Electric-field and temperature effects in a two-dimensional system with strong localization

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In thin crystals of $Bi_{14}Te_{11}S_{10}$ the similarity between temperature and electric-field effects has been demonstrated. At low temperatures and low fields we have observed the unifying parameter predicted by Marianer and Shklovskii, $T'=[(bE)^2+T^2]^{1/2}$.

In the region of strong localization, conductance in a two-dimensional (2D) sample can often be expressed by the Mott variable-range-hopping equation[1]

$$g = g_{0T}\exp[-(T^*/T)^{\nu}] , \tag{1}$$

where the dimensionless conductance $g=G_{\square}/(e^2/h)$, $G_{\square}=J/E$, $J=(I/\text{width})$, $E=(V/\text{length})$, I is the current, V is the source-drain voltage, and T is the temperature. g_{0T} and T^* are constants characteristic of the sample, although g_{0T} may be a universal constant, and ν is assumed to be a universal constant. Mott predicts $\nu=1/(1+d)$, where d is the dimensionality. For the electric-field dependence Shklovskii predicted[2]

$$I \propto \exp[-(E^*/E)^{\eta}] , \tag{2}$$

where E^* is a constant characteristic of the sample and $\eta=1/(d+1)$. We have analyzed our data in terms of an equation more similar to Eq. (1),

$$g = g_{0E}\exp[-(E^*/E)^{\Delta}] . \tag{3}$$

Equations (1) and (3) ought to be obeyed in the limit of E or $T=0$. There are not much data for the case where both T and E are nonzero. Faran and Ovadyahu[3] analyzed their data in terms of Eq. (2) and Licciardello and Soonpaa[4] attempted it in terms of Eq. (3). Over a limited range some agreement was observed.

In this paper we present data that were taken on a 2D system in which conductance can be varied over seven orders of magnitude through changes in temperature or source-drain electric fields. Thin single crystals of $Bi_{14}Te_{11}S_{10}$, five atoms thick, were used.[5,6] Characteristics pertinent to this work are as follows. (i) The wide range of conductances. With temperature or electric field we can change conductance from $G_{\square}<10^{-12}$ S to close to $G_{\square}=10^{-5}$ S. (ii) Sample and contacts consist of a continuous crystal, contacts are semimetallic, and the sample is semiconducting due to quantum size effects. There is no change in composition at the sample-contact boundary, only the thickness changes. We have not detected any rectification in our semimetal-semiconductor-semimetal contact-sample-contact arrangement. (iii) The five-atoms-thick sample is immersed in liquid helium. This means that no carriers are farther than 10 Å from liquid helium. That should assure the best possible separation of lattice and electron temperatures, T_l and T_e.

The thin crystals right after cleavage have conductances of $G_{\square}\approx 10^{-4}$ S, which are reduced by exposure to atmosphere. The process is reversible; initial conductance can be restored by pumping on the sample.[7] Adsorption/desorption of gases is the only method by which we can reversibly cross the conductance value $G_{\square}=e^2/h$. We have not been able to do this with temperature or electric field. Our experimental $g_0<e^2/h$, and according to Eqs. (1) and (3), $g<g_0$ for any value of T,E. Neither have we been able to cross $G_{\square}=e^2/h$ with magnetic-field, or gate-voltage variations. Our experimental data are from I-V measurements at constant temperatures. I increases nonlinearly and monotonically with V. In order to find the range over which Eq. (1) or (3) is valid we derived an expression that enabled us to find the exponent ν from a plot our $g(T)$ data.

$$\ln g = \ln g_{0T} - (T^*/T)^{\nu} , \tag{4}$$

$$\begin{aligned}\partial \ln g &= \nu T^{*\nu} T^{-(\nu+1)}\partial T = \nu(T^*/T)^{\nu}\partial T/T\\ &= \nu(T^*/T)^{\nu}\partial \ln T ,\end{aligned} \tag{5}$$

$$\partial \ln g/\partial \ln T = \nu(T^*/T)^{\nu} = -\nu(\ln g - \ln g_{0T}) . \tag{6}$$

The left-hand side of Eq. (6) is the same as the temperature scaling function of Davies, Pepper, and Kaveh.[8] We call it β_T,

$$\beta_T = -\partial \ln g/\partial \ln T = \nu(\ln g - \ln g_{0T}) . \tag{7}$$

We define β_E as the field scaling function

$$\beta_E = -\partial \ln g/\partial \ln E = \Delta(\ln g - \ln g_{0E}) . \tag{8}$$

In processing our data we initially calculated β_T and β_E by using differences between adjacent data points. The resulting data had lots of scatter (small differences between large values), but the data allowed us to identify ranges of the linear β vs $\ln g$ relationship. Then we found analytical expressions of $g(T)$ and $g(E)$ over those ranges, calculated β_T and β_E from those expressions, and plotted the results in Fig. 1.

