region would be of the order of the quasiparticle charge-relaxation length, $\lambda_{Q^*} \sim 1\,\mu m$, corresponding to a resistance of the order of $1\,m\Omega$. By comparison, the effective resistance due to the charge imbalance was of the order of $1\,n\Omega$. Furthermore, and most important, the sign of the measured voltage reversed when $\vec{\nabla} T$ was reversed, which would not be the case if we were observing a voltage across a normal region in the Sn film.

(ii) A simple calculation indicates that the thin films should not significantly perturb the temperature distribution of a glass substrate, and that the gradient in the Sn film should be the same as that in the substrate, even in the vicinity of the overlying films. As a check, we prepared a sample (5) on a Si substrate with a thermal conductance three orders of magnitude greater than glass. The signal generated was not significantly different (Table 1).

(iii) The temperature gradient along the copper film together with the magnetic field in its plane generated by I give rise to transverse thermoelectric effects. These thermoelectric effects vary strongly with the impurity content of the copper. However, such thermoelectric voltages are estimated to be two or more orders of magnitude smaller the voltages we observe, and have a different temperature dependence.

(iv) The uniformity of the supercurrent and charge imbalance through the Sn film is a complicated problem. We first consider the supercurrent distribution. The penetration depth, $\lambda(T)$, is greater than the film thickness, d, for samples 7 and 8 for $T > 0.95T_c$, but less than d for all other samples over the temperature range in which accurate data were obtained. Thus, one might expect the temperature dependent exclusion of the supercurrent from the interior of the film to show up as a different temperature dependence of Q^* in films of different thicknesses; in fact, to within the experimental resolution, no such effect was observed. In addition, the supercurrent tends to concentrate at the edges of the Sn film except where it passes under the Pb film, which acts as a ground plane. To investigate possible effects due to current redistribution in the Sn near the edges of the Pb film, after collecting data from sample 3 we coated the films with a thin ($\lesssim$ 1μm) layer of Duco cement, and deposited a large Pb ground plane. The mesured voltages without and with the ground plane agreed to within the scatter in the data. We conclude that the measured voltages are not seriously affected by nonuniformities in the current distribution across the width of the film. The second problem concerns the uniformity of Q*. In the usual charge imbalance situations one would expect Q* to be uniform over a length λ_{Q^*} which is much greater than d. However, in the present case the relevant decay length appears to be the elastic mean free path, ℓ , which exceeds d only for sample 4. Thus, for most samples, it is not clear how uniform the charge distribution is through the film. In summary, there are unanswered questions concerning the uniformity of both the supercurrent and the charge imbalance, but we feel that the resulting error in the magnitude of the measured voltages is at most a factor of 2.

3. EXPERIMENTAL RESULTS

In Figs. 3 and 4 we plot V vs. I for five values of ∇T, and V vs. ∇T for ten values of I, for a representative sample. The quasiparticle potential is positive relative to the pair potential if the (conventional) current and ∇T are in the same direction. V is proportional to I over the accessible current range (up to three decades) and very nearly proportional to ∇T. The small deviations from linearity in Fig. 4 are caused by errors in estimating the junction temperature from the two thermometer readings, and the fact that we did not correct the gradients estimated from the two thermometers for the temperature-dependent thermal conductance of the substrate. This approximation produces a small error for the higher gradients on the glass substrates; the gradients obtainable for the silicon substrate were always small.

The measured voltage is inversely proportional to the measured normalized junction conductance, g_{NS} [3,4] which we determined separately by applying a current to the lead i and one of the leads I. To eliminate the temperature dependence of g_{NS}, which was somewhat sample dependent (almost ideal for sample 6), we have plotted $Vg_{NS}/I\nabla T$ versus reduced temperature, t, in Fig. 5. $Vg_{NS}/I\nabla T$ diverges as $t \to 1$, and falls off steadily with decreasing temperature at low temperatures.

The temperature dependence is approximately the same for all 8 samples. As an example, in Fig. 6 we plot $Vg_{NS}T/I\nabla T$ vs. (1-t) for a clean and a dirty sample. The rather high junction resistance of sample 8 and resulting high level of Johnson noise prevented us from obtaining accurate data very close to T_c, but we have chosen to present this set of data because they extend to a lower temperature than those for any other sample. The divergence close to T_c seems to be slightly less pronounced for most of the dirty samples. This could be connected with the fact that the transition was wider ($\sim$ 40 mK) for these samples. On the other hand,

In Table 2 we list the measured values of $Vg_{NS}T(1-t)A/I\nabla T$ at $t=T/T_c \approx 0.9$, where A is the cross section area. The fact that the data do not scale exactly as $[T(1-t)]^{-1}$ over the range in which accurate data were obtained implies that the listed quantity is slightly temperature dependent, and the values for samples 1 to 5 differ somewhat from the values in ref. 5 where the data were fitted to lines of slope of -1 in plots like those in Fig. 6.

IV. COMPARISON WITH THEORY

All existing theories predict that the measured voltage should be proportional to $\vec{v}_s \cdot \vec{\nabla} T$, where v_s is the superfluid velocity, provided that v_s is much less than the critical velocity. To compare the theory with the experimental results, we need to express v_s in terms of the applied supercurrent. If we assume that the applied current is uniformly distributed in the superconductor, we can write $v_s = j_s/n_s e = \mu_0 j_s \lambda^2(T)\ e/m$, where j_s is the supercurrent density and $\lambda(T)$ is the penetration depth. Using the empirical relationship [12] $\lambda^2(T) = \lambda^2_L(0)(1 + \xi_0/\ell)(1 - t^4)^{-1}$ we find

$$v_s = \frac{\mu_0 j_s e \lambda_L^2(0)(1+\xi_0/\ell)}{m(1-t^4)} , \qquad (1)$$

where $\lambda_L(0)$ is the London penetration depth at $T = 0$, and $\xi_0 = \hbar v_F/\pi\Delta(0)$. Equation (1) should be a reasonable approximation for all temperatures and for both clean and dirty superconductors. When comparing their theory for the clean limit with experiment, Beyer Nielsen et al.[8] used an alternative expression for the superfluid electron density appropriate to the London limit, $n_s = n(1-Y)$, where $Y = 2\int_\Delta^\infty \rho(E)(-\partial f/\partial E)\,dE$ is the Yoshida function. Here, $\rho(E) = E/(E^2-\Delta^2)^{\frac{1}{2}}$, and $f(E)$ is the Fermi function.

