

Origin of Nonlinear Transport across the Magnetically Induced Superconductor-Metal-Insulator Transition in Two Dimensions

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We have studied the effect of perpendicular magnetic fields and temperatures on nonlinear electronic transport in amorphous Ta superconducting thin films. The films exhibit a magnetic field-induced metallic behavior intervening the superconductor-insulator transition in the zero temperature limit. We show that the phase-identifying nonlinear transport in the superconducting and metallic phases arises from an intrinsic origin, not from an electron heating effect. The nonlinear transport is found to accompany an extraordinarily long voltage response time.

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In recent years, the suppression of superconductivity in two dimensions (2D) by means of increasing disorder (usually controlled by film thickness) or applying magnetic fields (B) has been a focus of attention. Conventional treatments [1–5] of electronic transport predict that in 2D the suppression of the superconductivity leads to a direct superconductor-insulator transition (SIT) in the limit of zero temperature ($T = 0$). This traditional view has been challenged by the observation of B -induced metallic behavior in amorphous MoGe [6,7] and Ta thin films [8]. The unexpected metallic behavior, intervening the B -driven SIT, is characterized by a drop in resistance (ρ) followed by a saturation to a finite value as $T \rightarrow 0$. The metallic resistance can be orders of magnitude smaller than the normal state resistance (ρ_n), implying that the metallic state exists as a separate phase rather than a point in the phase diagram. Despite many theoretical treatments [7,9–15], a consensus on the mechanism behind the metallic behavior is yet to be reached. Proposed origins of the metallic behavior include bosonic interactions in the non-superconducting phase [9], contribution of fermionic quasiparticles to the conduction [10,11], and quantum phase fluctuations [12,13].

In a recent paper [8] on the B -induced metallic behavior in Ta films, we have reported the nonlinear voltage-current (I - V) characteristics that can be used to identify each phase. The superconducting phase is unique in having both a hysteretic I - V and an “immeasurably” small voltage response to currents below an apparent critical current I_c . The metallic phase can be identified by a differential resistance (dV/dI) that increases with increasing I , whereas the insulating phase is identified by a dV/dI that decreases with increasing I . The contrasting nonlinear I - V in the metallic and insulating phases is shown in Fig. 1(a).

The main purpose of this Letter is to report that the origin of the nonlinear transport, particularly in the superconducting and metallic phases, is not a simple reflection of T dependence of ρ via the unavoidable Joule heating.

We describe the effect of B and T on the nonlinear transport on which this conclusion is based. We also present our studies on a dynamic voltage response which reveal a strikingly long response time that accompanies the nonlinear transport.

