Hot-Electron Effects in Two-Dimensional Hopping with a Large Localization Length

M. E. Gershenson and Yu. B. Khavin
Serin Physics Laboratory, Rutgers University, Piscataway, New Jersey 08854-8019

D. Reuter, P. Schafmeister, and A. D. Wieck
Lehrstuhl fuer Angewandte Festkoerperphysik, Ruhr-Universitaet Bochum, Universitaetsstrasse 150 D-44780 Bochum, Germany
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We have studied nonlinear effects in the resistance of a two-dimensional system with a large localization length on both sides of the crossover from weak to strong localization. It is shown that nonlinearity in the hopping regime is due to electron overheating rather than the field effects. This qualitatively new behavior is a signature of a two-dimensional hopping transport with a large localization length.

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Observation of the low-temperature crossover from weak localization (WL) to strong localization (SL) provides an opportunity to study electron hopping in low-dimensional conductors with a large localization length ξ, up to a few microns (see, e.g., [1,2]). This hopping regime is qualitatively different in many respects from the conventional hopping in systems with a small ξ [3]. In the former case, electron motion is still diffusive within the localization domain, with the same electron mean free path l as in the WL regime. One of the consequences of the diffusive motion at small distances is an exponentially strong orbital magnetoresistance, which is observed for the large-ξ systems in a weak magnetic field B [2,4]. This magnetoresistance is due to suppression of backscattering at $L \leq \xi$, or, in other words, to the field-induced increase of ξ [5]. In contrast, the low-B magnetoresistance of the small-ξ hopping systems is associated with interference of the forward-scattering paths [6].

In this Letter we show that *the mechanisms of nonlinearity* of the two-dimensional (2D) hopping conductivity are also very different in systems with large and small ξ. In the conventional hopping regime with small ξ, the nonlinear effects are usually associated with "tilting" of electron hops in an electric field $E > k_B T/er_h$, where r_h is the hopping distance [7]. In contrast, the nonlinear effects in the 2D hopping transport with a large ξ are caused by *electron heating*. We draw this conclusion from two observations. First, we demonstrate a striking similarity between the nonlinear effects in the hopping and diffusive regimes (in the latter case, the hot-electron-induced nonlinearity is well documented [8,9]). Second, we show that in our experimental situation, the electric field affects the hopping conductivity only indirectly, via Joule heating. The hot-electron nonlinearity suggests that electron transport in the hopping regime is controlled by the electron temperature, and that the electron-electron interactions play an important role in hopping with a large localization length.

We have studied the resistance R of 2D Si δ-doped GaAs structures as a function of the bias current I over the temperature range $T = 0.05-1$ K at $B = 0-8$ T. A single δ-doped layer with a concentration of Si donors 1.3×10^{12} cm^{-2} is 0.1 μm under the surface of the molecular-beam-epitaxy-grown undoped GaAs. The electron concentration can be tuned by applying the voltage V_g to the gate electrode on top of the device. The width of the conducting channel was $\sim$100 μm; the length of the gate electrode in the direction of current was varied between 6 and 360 μm. All data discussed henceforth will be on a 360×120 $(\mu\text{m})^2$ device, except where the other samples are explicitly noted. The measurements were done in the four-probe configuration using a low-frequency lock-in technique in the range $R < 10^6$ Ω, and a dc current source and an electrometer for $10^6 < R < 10^9$ Ω.

The WL-SL crossover has been observed for these devices with lowering the electron concentration (see the inset in Fig. 3). The "zero-bias" dependences of the sheet resistance $R_\square$ on both sides of the crossover are shown in Figs. 1 and 2. The logarithmic dependence $R(T)$, observed in the WL regime, is due to the WL and interaction effects [10]. In the SL regime, the dependence $R(T)$ can be fitted by

$$R_\square(T) = R_{0\square}(T/1K)^m \exp(T_0/T)^\alpha \qquad (1)$$

with $m = 0$ and $\alpha = 0.7$ (see Fig. 2) or $m = 1$ and $\alpha = 0.5$, similar to previous observations for 2D semiconductor structures and ultrathin metal films [1,11–13].