The bilinearity of the measured voltage in I and ∇T, predicted by all theories, is well established experimentally. On the other hand, the theories differ in their predictions of the temperature dependence and magnitude of the voltage, as we shall now discuss. In Fig. 7 we compare the data from sample 4 with the theories, using $\ell = 4.28 \times 10^{-7}$m, $v_F = 6.5 \times 10^5$ms^{-1}, $\xi_0 = 2.3 \times 10^{-7}$m, and $\lambda_L(0) = 5 \times 10^{-8}$m.

4.1 Comparison of data with theories

Theory of Clarke and Tinkham

This theory, which is claimed to be valid for all temperatures and for the clean limit $\ell > \xi_0$, predicts that

$$V = \frac{1}{6}\,\frac{p_F\,\ell}{e g_{NS}}\,\frac{\vec{v}_s\cdot\vec{\nabla}T}{T}\,\frac{(\Delta/k_BT)}{\mathrm{ch}^2(\Delta/2k_BT)(1-Z)}\,. \tag{2}$$

In Eq. (2), p_F is the Fermi momentum, and $Z = 2\int_\Delta^\infty \rho^{-1}(E)(-\partial f/\partial E)\,dE$. In the limit $T \to T_c$, $\mathrm{ch}^2(\Delta/2k_BT) \to 1$, and $(1-Z) \to \pi\Delta/4k_BT$. Thus, near T_c the temperature dependence of V at constant current I is dominated by the temperature dependence of v_S, i.e. $(1-t)^{-1}$, in agreement with the experimental results. Equation (2), multiplied by a factor of about 2.4* to fit the data at $t = 0.99$, is plotted in Fig. 7.

Theory of Schmid and Schön

Two independent theoretical approaches valid in the clean and dirty limit, respectively, were developed by Schmid and Schön. Since their result in the clean limit was subsequently included in the more complete theory by Beyer Nielsen et al. (next section) we shall here give only the result of their dirty limit calculation.

The result quoted in their paper Eq.(9) is valid only in the limit $\Delta/k_BT \rightarrow 0$. At low temperatures Q^* is expected to vanish exponentially, and one can readily deduce an equation that also reveals this feature, which completely dominates at temperatures below $0.7T_c$. If† one uses the exact expression $n_T' \equiv \partial f(E)/\partial E = -1/4k_BT\mathrm{ch}^2(E/2k_BT)$ in their Eq. (7) for the function they have labelled V, and notes that the integrand is sharply peaked at $E = \Delta$, one finds $V = \left[\Delta/8k_BT\mathrm{ch}^2(\Delta/2k_BT)\right]\ln(8\Delta\tau_E/\hbar)$ in the limit where phonons are the only source of pair breaking. Inserting this expression in their Eq.(6) we arrive at the result for the voltage

$$V = \frac{1}{6}\frac{p_F\ell}{eg_{NS}}\frac{\vec{v}_s\cdot\vec{\nabla}T}{T}\frac{(\Delta/k_BT)}{\mathrm{ch}^2(\Delta/2k_BT)(1-Z)}\ln(8\Delta\tau_E/\hbar), \qquad (3)$$

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* The exact values of the fitting parameters should not be taken too seriously, since they refer to one sample only, and Beyer Nielsen *et al.* use a different expression for n_s than Clarke and Tinkham and Schmid and Schön.

† We are indebted to Dr. G. Schön for a discussion of this point.

where we have used the relation $V = Q^{*}/2N(0)eg_{NS}$ between the voltage and the charge imbalance[3]. Here, $N(0)$ is the single spin density of states and τ_E is the electron-phonon scattering time at T_c and at the Fermi energy.

This result exeeds Eq.(2) by the factor $\ln(8\Delta\tau_E/\hbar)$ which varies slowly over the temperature range $0.5 < t < 0.99$ with an average value of about 6. (It should be noted that τ_E is actually a function of both energy and temperature, a fact we neglect here.) We have plotted Eq. (3), multiplied by a factor of about 0.4 to fit it to the data at $t = 0.99$ and with $\tau_E = 2\times10^{-10}$s, in Fig. 7. The agreement between the fitted curve and the experimental data is good, but it is very likely that the procedure we have used to obtain the low temperature expression does not contain all the necessary corrections. The curve at low temperatures is dashed in order to stress this point.

<u>Theory of Beyer Nielsen et al.</u>

This theory is derived for all temperatures and in the clean limit $\tau_E v_F > \ell > \xi_0$. An approximate interpolation formula for the calculated voltage has been given by Pethick and Smith[13]

$$V = \frac{p_F \ell}{eg_{NS}} \frac{\vec{v}_s \cdot \vec{\nabla} T}{T} \left[\frac{1.93\Delta/k_B T}{ch^2(\Delta/2k_B T)} + \frac{8/15}{e^{\Delta/k_B T}+1} \right] . \qquad (4)$$

The first term in square brackets dominates the second for $T \lesssim 0.998\, T_c$, that is, over the entire temperature range that is experimentally accessible. For temperatures reasonably close to T_c (but below $0.998\, T_c$), V is proportional to $(1-t)^{-\frac{1}{2}}$ whereas in the experimental data V is proportional to $(1-t)^{-1}$. Equation (4) is plotted in Fig. 7 with no fitting parameters.

4.2 Discussion of the origin of the effect.

The observed linearity between the voltage and current has a significant implication for the mechanism generating the voltage, a discussion of which requires a brief digression on the origin of the observed effect. In the presence of a superfluid velocity, the quasiparticle excitation energies take the form[12,14] $E_k = (\xi_k^2 + \Delta^2)^{\frac{1}{2}} + \vec{p}_k \cdot \vec{v}_s$, where ξ_k is the electron kinetic energy relative to the pair chemical potential, and $\vec{p}_k$ is the electron momentum. The application of a supercurrent thus introduces an asymmetry in the excitation spectrum on opposite sides of the Fermi sphere. This asymmetry, when combined with the non-equilibrium distribution odd in ξ_k caused by the temperature gradient, can give rise to a non-zero value of Q^*.