For $g(T)$ there is good agreement with Eq. (1), covering the whole range of our data from $T=1.8$ to 295 K. Twenty-four experimental points yields a straight-line fit for $\ln g$ vs $T^{-0.66}$, with a standard deviation $\sigma=0.143$. $T^*=134.6°$, $g_{0T}=0.287$, and $\nu=0.66$. For $g(E)$ we have good agreement with Eq. (3) in the region of high electric

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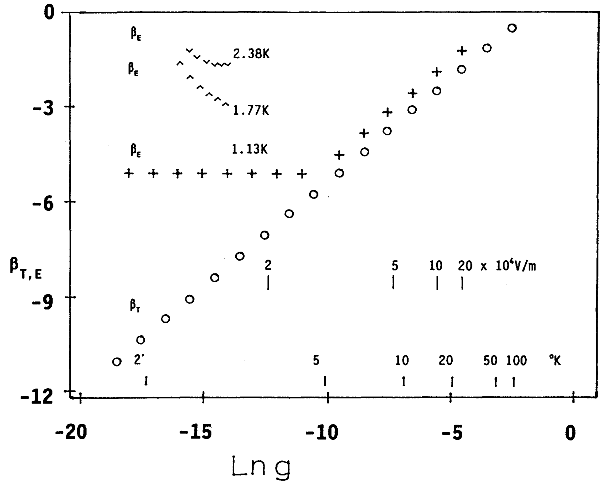

FIG. 1. β_T from 1.8 to 295 K vs lng. β_E at 1.13, 1.77, and 2.38 K vs lng.

fields. 235 experimental points yield a straight line for lng vs $E^{-0.65}$ with $\sigma=0.0177$. $E^*=544\,226$ V/m, $g_{0E}=0.074$, and $\Delta=0.65$. We tried to fit the same data to Eq. (2), $\ln I \propto E^{-\eta}$. The fit was good; for $\eta=0.47$, $\sigma=0.0203$. Equation (3) is more readily comparable to Eq. (1), and the exponents are virtually identical. For these reasons we treated the rest of our data in terms of Eq. (3).

At low fields and $T=1.13$ K we found a good empirical fit for $J \propto E^{\zeta}$, from which $-\beta_E=\zeta-1$. 110 experimental points fitted a straight line for $\ln J=\zeta \ln E$ with $\sigma=0.0277$. β_E values for $T=1.77$ and 2.38 K were obtained from polynomial fits of $\ln J$ vs E. At higher temperatures and lower fields we have observed the slope of the β_E vs lng curve become negative, and at higher temperatures yet $\beta_E>0$. This clearly indicates that the assumption of single parameter E scaling is not valid at low fields when $T>0$.

Our β_E vs lng curves resemble those predicted by Kaveh for two-parameter scaling.[9] Our observed values for the exponents $\nu=0.66$ and $\Delta=0.65$ are almost exactly double the value $\frac{1}{3}$ predicted by Mott. Interestingly, in scaling work the numerical value of the slope of β vs lng has been predicted on theoretical grounds to be approximately 0.7 and $g_0 \approx 0.1$.[10,11] Experimentally such values have been observed on different systems.[12–15]

Abrahams *et al.*[16] defined $\beta \equiv \partial \ln g/\partial \ln L$; L being the length scale and g_0 a dimensionless ratio of order unity. Davies *et al.*[8] related β to β_T through

$$\begin{aligned}\beta_T &= -\partial \ln g/\partial \ln L\\ &= -(\partial \ln g/\partial \ln T)(\partial \ln T/\partial \ln L)=\beta\gamma\ ;\\ \gamma &= -\partial \ln L/\partial \ln T\ .\end{aligned} \tag{9}$$

From $\beta_T \approx \beta$ we must conclude that $\gamma=1$. The systems in Refs. 12–15 are two-dimensional systems, which should yield $\nu=\frac{1}{3}$, if Eq. (1) was applicable.

Apart from the difference between the g_0 values for varying field and varying temperature measurements, the effects of E and T are quite similar in the limits of E $(T=0)$ and T $(E=0)$. Shklovskii *et al.*[17] have concluded that there should be one parameter T' which combines the electric-field and temperature effects. To explore such a relationship we paired $E(T_l)$ and T $(E=0)$ values, which result in the same conductance. T_l is the temperature at which the J-E readings were taken; T is the stepwise-incremented temperature at which $G_\square$ $(E=0)$ measurements were performed. These data came from the same I-V runs form which the data for Fig. 1 were taken. Our E vs T plots for such pairs resulted in a straight line, with T intercepts very close to the sample temperature T_l for runs below 4.2 K. We call $1/b$ the slope of E vs T; $bE=T$. If it were true that $g_{0T}=g_{0E}$ and $\nu=\Delta$ then $bE^*=T^*$. Both E and T represent rates at which carriers are moved to energies above the mobility edge,[17] $eE\xi=2kT$ and $b=e\xi/2k$, where e is the electron charge, ξ is the localization length, and k is the Boltzmann constant. For the sample of Fig. 1, $\xi=242$ Å at $T_l=1.33$ K, and it decreased with increasing temperature. No functional relationship between T and E in the combined T' could be established from these data, but approximately $\xi \propto T^{-1/2}$.