With increase of the bias current I, the I-V curves become nonlinear in both WL and SL regimes. The insets in Figs. 1 and 2 show the resistance $R = V/I$ versus the bias current power, $P = VI$, at a fixed mixing chamber (MC) temperature T. It is instructive to compare for both regimes the values of P which cause the same change of R as a small fixed increase of T (below we choose 10%) (see Fig. 3). In the WL hot-electron experiments, the effective electron temperature T_e is usually found from the dc bias power P^* at which the *differential* resistance $dV/dI(T_e, I)$ becomes equal to the zero-bias resistance

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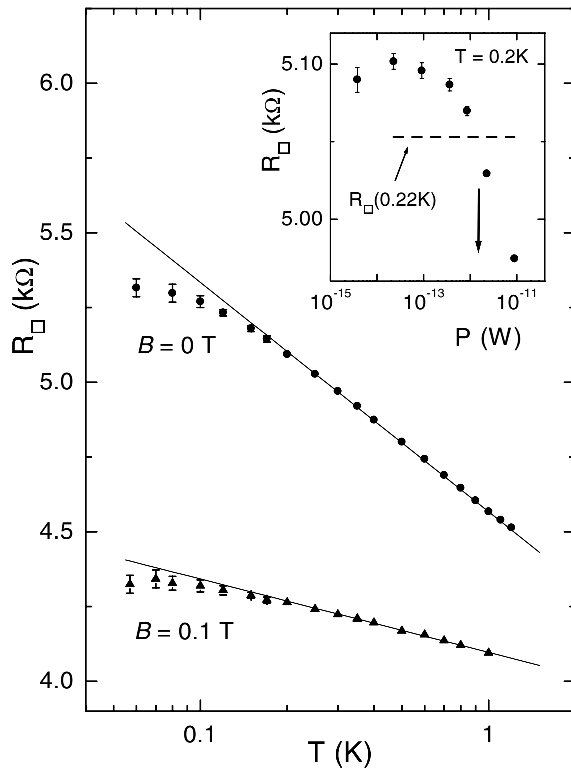

FIG. 1. The temperature dependences of the zero bias $R_\square$ in the WL regime ($V_g = 0.4$ V, $n = 1 \times 10^{12}$ cm^{-2}) at $B = 0$ and $B = 0.1$ T (this field is sufficiently strong to suppress the T dependence of the WL correction). The solid lines are the logarithmic fit $R_\square(T) = R_\square(1K)[1 - \alpha \frac{e^2 R_\square}{2\pi^2 \hbar} \ln(T/1K)]$ with $\alpha = 1.29$ ($B = 0$) and $\alpha = 0.52$ ($B = 0.1$ T). The inset shows $R = V/I$ versus $P = VI$ at a fixed MC temperature $T = 0.2$ K and $B = 0$. The horizontal dashed line corresponds to the zero bias $R_\square$ at $T = 0.22$ K.