Beyer Nielsen *et al.*[8], and subsequently Pethick and Smith[13], have emphasized that in the clean limit where the excitations have well defined energies one must treat quasiparticles in the "pocket" with energies between $\Delta - p_F v_s$ and $\Delta + p_F v_s$ differently from quasiparticles with energies greater than $\Delta + p_F v_s$.* Quasiparticles with energies below $\Delta + p_F v_s$ have fewer final states for elastic scattering available to them compared with quasiparticles with energies above $\Delta + p_F v_s$, the restriction being most severe for quasiparticle energies near $\Delta - p_F v_s$. As a result, the charge carried by a quasiparticle in the pocket takes a relatively long time to relax elastically compared with the charge carried by a quasiparticle above the pocket. In the Beyer Nielsen *et al.* picture, the contribution to Q* of quasiparticles in the pocket dominates at temperatures below $0.998\, T_c$. However, as we have seen, this model does not predict the observed temperature dependence, thereby raising questions about the contribution of the pocket in real samples.

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* The clean limit result of Schmid and Schön, Eq. (14), and the calculation of Clarke and Tinkham both neglected the pocket: See ref. 13 for a discussion.

Although in real materials the pocket may be smeared out for a variety of reasons, this smearing has so far not been included in any of the existing clean limit theories. In the following we mention three possible causes of such a smearing. First, inelastic scattering broadens the energy levels by an amount $\sim \hbar/\tau_E$. If $\hbar/\tau_E \gtrsim p_F v_s$, the charge contained in the pocket will be able to relax quite readily by elastic scattering. We can estimate the maximum value of $p_F v_s$ obtained in the experiment by multiplying Eq. (1) by p_F and inserting appropriate values of the various parameters. From the data for the clean sample in Fig. 3, we see that at $T/T_c \approx 0.8$ V is linear in I for currents up to 50 mA, corresponding to $j_s \approx 1.6 \times 10^9\ \mathrm{A\,m^{-2}}$. Using the values of v_F, $\lambda_L(0)$, ξ_0, and ℓ in Sec. 4.1, we find the maximum value of $p_F v_s/k_B T_c$ to be about 0.025. For the dirty films, we have also observed a linear relationship between V and I for currents up to 50 mA at a temperature of about 0.8 T_c. Using $\ell = 57$ nm, we find the maximum value of $p_F v_s/k_B T_c$ to be about 0.08. Since $k_B T_c \tau_E/\hbar \approx 100$ for Sn, the maximum values of $p_F v_s \tau_E/\hbar$ are about 2.5 and 8 for the clean and dirty samples, respectively (see Table 2). Thus, according to the picture of Beyer Nielsen et al.[8] and Pethick and Smith[13], one would expect a dominant contribution from quasiparticles in the pocket at high currents, but not at low currents. Since the contribution of the quasiparticles in the pocket in the former case is much larger than that of all the quasiparticles in the latter case, one would expect to observe a significant change in slope of the V vs. I curve when $p_F v_s \sim \hbar/\tau_E$. In fact, we observe a highly linear behavior experimentally, suggesting that the smearing of the pocket is much greater than $\hbar/\tau_E$.

A second mechanism by which elastic scattering could relax charge in the pocket is gap anisotropy[4] , provided $p_F v_s \lesssim \delta\Delta$, the difference between the maximum and minimum values of the gap. In our relatively clean films, we expect $\delta\Delta/\Delta$ to be close to the bulk value[15] of about 0.2, while in our dirty films, $\delta\Delta/\Delta$ will be reduced by a factor[16] $\sim [1+(\pi\xi_0/2\ell)^2]^{\frac{1}{2}} \sim 6$ to about 0.03. For the clean and dirty films we estimate the maximum values of $p_F v_s/\delta\Delta$ to be about 0.15 and 3, respectively (see Table 2). Thus, on this basis, one would expect a non-linearity in the V vs. I relationship for dirty films, but not for clean films. The linear behavior observed for dirty films again suggests that still more smearing is required.

G. Schön[17] has recently suggested that elastic scattering may smear out the quasiparticle energy levels sufficiently to modify or even eliminate the effect of the pocket. If the contribution of the pocket is thus reduced substantially by this smearing process, the first term in brackets in Eq.(4) will presumably be greatly reduced, although its exact form remains to be calculated. We note that the second term in brackets becomes independent of temperature as $T \to T_c$, so that Eq.(4) would predict the observed $(1-t)^{-1}$ temperature dependence near T_c if the first term is either negligible or also independent of temperature in this range. It should also be remarked that the second term was derived for $T \sim T_c$, and does not accurately represent the results of ref. 8 at low energies and at low temperatures[18]

4.3 Mean free path effects.

Finally, we briefly discuss the effects of mean free path, ℓ. The experimental results do not depend significantly on ℓ. As long as the problems concerning the clean limit calculations are unresolved, we cannot make any statements about the exact expected variation with impurity concentration. However, if we try to make an estimate using Eq. (1), we find that the numbers in column 5 in Table 1 should scale as $\ell(1+\xi_0/\ell)$. The ratio between the results for the cleanest and dirtiest sample should thus be 0.44, a not very substantial difference considering the variation of the results for samples with the same value of ℓ. Furthermore one should bear in mind that the addition of the In to samples 7 and 8 may change both $\lambda_L(0)$ and v_F significantly. To make a more stringent test of the mean free path dependence one should investigate samples with mean free paths $> 1\mu m$. This would imply that the Sn thickness would also have to exceed $1\mu m$, and would introduce further complications because $\lambda(T)$ would be much less than the film thickness. Thus, it seems that it will be difficult to make a meaningful test of the mean free path dependence.

