Direct determination of the temperature of overheated electrons in an insulator

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Highly disordered superconductors, in the magnetic-field-driven insulating state, can show discontinuous current-voltage characteristics. Electron overheating has been shown to give a consistent description of this behavior, but there are other possible explanations, including an electric-field-induced breakdown of the insulating state and a novel "superinsulating" state. We present ac-dc crossed measurements, in which the application of a dc voltage is applied along our sample, while a small ac voltage is applied in the transverse direction. We varied the dc voltage and observed a simultaneous discontinuity in both ac and dc currents. We show that the inferred electron temperature in the transverse measurement matches that in the longitudinal one, strongly supporting electron overheating as the source of observed current-voltage characteristics. Our measurement technique may be applicable as a method of probing electron overheating in various other physical systems, which show discontinuous or nonlinear current-voltage characteristics.

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Highly disordered superconductors can undergo a transition to an insulating state. This superconductor-to-insulator transition (SIT) can be driven by several parameters such as disorder strength, thickness, or magnetic field (B) [1–4]. While studying the B-driven insulating state in amorphous indium oxide (a:InO) thin films, Sambandamurthy *et al.* discovered that at low temperature (T), discontinuities appear in the current-voltage characteristics ($I-V$'s) [5]. Similar findings were later seen in disordered titanium nitride thin films [6], where they have been interpreted as evidence for a novel insulating state, termed a superinsulator [7].

More recently, Altshuler *et al.* [8] argued that the discontinuous $I-V$'s can be accounted for by electron overheating. Their theory is based on the assumptions that the electrons interact weakly with the phonons but strongly with each other, thus leading to the possibility that they will have their own well-defined T ($T_{\rm el}$), which can be very different from that of the phonons ($T_{\rm ph}$). Additionally, they assumed that Ohm's law holds for the entire voltage (V) range of the measurements, i.e., $V = IR(T_{\rm el})$, where I is the current and R is the resistance. In a steady state, they could obtain $T_{\rm el}$ from a heat-balance equation,

$$\frac{V^2}{R[T_{\rm el}(V)]} = \Gamma\Omega * \left(T_{\rm el}^{\beta} - T_{\rm ph}^{\beta}\right), \qquad (1)$$

where Ω is the sample volume, Γ is the electron-phonon coupling coefficient [8,9], and β is a material-dependent constant.

By numerically solving Eq. (1) for the experimentally relevant parameters, Altshuler *et al.* [8] found that below a certain $T_{\rm ph}$, $T_{\rm el}(V)$ develops a bistable region, i.e., for a certain range of V, Eq. (1) can have two stable solutions: a low-$T_{\rm el}$ solution, in which $T_{\rm el} \approx T_{\rm ph}$ resulting in high R, and a high $T_{\rm el}$ solution, in which $T_{\rm el}$ can be much higher than $T_{\rm ph}$ with much lower R. At equilibrium ($V = 0$), the system is in the low-$T_{\rm el}$ solution. As V is increased above a threshold value, the system enters the bistable region where it can spontaneously jump to the high-$T_{\rm el}$ solution, resulting in a discontinuous jump in I. Alongside Ref. [8], Ovadia *et al.* conducted a detailed experimental study of the $I-V$'s, showing that they are consistent with the overheated electron framework [9].

If this framework properly describes the physics behind observed $I-V$'s, an interesting scenario emerges. At low T, the application of a V can result in an analog of the liquid-to-gas phase transition, but under nonequilibrium conditions [10]. The electronic system can be driven far from equilibrium, offering an experimental tool to study the nature of highly disordered, strongly interacting quantum systems under such conditions.

Despite the consistency shown by the experimental results of Ovadia *et al.* [9], a direct demonstration that electron overheating is behind the reported $I-V$'s via a direct measurement of $T_{\rm el}$ is still lacking. This demonstration is essential because there are other theoretical approaches that offer a distinctly different view of the discontinuous $I-V$'s in our and others' systems [5,6,9,11–15]. One such theory is that the low-I branch of the experimental $I-V$'s is evidence of a "superinsulating" state, which is destroyed at a critical V [7], dual to the critical I in a superconductor. Another competing theory is that the observed $I-V$'s are a manifestation of a novel many-body localized state, as explained in Ref. [16]. A third possible explanation, which offers a more detailed description of the $I-V$ dependence, is that application of an electric field (E) tilts the random potential created by disorder until, at a threshold E value, a conduction channel connecting the two ends of the sample forms, resulting in a breakdown of the insulating state. This model was treated in Ref. [17] in the context of metallic islands in a disordered potential. It was used in order to explain discontinuous and nonlinear $I-V$'s observed in various systems [11–13,15], including insulating films [15].