To establish a functional relationship we used some of our J-E data, in which curves at different temperatures were plotted on the same graph, Fig. 2. From the origin we drew straight lines, which intersected the different temperature J-E curves at different places. These straight lines represent a constant conductance $G_\square=J/E$; we call them isoconductance lines. They yield a set of E,T pairs of values at $T\neq 0$, $E\neq 0$. By plotting values as bE vs T, scaled so that on the graph $bE(T=0)=T(E=0)$, we can get a good idea of the $T'=f(E,T)$ relationship. Assuming

$$T'=[(bE)^{\alpha}+T^{\alpha}]^{1/\alpha}\ , \tag{10}$$

$\alpha=1$ would result in a straight line between $E(T=0)$ and $T(E=0)$ and $\alpha=2$ would give a circle with center at $T=0$, $E=0$. In Fig. 3 results for $\alpha=2$ and a circle of radius T' are shown. In Table I our best fit data are listed.

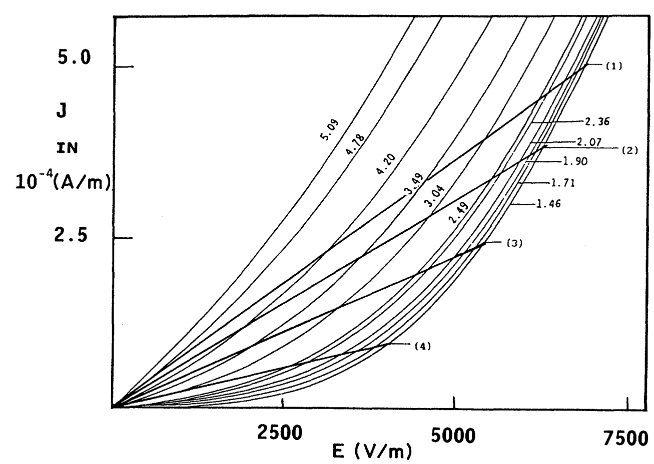

FIG. 2. J vs E at different temperatures, 1.46–5.09 K. The straight lines are isoconductance lines for $g=0.0038$, 0.0032, 0.0023, and 0.0011.

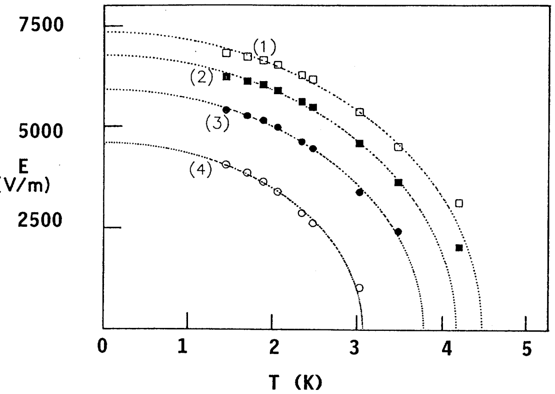

FIG. 3. E vs T for isoconductance lines from Fig. 2. For the calculation for T' the 4.2 K points were omitted.

TABLE I. Localization length ξ and unifying parameter T' calculated from isoconductance lines of Fig. 2.

	g	α	b	ξ	T'
Units:	(e^2/h)		(K m/V)	$(10^{-8}$ m)	(K)
1	0.0038	2.5	5.74	7.38	4.07
		2.0	6.11	7.86	4.48
2	0.0032	2.3	6.01	7.73	3.95
		2.0	6.16	7.92	4.17
3	0.0023	1.9	6.40	8.23	3.84
		2.0	6.40	8.23	3.78
4	0.0011	1.8	6.53	8.40	3.14
		2.0	6.70	8.61	3.07

The α values are in the proximity of 2; b and T' are not very sensitive to α near $\alpha=2$. At lower temperatures $\alpha=2$ is in better agreement with experiment. Marianer and Shklovskii[18] in their Eq. (12) find $b=0.67e\xi/k$, where e is the electron charge and k is the Boltzmann constant. ξ values in Table I were calculated from this relationship.

The model of Marianer and Shklovskii deals with hopping conductivity in the region of strong localization. Their Eq. (12) has the same functional relationship between T', T, and E as our Eq. (10) with $\alpha=2$. Interestingly, Payne *et al.*[19] find the same functional relationship between electron temperature, lattice temperature, and field; Te, T_l, and E; in their model of weak-localization hot-electron conduction.

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