5. CONCLUDING SUMMARY

We have measured the voltage due to charge imbalance generated by a temperature gradient and a supercurrent in 8 Sn films. The voltage for all samples was bilinear in I and ∇T, and the quantity $Vg_{NS}T/I\nabla T$ showed a universal temperature dependence, diverging near T_c approximately as $(1-t)^{-1}$. The magnitude of the voltage is within a factor of 2 or 3 of the theoretical predictions. The temperature dependence is in excellent agreement with the theories of Schmid and Schön[6] [Eq. (3)] and Clarke and Tinkham[7] [Eq. (2)]. The theory of Beyer Nielsen et al.[8] [Eq. (4)] is not in as good an agreement with the data, and, in particular, predicts a $(1-t)^{-\frac{1}{2}}$ temperature dependence near T_c (but below 0.998). Their result is dominated by the charge imbalance of quasiparticles in the energy range $\Delta - p_F v_s$ to $\Delta + p_F v_s$ which have a slower relaxation rate due to elastic scattering than quasiparticles with energies above $\Delta + p_F v_s$. However, a likely explanation of this discrepancy is that the low-lying energy levels are smeared out by elastic scattering, and that the enhancement of the charge in the pocket is modified in real metals. Finally, the effects of inelastic scattering have been ignored in both of the clean limit calculations. It is to be hoped that a more definitive explanation of the role of inelastic scattering and the effect of the pocket in the clean limit will be forthcoming.

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TABLE 1

Properties of 8 samples

Sample	Sn thickness (nm)	ℓ^{a} (nm)	$R_{jn}(T_c)$ (Ω)	$Vg_{NS}T(1-t)A/I\nabla T$ [b] ($10^{-16}\ \Omega cm^3$)	Substrate/ Comments[c]
1	400	57	1.1×10^{-4}	2.9	Glass, LN, samples on same substrate (1, 2)
2	400	57	1.35×10^{-3}	3.5	
3	250	57	1.2×10^{-5}	0.7	Glass, LN, groundplane added
4	320	428	2.0×10^{-5}	1.2	Glass, R
5	310	57	2.0×10^{-5}	1.1	Si, LN
6	430	294	2.4×10^{-4}	1.0	Glass, R
7	190	61	3.2×10^{-3}	0.8	Glass, R, Sn+3wt%In, samples on same substrate, groundplane on 8 (7, 8)
8	190	61	2.4×10^{-3}	0.8	

a The mean free path, ℓ, was calculated from the resistance ratio without corrections for size effects.

b Evaluated at $t\approx0.9$; this procedure leads to slightly different numerical results for samples 1 to 5 compared with those in ref. 5.

c LN (liquid nitrogen temperature) and R (room temperature) refer to the temperature of the substrate during the Sn evaporation.

TABLE 2

Estimated values of v_s normalized in various ways for clean and dirty Sn films at $0.8\,T_c$ with a supercurrent density of $1.6\times10^9\ \mathrm{Am}^{-2}$ and with $k_B T_c \tau_E/\hbar = 100$.

	$\frac{p_F v_s}{k_B T_c}$	$\frac{p_F v_s}{\Delta(0.8\,T_c)}$	$\frac{p_F v_s}{\hbar/\tau_E}$	$\frac{p_F v_s}{\delta\Delta}$
clean ($\ell = 428$nm)	0.025	0.03	2.5	0.15
dirty ($\ell = 57$ nm)	0.08	0.1	8	3

FIGURE CAPTIONS

Fig. 1 Sample configuration.

Fig. 2 Voltages measured by SQUID on sample 4 at $T = 3.654$ K and $\nabla T = 0.15$ K/cm. The currents marked refer to the supercurrent I, and the times between the arrows indicate when the current was being changed.

Fig. 3 V vs. I for 5 values of $\vec{\nabla} T$ for sample 4.

Fig. 4 V vs. $\vec{\nabla} T$ for 10 values of I for sample 4. At each value of $\vec{\nabla} T$, the voltage is defined to be zero at $I = 0$.

Fig. 5 $Vg_{NS}/I\vec{\nabla} T$ vs. reduced temperature, t, for sample 4.

Fig. 6 $Vg_{NS}T/I\nabla T$ vs. (1-t) for samples 6(ℓ = 294nm) and 8 (ℓ = 61 nm).

Fig. 7 $Vg_{NS}T/I\nabla T$ vs. (1-t) for sample 4. The three theoretical formulas have been fitted to the experimental data by scaling them appropriately.

