Electron-Phonon Decoupling in Disordered Insulators

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The current-voltage characteristics measured in the insulating state terminating the superconducting phase in disordered superconductors exhibit sharp threshold voltages, where the current abruptly changes by as much as 5 orders of magnitude. We analyze the current-voltage characteristics of an amorphous indium oxide film in the field-tuned insulating state, and show that they are consistent with a bistability of the electron temperature, and with a significant overheating of the electron system above the lattice temperature. An analysis of these current jumps indicates that, in the insulating state, the electrons are thermally decoupled from the phonon bath.

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In recent years, several unusual features of the insulating state terminating superconductivity in disordered superconductors [1] have been revealed. First, its resistance (R) shows a nonmonotonic dependence on magnetic field (B), with an initial increase as superconductivity is destroyed, going through a pronounced maximum with a resistance of more than a $G\Omega$, followed by a sharp drop of several orders of magnitude as B is increased further [2–6]. Second, the temperature (T) dependence of R has an Arrhenius form in a broad range of temperatures, with an activation energy close to T_c of the films at $B = 0$, indicating a possible relation of the insulator to superconductivity [7–11]. Third, the power-law dependence of R vs B at a fixed T, usually seen as indicative of vortex-dominated transport, was seen to extend into the insulating regime, again alluding to superconductivity playing a role in the insulator [12].

A fourth feature is the focus of this Letter. In the insulating state, the current-voltage (I-V) characteristics exhibit an abrupt jump of I at a B-dependent voltage threshold [13]. Because of the fact that this sharp jump is observed only at very low $T < 0.15$ K, it was taken as an indication that a new correlated state of electrons is formed [13–15]. It is important to mention that similar instabilities have been observed in an earlier study of Y_xSi_{1-x} insulating films close to the Mott-Anderson transition [16], in which no significant superconducting correlations are known to exist [17,18]. In light of this we adopt here an alternative view of the I-V data that encompasses all the features we observe without invoking a new state of matter.

The full theoretical description of this view is given in the accompanying Letter [19]. We outline here the main ingredients that are relevant to the understanding of the data. The basic premise of the approach is that the electrons are heated by the applied power and so maintain an effective T, T_{el}, that is significantly higher than that of the phonon bath of the embedding material, T_{ph} [20,21]. In contrast to other known disordered insulators, R is determined, not by T_{ph}, but solely by T_{el}. The existence of electron overheating in the immediate vicinity of the superconductor-insulator transition has been observed previously, and was shown to cause a saturation of the measured resistance at low temperatures [22]. In this Letter we show that the electron overheating phenomenon persists deep within the insulating state.

In order to proceed with the theoretical analysis several assumptions are needed. First, the electrons are strongly interacting so that T_{el} can be meaningfully assigned to them. This allows $R(T_{el})$ to be defined as R when the electrons are at T_{el}. Second, despite the severely nonlinear appearance of the data, the intrinsic I-V's of the system are linear at constant T_{el}, and the apparent nonlinearity is simply a reflection of the electrons being overheated in comparison to the phonon bath. Third, $R(T)$ is assumed to be a strongly decreasing function.

The next step is to write a heat-balance equation applicable for the electronic system under nonlinear conditions:

$$\frac{V^2}{R(T_{el})} = \Gamma\Omega(T_{el}^{\beta} - T_{ph}^{\beta}), \tag{1}$$

where Γ is the electron-phonon coupling strength, Ω is the volume of the sample, and the power $\beta = 6$ was calculated for a metal in the dirty limit [19,23,24].

Using the experimentally obtained $R(T)$, Eq. (1) can be solved numerically for $T_{el}(V)$. For low enough T_{ph}, it develops a bistability where two values of T_{el} provide a stable solution. The authors of Ref. [19] suggest that it is this bistability which is behind the I jumps in our data.