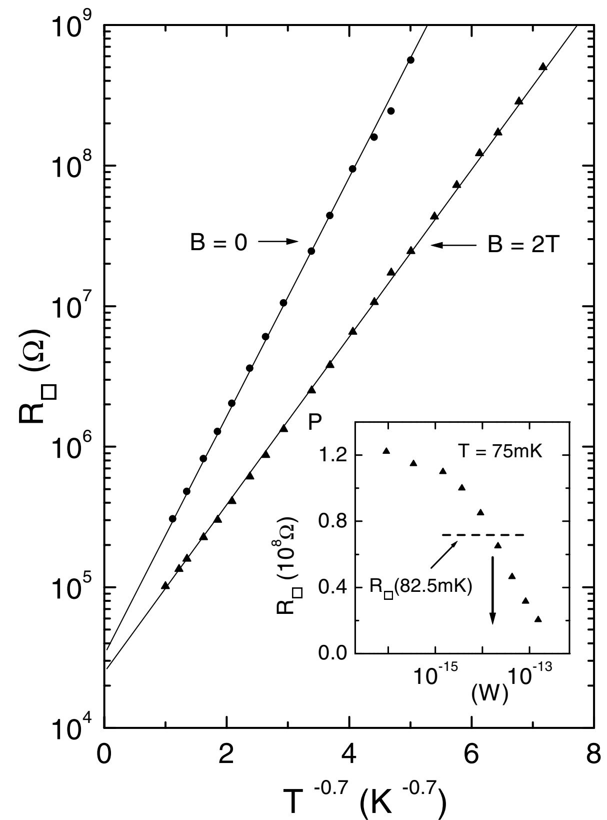

FIG. 2. The temperature dependences of the zero bias $R_\square$ in the SL regime ($V_g = -0.7$ V) at $B = 0$ and $B = 2$ T. The solid lines correspond to $R_\square(T) = (33.3\ \mathrm{k}\Omega)\exp[(2.6K/T)^{0.7}]$ at $B = 0$, and $R_\square(T) = (25\ \mathrm{k}\Omega)\exp[(1.57K/T)^{0.7}]$ at $B = 2$ T. The inset shows $R = V/I$ versus $P = VI$ at a fixed MC temperature $T = 75$ mK and $B = 2$ T. The horizontal dashed line corresponds to the zero bias $R_\square$ at $T = 82.5$ mK.

$dV/dI(T + \Delta T, I = 0)$. Because of the difficulty of direct ac measurements of dV/dI at $R \sim 10^9\ \Omega$, we have chosen to use P instead of P^* in our analysis. For a small overheating, which corresponds to a quadratic nonlinearity of the I-V curves, $P = 4P^*$; this was taken into account in comparison with the theory [14,15]. Below we analyze separately data for the WL and SL regimes.

In the WL regime, all assumptions of the hot-electron model [8,9] can be easily justified. Indeed, at sub-Kelvin temperatures, the electron-electron scattering rate is much greater than the electron-phonon one, and a nonequilibrium electron distribution function can be described by an effective T_e. Both the WL and interaction corrections are only T_e dependent, since the dominant dephasing mechanism at low T is the quasielastic electron-electron scattering [2,16]. For this reason, the dependence $R(T)$ can be used as an electron thermometer. We have also verified that the electron-phonon interaction is the bottleneck in the energy transfer from electrons to the heat sink, and the phonons in bulk GaAs remain in equilibrium (the phonon temperature T_{ph} is the same as T). In this test, two identical devices were formed side-by-side on the same chip with dimensions $5 \times 6 \times 0.5$ mm^3. The zero bias R of one of the devices (a phonon "thermometer") was measured at $T = 0.1$ K as a function of the Joule heat released in the other device (a "heater") (see the inset of Fig. 4). The power required for a 10% increase of the temperature of the whole chip is by 4 orders of magnitude greater than P that causes nonlinear effects when the same device combines functions of the heater and thermometer.

The outdiffusion of "hot" electrons in cooler leads can be neglected for the 360-μm-long sample at $T > 0.1$ K [9,17], and the energy is transferred from electrons to the heat sink due to the electron-phonon interaction only. The experimental values of P are shown in Fig. 3 for a device with the mean free path $l \sim 20$ nm at $V_g = 0.4$ V. These data are in agreement with the hot-electron experiments on disordered GaAs heterostructures [9].

We compare our data with calculations of the energy flow from 2D electrons to bulk phonons due to piezoelectric coupling in GaAs [14,15] (note that this comparison does not use *any* fitting parameters). For the clean case $q_t l > 1$ ($q_t = k_B T/\hbar u_t$ is the wave vector of a transverse phonon, u_t is the transverse sound velocity,