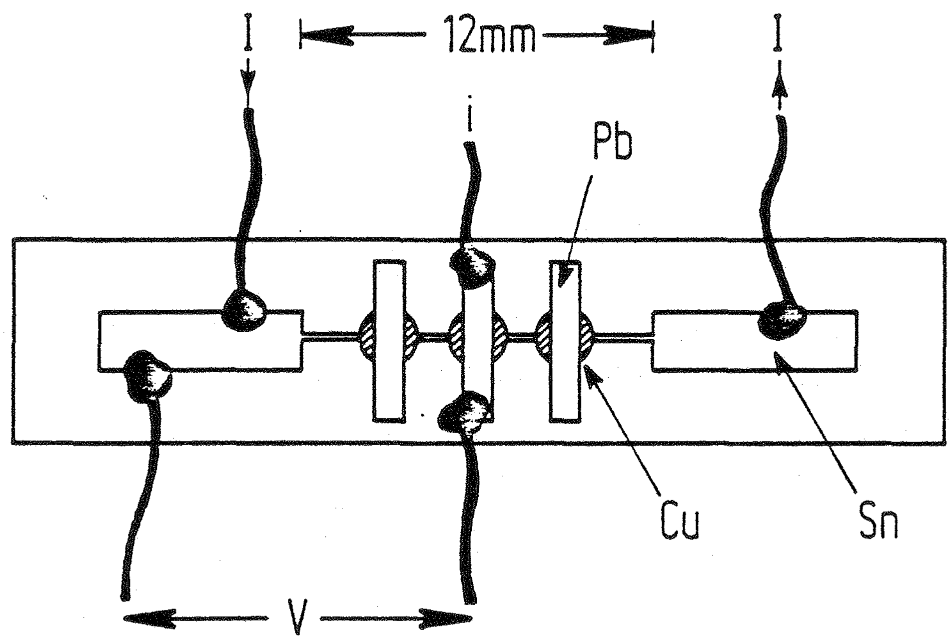


Fig. 1

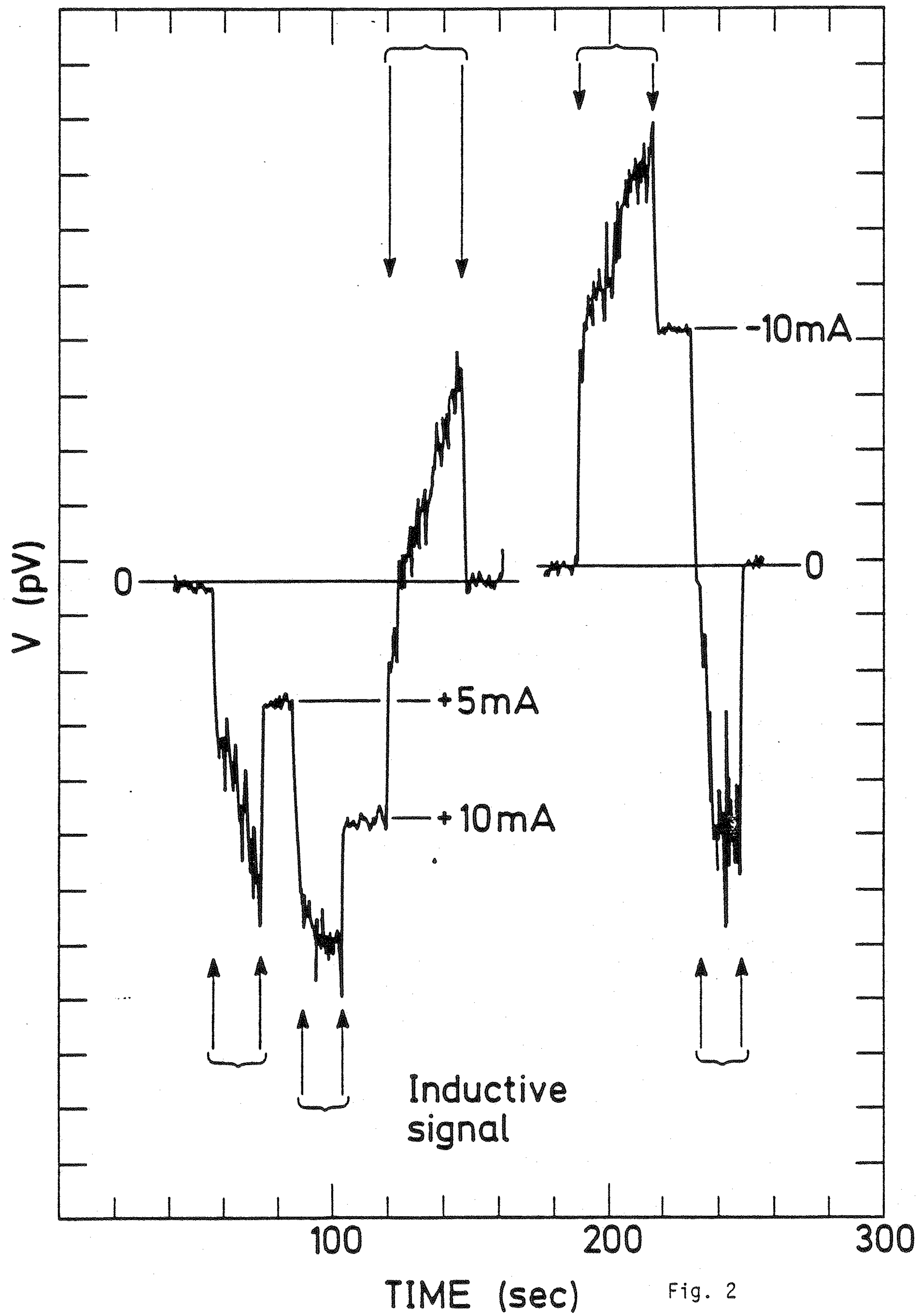