In light of these theoretical developments we conducted systematic measurements on disordered superconductors that exhibit clear and pronounced jumps in the I-V characteristics in the insulating state terminating superconductivity. The samples under study are 30 nm-thick amorphous InO_x films, deposited by e-gun evaporation of In_2O_3 [7,25] onto SiO_2 in an O_2 background. The films are patterned into a 2 mm × 0.5 mm strip via a shadow mask, and contacts are made using pressed indium and gold wire. Contact resistances are negligible, as checked by comparing two-probe and four-probe measurements. The *I*-*V* characteristics are measured in a two-probe dc configuration. Data presented here are from a film, initially insulating, which became superconducting at $B = 0$ after several days' annealing in air at room temperature [7].

In Fig. 1 we show isotherms of the *I*-*V* curves measured at $B = 11$ T, above the B value of the maximum of the magnetoresistance peak that, for this sample, is at $B = 8$ T. For the isotherms below $T = 0.1$ K, discontinuities in I of up to 5 orders of magnitude are observed. The new aspect of the data presented here is that, by using a more sensitive measurement setup, we are able to extend our I range to values that are much lower than in previous experiments [13]. This opens the route to a very stringent test of theoretical models.

There are four central observations that can be made on these $T < 0.1$ K data. First, large discontinuities in I at well-defined V thresholds clearly separate a high-R (HR) and a low-R (LR) state. The R before and after the jumps can differ by 5 orders of magnitude. Second, there are two distinct I jumps for each isotherm that seem nonsymmetric upon V reversal. This apparent asymmetry reflects the fact that V is swept from -0.25 to 0.25 V in our experiment, so on the $V < 0$ side the jump occurs while reducing $|V|$, while on the $V > 0$ side it takes place while increasing $|V|$, indicating that our *I*-*V*'s are hysteretic [15]. We denote by V_{LH} the V of the LR → HR transition on the $V < 0$ side, and by and V_{HL} the V of then HR → LR transition on the $V > 0$ side. Third, V_{HL} clearly depends on T, changing from 0.18 to 0.22 V for $T = 0.1 - 0.011$ K, while V_{LH} is T independent in the same T range. Fourth, the magnitude of the jumps depends strongly on T for both V_{HL} and V_{LH}. In what follows we present a detailed analysis of our *I*-*V* data along the lines of the heating scenario of Ref. [19], and show that it is consistent with our observations.

We begin by adopting the assumption in [19], that the measured *I*-*V*'s nonlinearity results solely from electron overheating. At $V = 0$, there is no external heating and $T_{el} = T_{ph}$. As we increase $|V|$ an increasing amount of power is supplied to the electrons and T_{el} can become larger than T_{ph}, producing a change in R that causes the apparent nonlinearity of our *I*-*V*'s. If we now calculate, for each (I_i, V_i) data point on each *I*-*V* curve in Fig. 1, the quantity $R = V_i/I_i$ we can extract the effective T_{el} simply by inverting the independently measured $R(T)$ taken near zero V (where it is assumed $T_{el} = T$). When we plot, in Fig. 2(a), the V dependence of the calculated T_{el}, we find that at both V_{HL} and V_{LH}, T_{el} is discontinuous. While this is guaranteed by our method of obtaining T_{el} from our data [the measured $R(T)$ is a continuous function], we claim that the bistability of T_{el} is the actual physical phenomenon underlying the discontinuities observed in our *I*-*V* curves.

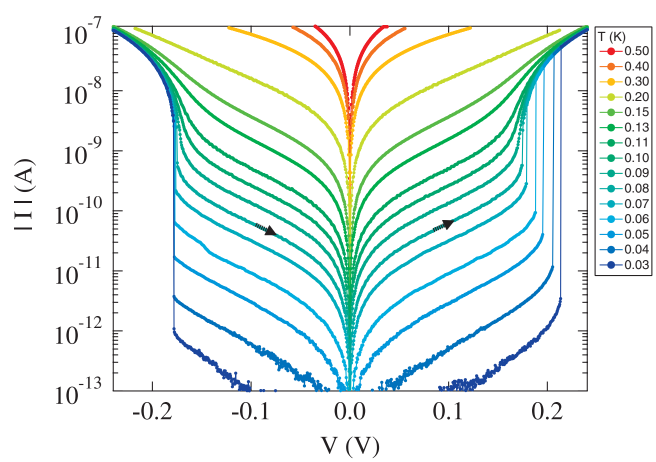

FIG. 1 (color online). *I*-*V* isotherms measured on the magnetic field-tuned insulator at $B = 11$ T. The voltage is swept from -0.25 to 0.25 V, indicated by the arrows on one of the curves.