We considered electronic noise measurements as a possible method to directly measure $T_{\rm el}$. These measurements, an obvious option because equilibrium noise is a commonly used thermometer, proved unfeasible. The combination of low $T_{\rm el}$ ($\approx$50 mK), high R (typically $> 10^8\,\Omega$), and the need to flow a dc I while conducting the measurement is yet too challenging experimentally.

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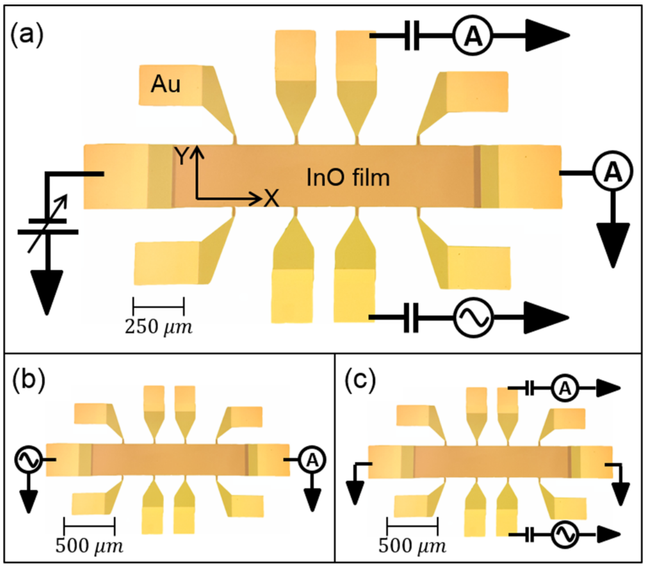

FIG. 1. Our experimental setup. (a) The setup used to measure $I_{X,Y}(V_X)$ (see Supplemental Material for more information [18]). The electronic circuit shown schematically was comprised of two transimpedance amplifiers, a lock-in amplifier, a dc V source, and two 10 μF capacitors used as dc blocks. (b) The setup used to measure $R_X|_{V=0}(T)$. (c) The ac-equivalent electronic circuit of the full experimental setup, which is the setup used to measure $R_Y|_{V=0}(T)$.