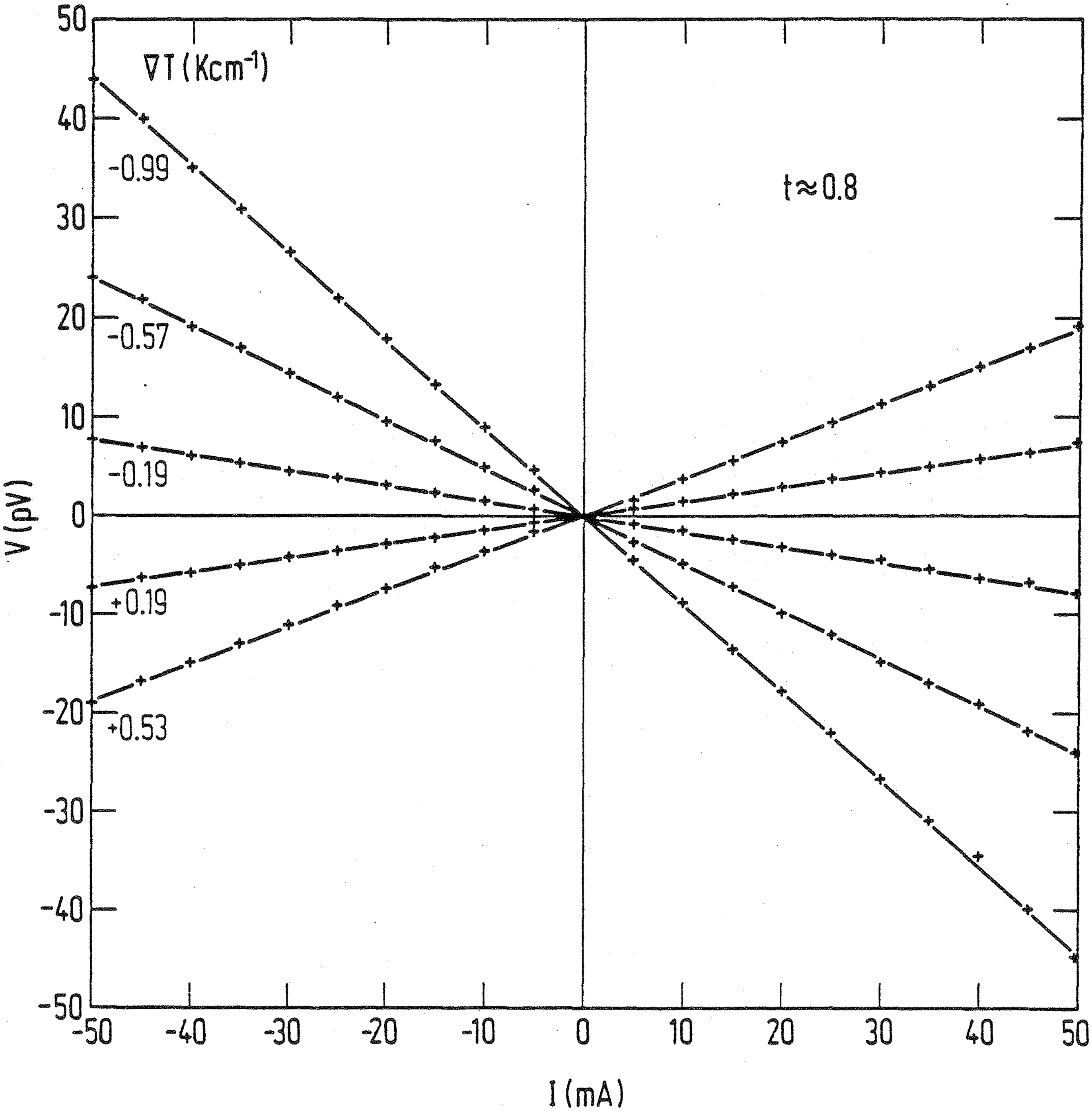
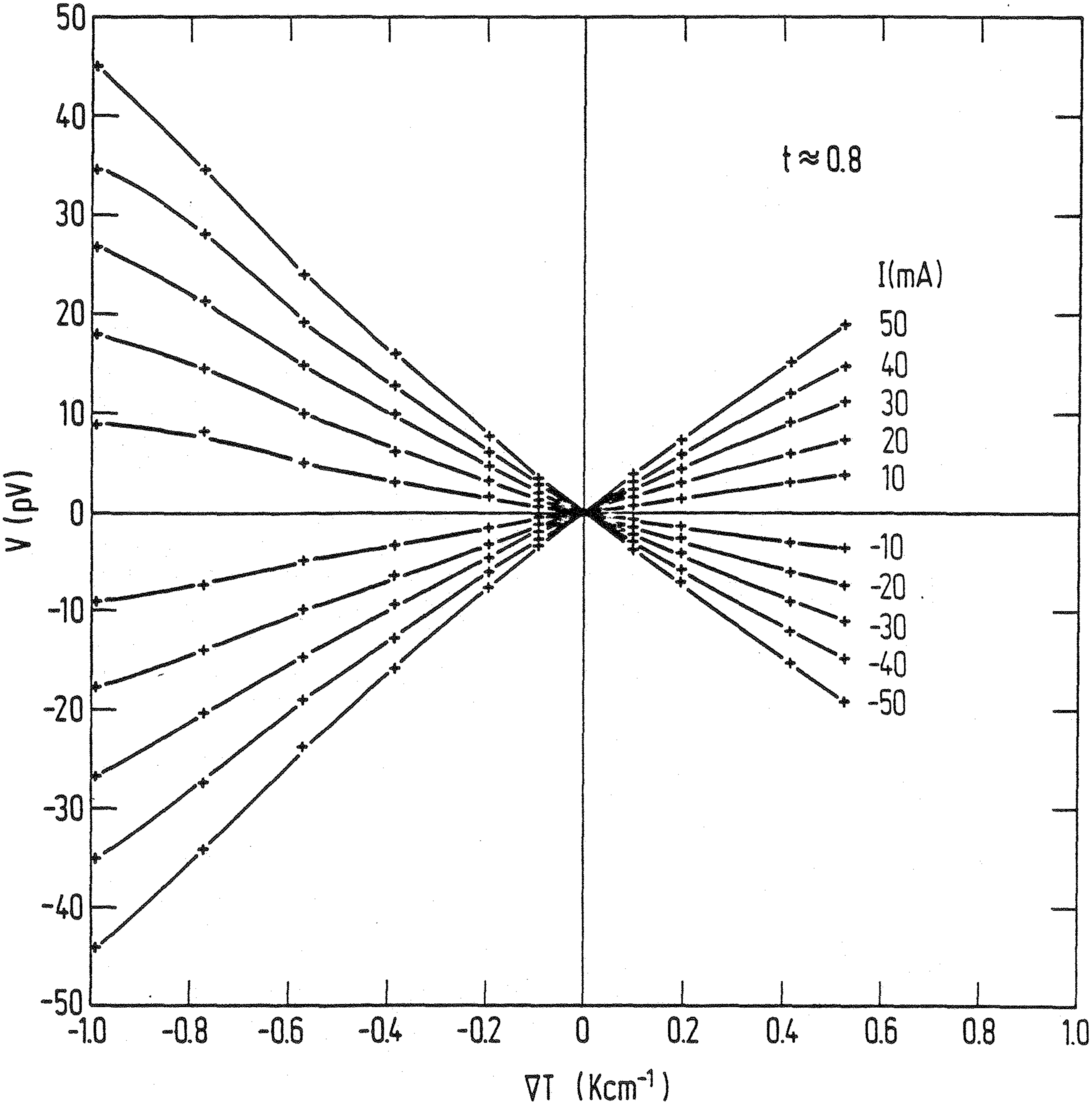