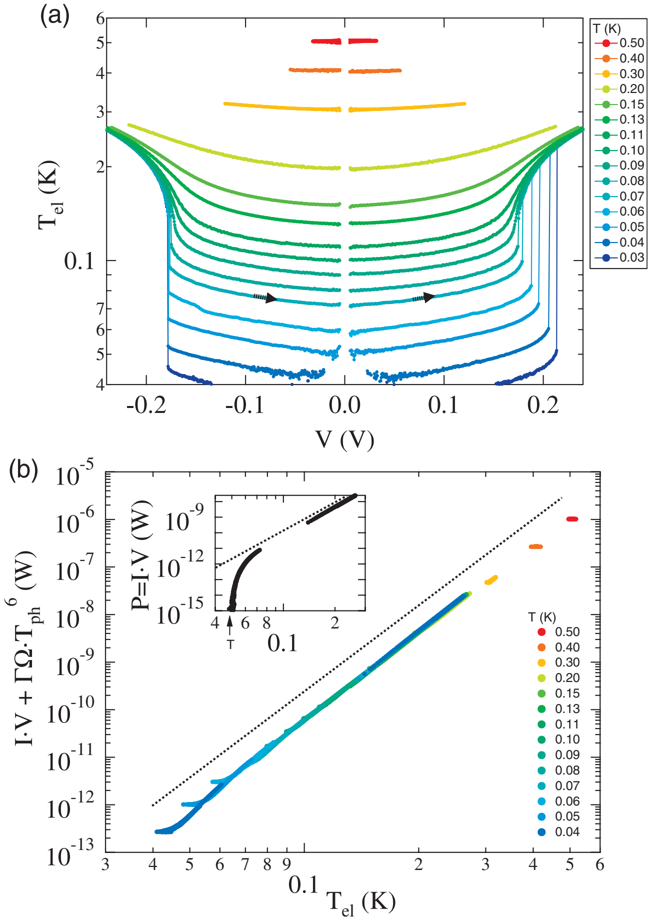

FIG. 2 (color online). (a) T_{el} vs V, extracted from the *I*-*V* curve and calibrated using the measured $R(T)$ at $V = 0$. The sweep direction is indicated by the arrows. Points near $V = 0$ have been omitted due to the large relative noise in I which causes excessive errors in the calculation of T_{el}. (b) Plot of $IV + \Gamma\Omega T_{ph}^{\beta}$ versus T_{el}. A single adjustable parameter $\Gamma\Omega$ is used for all T_{ph}, and a dotted line with slope 6 is plotted alongside the data for comparison (shifted for clarity). [(b), inset] Plot of $P = IV$ versus T_{el} for $T = 0.05$ K. At high P, $P \propto T_{el}^6$ (the dotted line has slope 6 for comparison).

Having obtained, in the manner described above, T_{el} for each point on our I-V curves, we are now ready to test the validity of the heat-balance equation [Eq. (1)]. In order to do so we wish to plot $I \cdot V + \Gamma\Omega T_{ph}^{\beta}$ as a function of T_{el}, and therefore we must first determine T_{ph} and β.

For the values of T_{ph} we use the reading of the refrigerator thermometer and assuming that the phonons are well coupled to the refrigerator bath. The observation of similar discontinuous I-V curves in diverse systems cooled in refrigerators with widely varying cooling environments is a good indication that the thermal coupling of the sample to the refrigerator bath is strong, and that we can safely identify T_{ph} with the refrigerator temperature T.

To determine β we plot, in the inset of Fig. 2(b), $P = I \cdot V$ vs T_{el} for the I-V taken at $T = 0.05$ K. At low P, T_{el} approaches T (vertical arrow). For large P, when $T_{el} \gg T_{ph}$, T_{ph} can be neglected in Eq. (1), $P \propto T_{el}^{\beta}$, and $\beta = 6$ can be determined from the slope (dotted line in the figure).