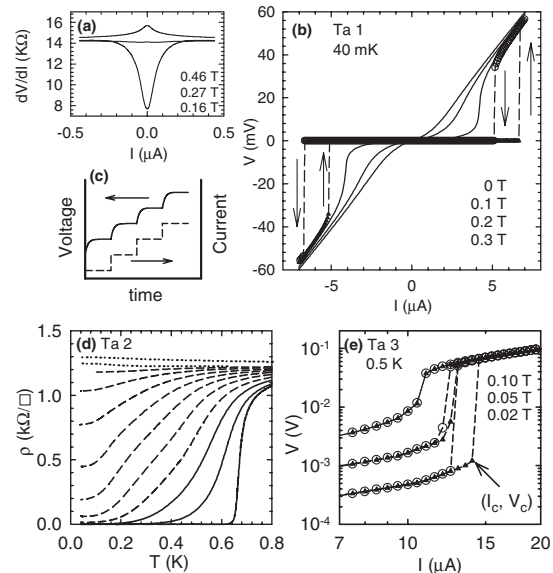


FIG. 1. (a) dV/dI vs I at 20 mK across the metal-insulator boundary for a Ta film with $T_c = 0.23$ K, adapted from Ref. [8]. (b) Current biased I - V curves of sample Ta 1 at 40 mK and the indicated B . (c) Our method of I - V measurements is illustrated. (d) The T dependence of ρ for sample Ta 2 at $B = 0$ –1.0 T with a 0.1 T interval and 3.0 T, measured at 7 Hz with a current amplitude of 1 nA. The solid lines are to indicate the superconducting phase in the low T limit, the dashed lines the metallic phase, and the dotted lines the insulating phase. (e) I - V curves in log-log scale for sample Ta 3. Solid triangles (open circles) are for the current increasing (decreasing) branch. The data density is reduced to make individual symbols visible. The arrow marks the critical current I_c and voltage V_c .

Our samples are dc sputter deposited Ta thin films on Si substrates. The sputter chamber is baked at $\sim 110^\circ\text{C}$ for several days, reaching a base pressure of $\sim 10^{-8}$ Torr. The chamber and Ta source were cleaned by presputtering for ~ 30 min at a rate of ~ 1 nm/s. Films are grown at a rate of ~ 0.05 nm/s at an Ar pressure of ~ 4 mTorr. Using a rotatable substrate holder, up to 12 films, each with a different thickness, can be grown without breaking the vacuum. In order to facilitate four point measurements, the samples are patterned into a bridge (1 mm wide and 5 mm long) using a shadow mask. Even though there were noticeable batch to batch variations, the degree of disorder (evidenced by the values of ρ_n) for films of the same batch increases monotonically with decreasing film thickness. The superconducting properties of the films are characteristic of homogeneously disordered thin films [16] and consistent with the results of x-ray structural investigations [8]. The data presented in this Letter are from 5 films grown in 4 batches. Parameters of the films are summarized in Table I.

The evolution of the I - V curves across the superconductor-metal boundary at 40 mK is shown in Fig. 1(b) for sample Ta 1. The hysteretic I - V , unique to the superconducting phase, is indicated by the dashed lines. As I is increased, the superconductivity is abruptly quenched at a well-defined critical current I_c . As I is decreased from above I_c , the superconductivity suddenly appears at a different current $I_c' < I_c$. The hysteresis becomes smaller with increasing B and vanishes near 0.1 T as the film is driven into the metallic phase [solid lines in Fig. 1(b)]. Typical T dependence of ρ at various B is shown in Fig. 1(d) for sample Ta 2. In this sample, which is less disordered than Ta 1, the superconducting phase extends up to ~ 0.2 T [solid lines in Fig. 1(d)] and the metallic behavior is observed at higher B up to ~ 0.9 T (dashed lines). Hereafter, “superconducting regime” refers to the transport regime with hysteretic I - V and “metallic regime” to the regime with nonlinear (and reversible) I - V with increasing dV/dI with increasing I .

All I - V curves are constructed by plotting the steady state voltage at each bias current that is changed in small discrete steps [see Fig. 1(c)]. In order to ensure that the

TABLE I. List of sample parameters: nominal film thickness, mean field T_c at $B = 0$, normal state resistivity at 4.2 K, critical magnetic field at which the resistance reaches 90% of the high field saturation value, and correlation length calculated from $\xi = \sqrt{\Phi_0/2\pi B_c}$, where Φ_0 is the flux quantum.

Samples	Batch	t (nm)	T_c (K)	ρ_n (Ω/\square)	B_c (T)	ξ (nm)
Ta 1	1	3.5	0.584	1769	0.72	21
Ta 2	1	5.0	0.675	1180	0.88	19
Ta 3	2	5.7	0.770	1056	0.9	19
Ta 4	3	5.0	0.598	770
Ta 5	4	36	0.995	69	2.0	13

steady state is reached at each step, the voltage is monitored every 50 ms for up to 55 s while the current is kept constant. The magnitude of the voltage jump at I_c (or I_c'), which could be as large as several orders of magnitude, was almost independent of the current step size in the range 5–100 nA. Even with our smallest steps of 5 nA, no steady state with a voltage within the range covered by the jump was observed.