Fig. 2



∇T (Kcm⁻¹)
-0.99
-0.57
-0.19
+0.19
+0.53
t≈0.8
V (pV)
I (mA)
50
40
30
20
10
0
-10
-20
-30
-40
-50

Fig. 3



V (pV)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-1.0
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1.0
∇T (Kcm⁻¹)
t ≈ 0.8
I(mA)
50
40
30
20
10
-10
-20
-30
-40
-50

Fig. 4

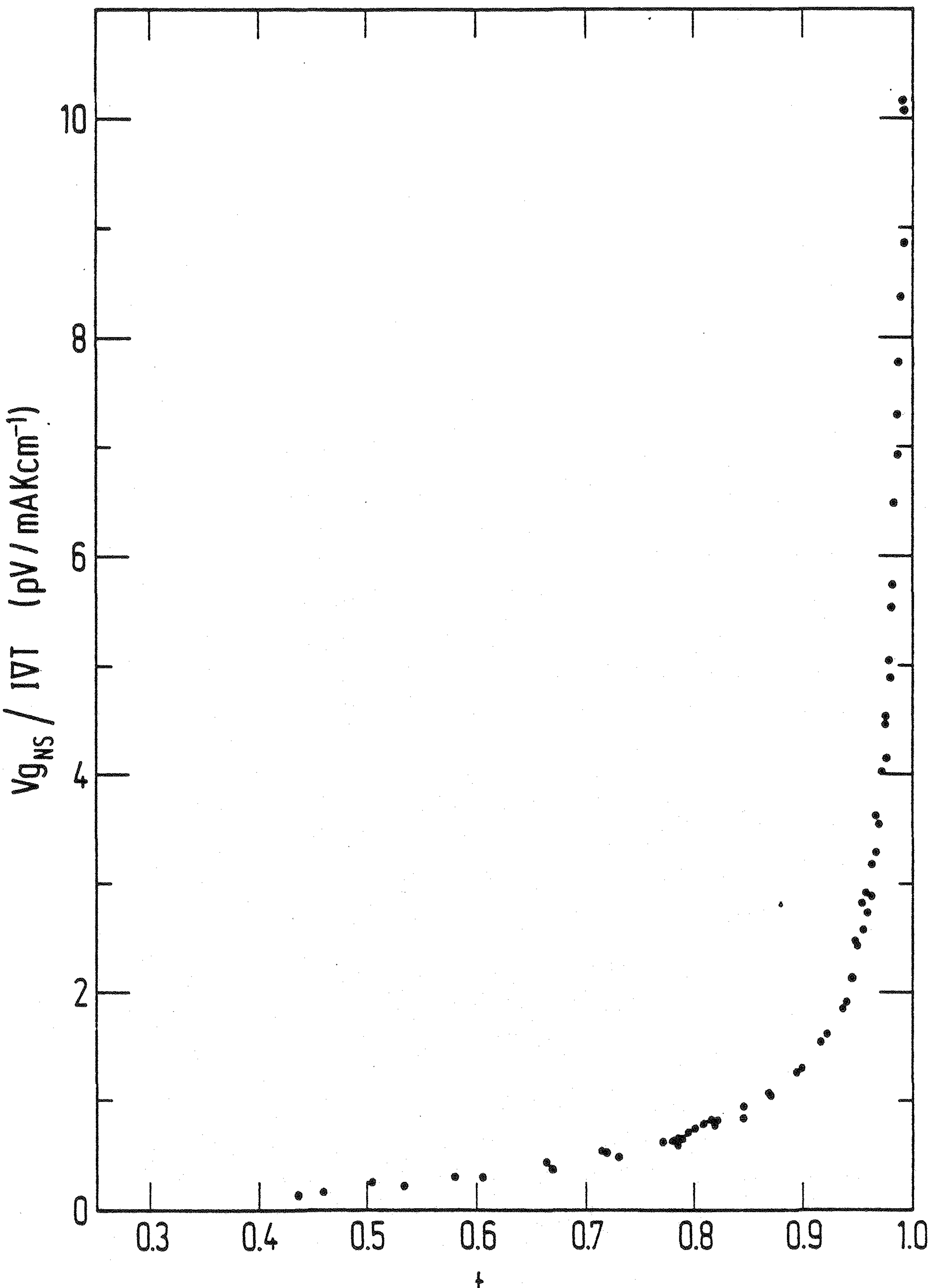


Fig. 5

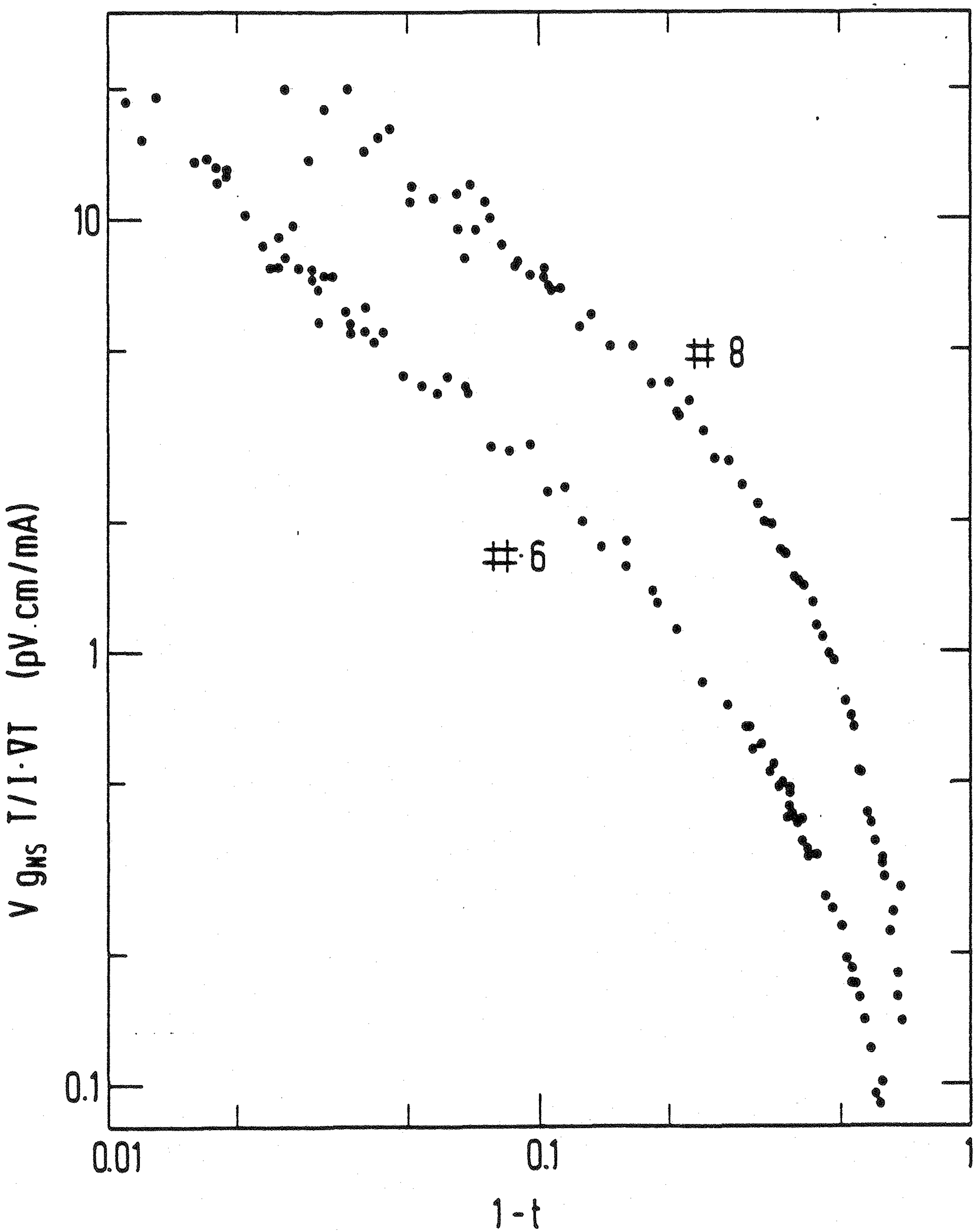


Fig. 6

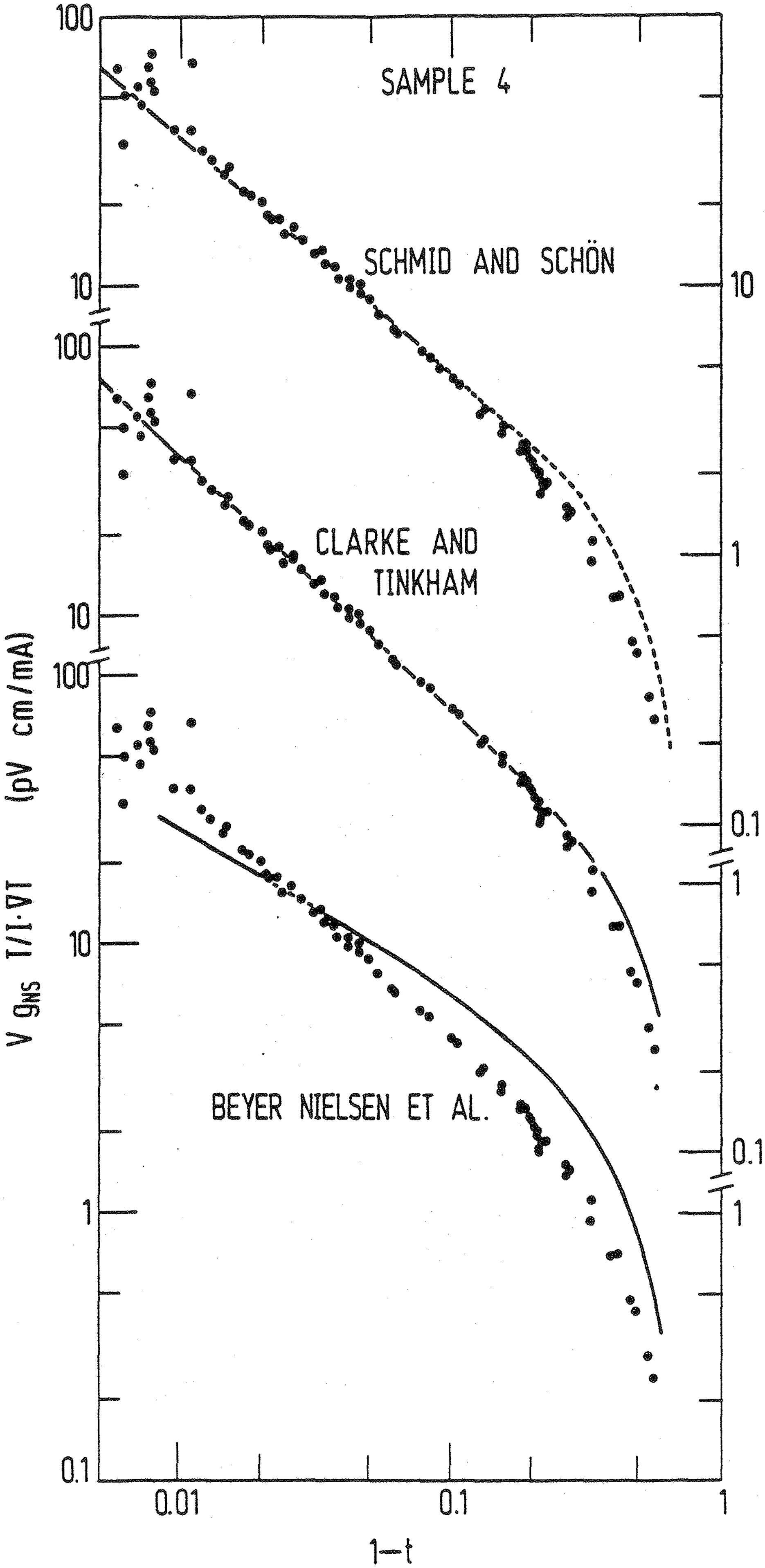

SAMPLE 4
SCHMID AND SCHÖN
CLARKE AND
TINKHAM
BEYER NIELSEN ET AL.
V g_{NS} T/I·∇T (pV cm/mA)
1−t
100
10
1
0.1
0.01

Fig. 7