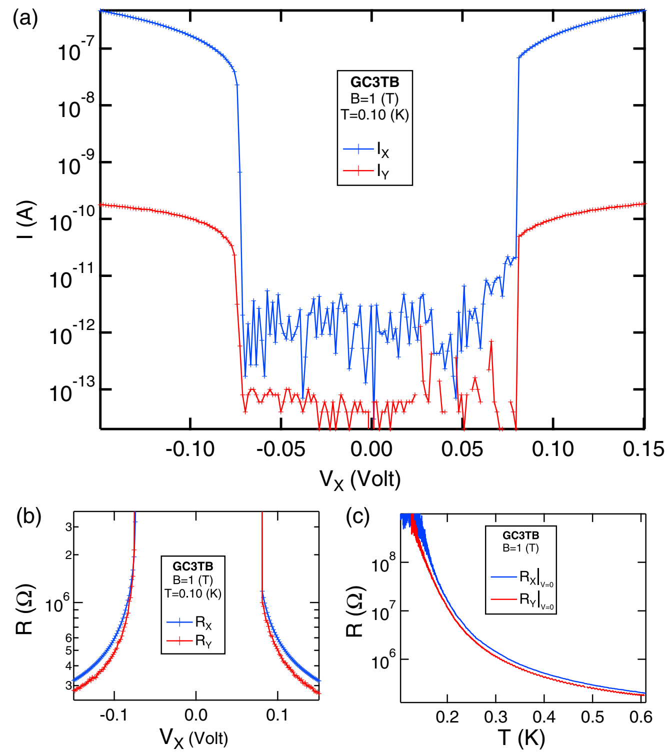

FIG. 2. (a) I_X and I_Y vs V_X. While V_X was swept, a constant V_Y = 50 mV (rms) was applied and I_X, I_Y were simultaneously measured. (b) R_X and R_Y vs V_X, calculated from the data shown in (a). (c) $R_X|_{V=0}(T)$ and $R_Y|_{V=0}(T)$ vs T. All subfigures are plotted on a semilogarithmic scale. The data were measured at $B = 1$ T; the data in (a) and (b) were taken at $T = 100$ mK.

In this paper, we have taken a different approach. We used the sample itself as a thermometer; thermometry that is based on a R measurement is standard practice and can be very accurate at low T. The crux of our method was to sweep V and infer $T_{\rm el}$ from two independent measurements of R: one in the direction parallel to V and another in a perpendicular direction, in a V range where the sample was found to remain ohmic.

According to Ref. [8], R is determined by $T_{\rm el}$ that, in turn, is determined by the power input into the electronic system. As a result, $T_{\rm el}$, as inferred by a measurement of R in a given orientation, should be the same regardless of the direction in which V is applied. The same cannot be said for the case of electric-field-induced breakdown of the insulating state [17].

It is important to note that our method cannot directly distinguish between the scenario described above, where $T_{\rm el}$ differs from $T_{\rm ph}$, which in turn remains equal to the T of the external bath (T_B), and a scenario where the entire sample decouples from the external bath, i.e., $T_{\rm el} = T_{\rm ph} \neq T_B$. Nevertheless, it does provide a direct measurement of $T_{\rm el}$. In the Supplemental Material [18], we present arguments that support electron heating in favor of heating of the entire sample.

The results presented in this work were obtained from a 1500-μm-long, 300-μm-wide, 10-contact Hall-bar sample of 30-nm-thick a:InO (see Fig. 1). The critical B (B_c) at which our sample showed a SIT was 0.009 T. A dc V was applied in the longitudinal (X) direction, while a small 50$\mu V_{\rm rms}$ ac, V, was applied in the transverse (Y) direction [18]. The longitudinal V (V_X) was swept from -150 to 150 mV, while the transverse V (V_Y) was held constant. During this, the longitudinal dc I (I_X) and the transverse ac I (I_Y) were measured.

I_X and I_Y vs V_X are shown in Fig. 2(a). At low V_X, both I_X and I_Y are within the noise. As V_X is increased, at $V_X \approx 80$ mV, I_X and I_Y each attain a value that appears abruptly, well above the noise, and grows progressively as V_X is increased further. Upon reducing V_X (going from -150 to 0 mV), I_X and I_Y decrease gradually, until rapidly dropping at $V_X \approx 72.5$ mV.

Following the assumptions stated above, we calculated the longitudinal and transverse R's (R_X and R_Y) by applying Ohm's law: $R_{X,Y} = V_{X,Y}/I_{X,Y}$. In Fig. 2(b), R_X and R_Y are plotted against V_X, showing the same abrupt escape from the noise as seen for the I's. The maximum R that we could measure, given our noise level in this setup, was $\approx 10^8$ Ω.

In order to infer a value of $T_{\rm el}$ from each of the data points, we used the zero-bias $R(T)$ of the sample [$R|_{V=0}(T)$], where T refers to the cryostat temperature. We conducted a two-terminal measurement of $R|_{V=0}(T)$, while sweeping T slowly (in order to ensure $T_{\rm ph} = T$). At low V, the $I - V$'s were linear, as was verified by $I - V$ measurements [18], indicating that $T_{\rm el} = T_{\rm ph}$. Thus, by measuring in the linear range, we ensured $R|_{V=0}(T) = R(T_{\rm el})$.