Our investigations on how B and T influence the nonlinear transport indicate that these quantities play similar roles. The main effect of increasing T is to lower the superconductor-metal “critical” field B_c^{sm} ; the B -driven evolution of the I - V curves at an elevated T [Fig. 1(e)] remains qualitatively the same as that in the low T limit [Fig. 1(b)]. More importantly, the evolution of the I - V curves as a function of T [Figs. 2(a) and 2(c)] is strikingly similar to that caused by B [Figs. 1(b) and 1(e)].

The field B_c^{sm} decreases with increasing T and reaches zero at a well-defined temperature T^* , which is close to T_c as shown by the arrows in Figs. 2(b) and 2(d). This, together with the observations described above, means that B_c^{sm} is a well-defined line in the B - T plane separating the superconducting and metallic regimes. We point out that, in terms of nonlinear transport, the electronic properties at $B \gtrsim B_c^{\text{sm}}$ in the low T limit, where the unexpected metallic behavior intervening SIT is observed, are indistinguishable from those at high temperatures, for example, at $T \gtrsim T^*$ and $B = 0$.

In the superconducting regime, the voltage jump is found to be of nonthermal origin (i.e., not the result of Joule heating). If Joule heating is significant, the electron

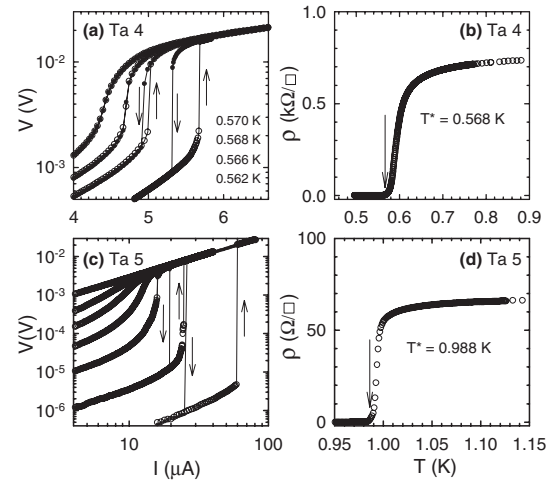


FIG. 2. (a) I - V curves of sample Ta 4 at $B = 0$ and the indicated T . Open (solid) circles are for the current increasing (decreasing) branch. (b) T dependence of ρ for sample Ta 4 at $B = 0$. The arrow is to indicate the temperature T^* where the hysteresis vanishes. (c) The I - V of the sample Ta 5 at $B = 0$. The temperature of each trace is, from the top, 1.000, 0.994, 0.992, 0.990, 0.988, 0.984, and 0.976 K. (d) The T dependence of ρ for sample Ta 5 at $B = 0$.

temperature T_e would be determined by the balance of the Joule heating power and the heat drain rate to the stage where the sample is thermally anchored. A large heating power at a high bias current could make T_e substantially higher than the stage temperature. If T_e reaches near T_c where ρ sharply rises with T , an increase in T_e could cause an increase in the heating power, which in turn causes a further increase in T_e . Such a positive self-feedback would make T_e unstable and run away beyond T_c , resulting in a sudden quenching of the superconductivity appearing as a voltage jump. This scenario can be tested by applying weak B . The magnetic fields lower T_c while the net thermal conductance between the sample and the stage would remain almost unaffected. Therefore, in the heating scenario, the critical power $P_c = I_c \times V_c$, where I_c and V_c are the current and voltage at the onset of the voltage jump, respectively [marked by an arrow in Fig. 1(e)], is expected to be a weakly decreasing function of B . However, as shown in Figs. 3(a) and 3(b), P_c is found to increase by an order of magnitude or more under weak B . This demonstrates that the voltage jump has a nonthermal origin. We note that V_c is the highest steady state voltage in the superconducting state before the I -induced sudden quenching of the superconductivity. In repeated runs after thermal cyclings to above 10 K, the value of V_c was reproducible within several percent even with different current step sizes in the range 5–100 nA.