The main result of our work is evident in Fig. 2(b). By adjusting the parameter $\Gamma\Omega$ we obtain a collapse of the entire data set onto a single power-law curve with slope $\beta = 6$ on a log-log scale (the dotted line in the figure has slope of 6, and is shifted for clarity). We wish to emphasize that this plot contains the entire data of Fig. 1 including the several-orders-of-magnitude discontinuities of I at V_{th}. The prefactor of T_{el}^{β} obtained in this way is also equal to $\Gamma\Omega$, thus satisfying Eq. (1).

The approximate sample volume is $\Omega = 3.45 \times 10^{-5}$ mm^3. From the fitted value of $\Gamma\Omega$ we obtain the electron-phonon coupling constant $\Gamma = 1.85$ nW μm^{-3} K^{-6}. We note that the power $\beta = 6$ was measured in a heavily doped silicon on insulator film [26], with Γ in the same range of values.

While the data presentation of Fig. 2 constitutes a convincing case for the validity of the electron overheating approach to our I-V data, it obscures the physical bistability that exists in the model [19]. To clarify this aspect of the data, we plot T_{el} as a function of T_{ph} in Fig. 3. Blue (dark gray) circles correspond to data measured while increasing $|V|$ and red (gray) crosses represent data taken while decreasing $|V|$. The data are clearly separated into two regimes. The first is at $T_{ph} > 0.1$ K, where T_{el} is continuous, ranging from $T_{el} = T_{ph}$ (diagonal line in Fig. 3) and increasing with $|V|$ as greater power is injected into the electron system. In this regime, the $T_{el}(T_{ph})$ data are also symmetric with respect to sweep direction [the blue and red data overlap].

In contrast, in the $T_{ph} < 0.1$ K regime, discontinuities in T_{el} appear alongside the development of hysteretic behavior. Upon increasing $|V|$ [blue (dark gray) circles], T_{el} jumps to higher values as T_{ph} is lowered, corresponding to the $V > 0$ side of the I-V in Fig. 1. When $|V|$ is then decreased towards $V = 0$ [red (gray) crosses], lower T_{el} can be sustained in the high-T_{el} state before the discontinuous jump to the low-T_{el} state. As seen in the $V < 0$ side of Fig. 2(a), this transition takes place at a V_{LH} and T_{el} which are nearly independent of T_{ph}.

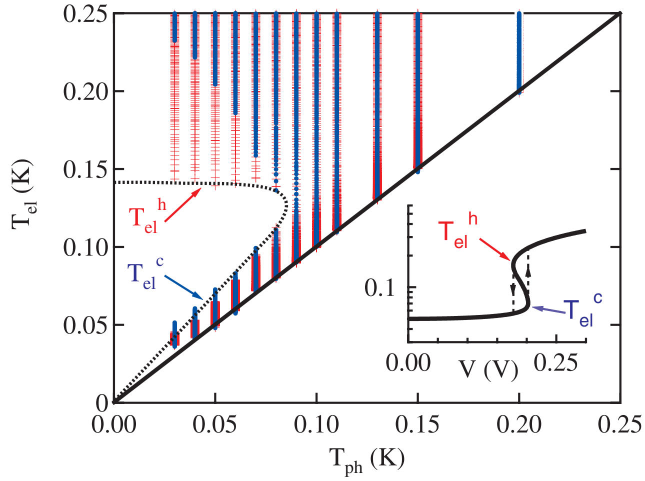

FIG. 3 (color online). T_{el} versus T_{ph}, showing the excluded region of temperatures which appears below $T_{ph} = 0.1$ K, and the accompanying hysteresis. Blue (dark gray) circles correspond to data measured while increasing $|V|$ and red (gray) crosses represent data taken while decreasing $|V|$. Inset: "S"-shaped $T_{el}(V)$ obtained from the numerical solution of Eq. (1), with the measured $R(T)$ and at $T_{ph} = 0.05$ K. The curve is not single valued, and explains the hysteretic switching between LR and HR states at the stability boundaries T_{el}^{c} and T_{el}^{h}. The blue arrow depicts the HR → LR transition and the red one depicts the LR → HR transition.