We measured $R|_{V=0}(T)$ in two different setups. The first was the setup, shown in Fig. 1(b), which we used to measure $R_X|_{V=0}(T)$, and the second was the ac equivalent of our experimental setup, shown in Fig. 1(c), which we used to

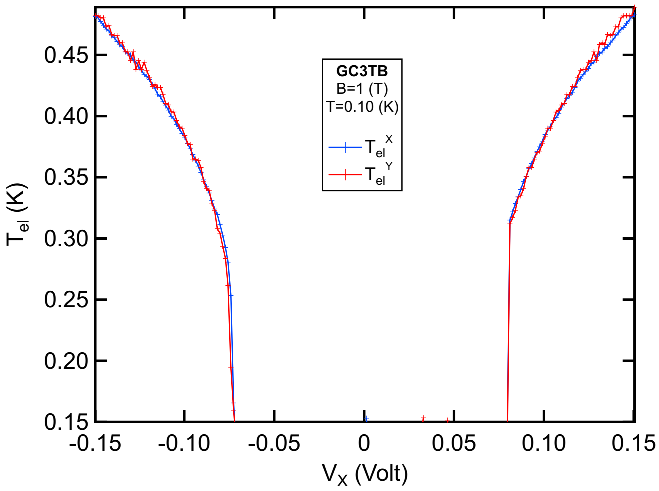

FIG. 3. T_{el}^X and T_{el}^Y vs V_X, plotted on a linear scale. $T_{el}^{X,Y}$ were calculated from $R_{X,Y}$ and $R_{X,Y}|_{V=0}(T)$ plotted in Fig. 2. Our experimental error did not allow us to infer a T_{el} value below 150 mK in a reliable way, and thus no data points appear below this value.

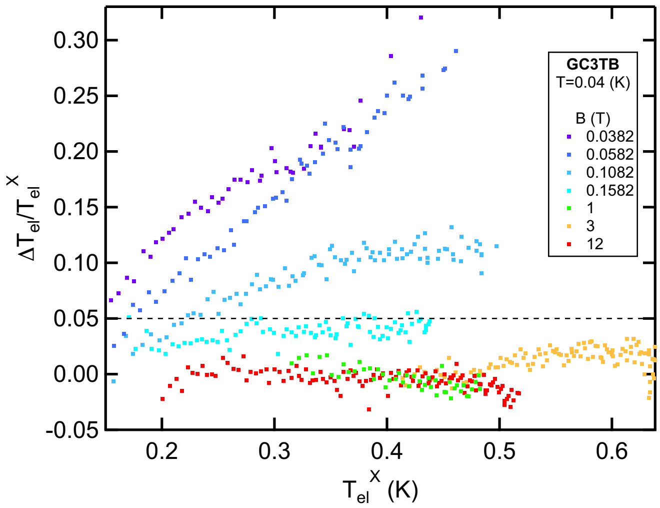

FIG. 4. $\frac{\Delta T_{el}}{T_{el}^X}$ vs T_{el}^X, plotted on a linear scale. The dashed line represents $\frac{\Delta T_{el}}{T_{el}^X} = 5\%$. The color scale represents the B corresponding to each data set. All data were calculated from measurements conducted at $T = 40$ mK and from $R_{X,Y}|_{V=0}(T)$ similar to those plotted in Fig. 2.

measure $R_Y|_{V=0}(T)$. In both cases, we used an ac V of $50\mu V_{rms}$, which is well within the linear $I-V$ range. $R_X|_{V=0}$ and $R_Y|_{V=0}$ vs T are shown in Fig. 2(b).

We inverted $R_{X,Y}|_{V=0}(T)$, attained $T_{el}^{X,Y} \equiv T_{el}(R_{X,Y})$, and inferred a T_{el} value from each data point of $R_{X,Y}(V_X)$. In Fig. 3, we plotted T_{el}^X and T_{el}^Y vs V_X. Our experimental error in $R_{X,Y}$ allowed us to measure T_{el} down to 150 mK. The agreement between T_{el}^X and T_{el}^Y is nearly perfect.