The I - V curves in Figs. 1 and 2 clearly show that the discontinuity in I - V in the superconducting regime evolves into the point of the largest slope in the continuous I - V in the metallic regime. This suggests that the sudden quenching of the superconductivity at I_c and the nonlinear transport in the metallic regime are caused by the same mechanism, which has been shown above to be of non-thermal origin.

Now we turn to the discussion on the dynamic voltage response. The dynamic voltage response was studied by analyzing the voltage-time (V - t) traces to determine how fast the steady state is reached at each I . As shown by the solid line in Fig. 4(a), the t dependence is well described by an exponential function. The parameters V_0 and V_1 are determined from the measured steady state voltage and $V(t=0)$, which is the steady state voltage at the previous

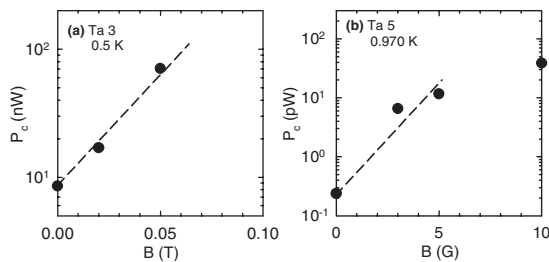


FIG. 3. (a) The B dependence of the critical power $P_c = I_c \times V_c$ for sample Ta 3 at 0.5 K. The dashed line is to guide the eye. (b) P_c vs B plot for sample Ta 5 at 0.970 K.

I . The parameter τ is defined as the voltage response time constant.

Figure 4(b) shows the τ - I plots at three different B across the superconductor-metal boundary. In the superconducting regime ($B = 100$ G), τ exhibits a hysteretic and diverging behavior with approaching I_c from below (I_c' from above) where the I - V is discontinuous. In the metallic regime (150 and 200 G) where I - V is continuous and reversible, the τ traces are also continuous and reversible. However, a prominent peak structure is evident in the data. Interestingly, the peak or diverging feature in τ almost exactly coincides with the nonlinear transport. The inset shows the slopes of I - V curves in log-log scale. At I where τ is large, the transport is nonlinear [$d(\log V)/d(\log I) > 1$], and at I where τ is almost zero the transport is linear [$d(\log V)/d(\log I) = 1$]. Qualitatively, the same τ behavior is observed when the superconductor-metal boundary is crossed by increasing T . This is shown in