The striking feature of Fig. 3 is that there is a well-defined region in the $T_{el} - T_{ph}$ plane from which the measured data are excluded (marked by the black dotted curve), and whose boundaries are qualitatively the same as those in Fig. 1 of [19]. The origin of this excluded region, and the concomitant appearance of hysteresis, can be understood by solving Eq. (1) with the measured $R(T)$ and experimentally obtained $\Gamma\Omega$. The resulting $T_{el}(V)$ (inset of Fig. 3) is "S" shaped for $V_{LH} < V < V_{HL}$. This gives rise to a bistability since there is a range of V where two stable solutions are available for T_{el}. When the voltage is increased from $V = 0$ the system is initially in the "cold" HR state, and jumps to the "hot" LR state at $V = V_{HL}$ and $T_{el} = T_{el}^{c}$. On the other hand when the voltage is decreased from a high value towards $V = 0$, the system jumps from the LR state to the HR state at a lower voltage $V = V_{LH}$ and *higher* temperature $T_{el} = T_{el}^{h}$. This is the origin of the hysteresis with respect to voltage sweep direction, and the existence of an excluded temperature region simply reflects the fact that solutions of Eq. (1) with $T_{el}^{c} < T_{el} < T_{el}^{h}$ are unstable.

Another way of showing the validity of the heating scenario is by inverting the analysis and calculating the I-V's from our experimentally determined parameters. Using the previously determined solution of the heat-

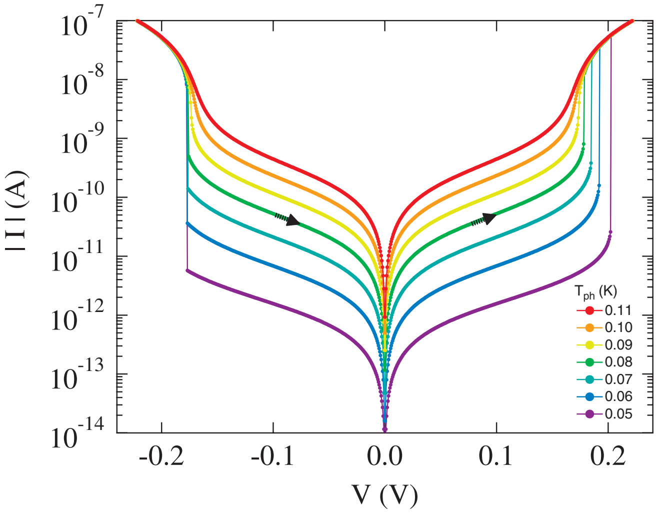

FIG. 4 (color online). Simulated *I*-*V* isotherms, computed by numerical solution of the heat-balance equation with the experimentally determined $R(T)$ and $\Gamma\Omega$.

balance equation as shown in the inset of Fig. 3, and assuming that R is indeed determined by T_{el}, we compute $I(V) = V/R(T_{el})$ for a given sweep direction. The results of this simulation, plotted in Fig. 4, were obtained for a V sweep from negative to positive values. Both V_{LH} and V_{HL}, as well as the critical $T_{ph} \simeq 0.09$ K, compare well with the data of Fig. 1. For instance, at $T_{ph} = 0.05$ K, $V_{LH} = -0.177$ V and $V_{HL} = 0.200$ V for the simulated *I*-*V*, close to the measured values $V_{LH} = -0.177$ V and $V_{HL} = 0.195$ V. The fact that the measured V_{HL} are lower than the simulated values could be due to premature triggering of the HR → LR transition by local inhomogeneities or fluctuations [19]. Because of the difficulty in accurately determining $R(T)$ at very low temperatures, curves for $T < 0.05$ K are not shown.

In conclusion, we have provided evidence that the strong nonlinearity and the I jumps in the *I*-*V* characteristics of our samples in the insulating state result from a thermal decoupling of the electrons from the phonon bath. If indeed the electron transport depends on T_{el} alone, a new phonon-independent mechanism leading to the observed insulating behavior must be identified (see discussion in Ref. [19]).

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