We next turned our focus to a B-dependent study of the $I-V$'s using our technique. We defined $\Delta T_{el} \equiv T_{el}^X - T_{el}^Y$. In Fig. 4, we plotted $\frac{\Delta T_{el}}{T_{el}^X}$ vs T_{el}^X for various B's ranging from 0.0382 up to 12 T. For the sake of clarity, we only displayed a portion of the B's that were studied, which represents the trend observed for all B's examined. For $B > 0.15$ T, all measured T_{el}^X were within 5% of T_{el}^Y, i.e., below the dashed line in Fig. 4. For $B < 0.15$ T, as B approached B_c, T_{el}^X became systematically larger than T_{el}^Y. Both noise and systematic error in $T_{el}^{X,Y}$ grew significantly as B approached B_c. This is due to $R(T_{el})$ becoming a progressively slow-varying function of T_{el}, and thus inverting it caused large uncertainty. Nevertheless, our measurements point to a possible deviation from the overheated electron picture as B_c is approached.

The main conclusion of our work stems from the near-perfect agreement we observed between T_{el}^X and T_{el}^Y. This agreement supports the theory of electron overheating, and rules out the electric-field breakdown as the cause of our discontinuous, nonlinear, hysteretic $I-V$'s. The degree to which T_{el}^X and T_{el}^Y agree adds a constraint to any physical description of the observed $I-V$'s. We identified a possible deviation between T_{el}^X and T_{el}^Y in the vicinity of B_c, requiring further investigation. We demonstrated a simple technique to measure the electronic temperature of systems which exhibit nonlinear $I-V$'s. Many condensed-matter systems, such as Anderson-Mott insulators [15], disordered quantum dot arrays [11,12], metallic island arrays [13], and transport through constrictions [14], exhibit similar $I-V$'s. Applying our technique to these systems may serve to enhance our understanding of them and show whether electron overheating is involved in the nonlinear $I-V$'s observed in these systems.

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[1] A. F. Hebard and M. A. Paalanen, Phys. Rev. Lett. **65**, 927 (1990).
[2] A. M. Goldman and N. Markovic, Phys. Today **51**, 39 (1998).
[3] S. L. Sondhi, S. M. Girvin, J. P. Carini, and D. Shahar, Rev. Mod. Phys. **69**, 315 (1997).
[4] V. F. Gantmakher and V. T. Dolgopolov, Phys. Usp. **53**, 1 (2010).
[5] G. Sambandamurthy, L. W. Engel, A. Johansson, E. Peled, and D. Shahar, Phys. Rev. Lett. **94**, 017003 (2005).
[6] T. I. Baturina, A. Y. Mironov, V. M. Vinokur, M. R. Baklanov, and C. Strunk, Phys. Rev. Lett. **99**, 257003 (2007).
[7] V. M. Vinokur, T. I. Baturina, M. V. Fistul, A. Y. Mironov, M. R. Baklanov, and C. Strunk, Nature (London) **452**, 613 (2008).
[8] B. L. Altshuler, V. E. Kravtsov, I. V. Lerner, and I. L. Aleiner, Phys. Rev. Lett. **102**, 176803 (2009).

[9] M. Ovadia, B. Sacepe, and D. Shahar, Phys. Rev. Lett. **102**, 176802 (2009).
[10] A. Doron, I. Tamir, S. Mitra, G. Zeltzer, M. Ovadia, and D. Shahar, Phys. Rev. Lett. **116**, 057001 (2016).
[11] C. I. Duruöz, R. M. Clarke, C. M. Marcus, and J. S. Harris, Jr., Phys. Rev. Lett. **74**, 3237 (1995).
[12] N. E. Staley, N. Ray, M. A. Kastner, M. P. Hanson, and A. C. Gossard, Phys. Rev. B **90**, 195443 (2014).
[13] C. Kurdak, A. J. Rimberg, T. R. Ho, and J. Clarke, Phys. Rev. B **57**, R6842 (1998).
[14] G. Pilling, D. H. Cobden, P. L. McEuen, C. I. Duruöz, and J. S. Harris, Jr., Surf. Sci. **361**, 652 (1996).
[15] F. Ladieu, M. Sanquer, and J. P. Bouchaud, Phys. Rev. B **53**, 973 (1996).
[16] D. M. Basko, I. L. Aleiner, and B. L. Altshuler, Phys. Rev. B **76**, 052203 (2007).
[17] A. A. Middleton and N. S. Wingreen, Phys. Rev. Lett. **71**, 3198 (1993).
[18] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevB.94.174204 for sample fabrication, experimental methods and supplementary experiment including its results.