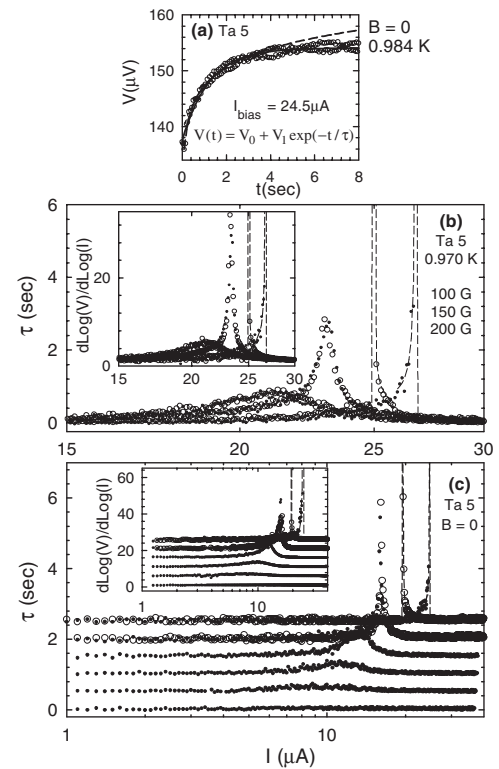


FIG. 4. (a) An example of V - t trace at $I = 24.5 \mu\text{A}$. The solid line is a fit to the exponential function shown. The dashed line is a fit to a logarithmic t dependence for the first 3 s. (b) τ vs I plot at the indicated B and T . Solid (open) circles are for the current increasing (decreasing) branch. The dashed lines are to guide the eye. Inset: The slope of I - V curves in log-log scale at the same B and T . (c) τ - I plot at $B = 0$. The temperature of each trace is, from the top, 0.984, 0.988, 0.990, 0.992, 0.994, and 1.000 K. Each trace is vertically shifted successively. For the bottom four traces, only the current increasing branch is shown. Inset: $d(\log V)/d(\log I)$ is plotted at the same T and B . Each trace is vertically shifted successively.

Fig. 4(c). Note that the traces in Fig. 4(c) and the inset are successively shifted vertically.

It is surprising to find that the time constant in the peak or diverging region is as long as several seconds. We emphasize that the long time constant is not due to instrumentation. This is best demonstrated by the systematics of the data. Changing B or T systematically shifts the peak or divergence, while outside the narrow peak or diverging region τ remains almost zero. The time constants were measured to be the same within the scatter of the data for current steps of 5 (not shown) and 100 nA (shown).

In the past, hysteresis accompanying a long response time has been studied in the context of irreversible magnetic properties in type II superconductors [17]. Large magnetic relaxation rates observed in magnetization measurements are believed to arise from thermal activation of magnetic flux lines out of pinning sites. The depinning process leads to a redistribution of flux lines causing a change in magnetization with time. Although our hysteresis with a long response time is observed in transport, it still may be possible to understand in terms of pinning-depinning of vortices. A pinning-depinning transition arises from the competition between disorder-induced pinning force and Lorentz driving force due to the bias current. Under such a competition, the vortex motion is analogous to the flow of sand grains in a sand pile [18], where the competition is between the jamming due to the granularity of the system and gravitational force. Indeed, hysteresis [19] and slow relaxation rates [20] have been observed in granular flow under mechanical vibrations. Logarithmic time dependence has been observed in measurements on magnetization [17] and granular flow [20]. The dashed line in Fig. 4(a) is a logarithmic fit, which describes the data well for $t < 3$ s. Nevertheless, over the entire range of the data, the exponential function (solid line) fits our data better.

Finally, we briefly discuss an interesting implication of the unusually long response time accompanying the nonlinear transport at $B = 0$ and $T \geq T^*$. Nonlinear transport of 2D superconductors at $B = 0$ is usually understood in the framework of Kosterlitz-Thouless (KT) theory [21], where the superconducting transition corresponds to a thermodynamic instability of vortex-antivortex pairs in 2D. In this picture, I -induced dissociation of vortex pairs in the superconducting phase leads to nonlinear transport of the fashion $V \propto I^a$, with $a > 3$ [22]. It has been argued [23] that in a real system the finite size effect can induce free vortices altering the power law. The resulting I - V curves obtained in numerical simulations [23] show a pronounced peak structure in $d(\log V)/d \log(I)$ resembling those shown in the inset in Fig. 4(c). Although the dynamics of KT vortices in the presence of disorder has not been studied rigorously, the time scale for the I -induced vortex pair dissociation is likely to be of the order of quasiparticle scattering time, which is typically $\sim 10^{-9}$ s [24]. However,

in our experiments the nonlinear transport is found to accompany a voltage response time as long as several seconds. This suggests that the KT mechanism is unlikely to be the origin of the observed nonlinear transport.

In summary, we have shown the B - and T -driven evolution of phase-identifying nonlinear I - V characteristics of Ta thin films that exhibit an unexpected metallic phase at $T \rightarrow 0$. The nonlinear transport in the metallic and superconducting phase is found to arise from an intrinsic mechanism, not the result of electron heating. Our dynamic voltage response studies suggest a possible link of the metallic behavior to the dynamics of vortices in the presence of disorder.

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