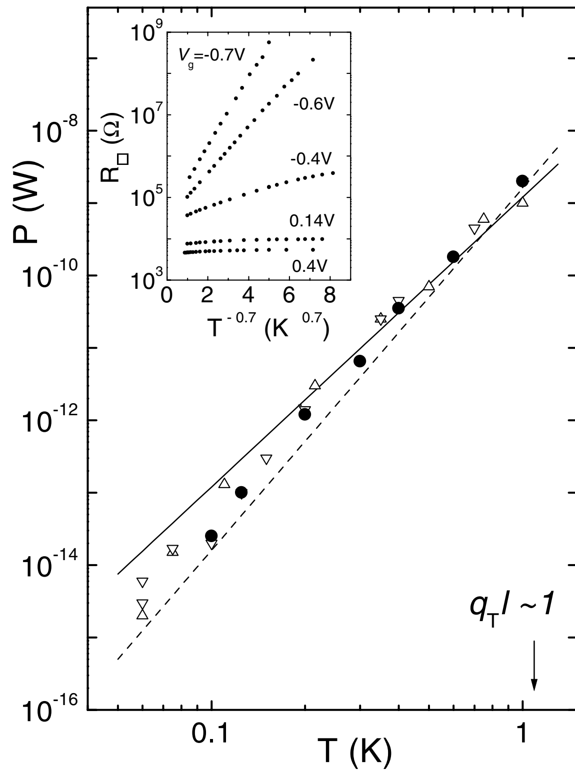

FIG. 3. The temperature dependence of the Joule power $P = VI$, which causes the same change of $R = V/I$ for the 360×120 $(\mu\text{m})^2$ device as an increase of the MC temperature T by 10% (•) in the WL regime ($V_g = 0.4$ V, $B = 0$); (▽, △) in the SL regime ($V_g = -0.7$ V) at $B = 0$ and $B = 2$ T, correspondingly. The dependences $P(T_e = 1.1T)$ are calculated for the cooling of 2D electrons in bulk GaAs due to piezoelectric coupling: the solid line in the disordered case $q_t l < 1$ [15]; the dashed line in the clean case $q_t l > 1$ [14]. The theoretical results (2) and (3) have been multiplied by a factor of 4 (note the difference between P and P^*). The inset: the zero-bias dependences $R_\square(T)$ for several values of V_g.

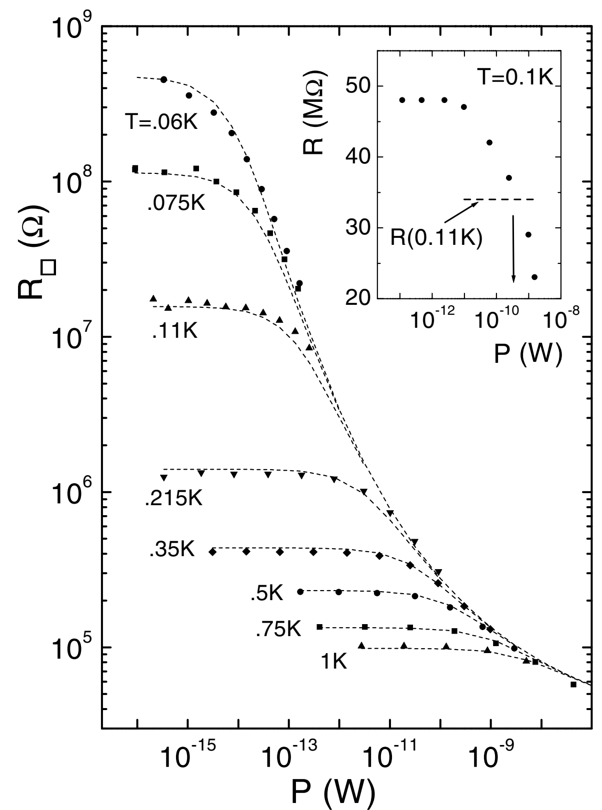

FIG. 4. The resistance $R = V/I$ in the SL regime ($V_g = -0.7$ V, $B = 2$ T) at different MC temperatures as a function of the power $P = VI$ released in the device. The dashed lines are the fit $R_\square(T) = R_\square \exp[(T_0/T_e)^{0.7}]$ with $R_\square = 25$ kΩ, $T_0 = 1.57$ K (see Fig. 2), and T_e found from $P = 3.7 \times 10^{-9}[W](T_e^{4.5} - T^{4.5})$, the best approximation for the experimental data in Fig. 3. The inset: the zero bias R in the SL regime ($V_g = -0.6$ V, $T = 0.1$ K) versus the power released in the other device on the same chip. The horizontal dashed line corresponds to the zero bias R at $T = 0.11$ K.

$\simeq 3 \times 10^3$ m/s for GaAs) [14]

$$P^*[W] \simeq 1.7 \times 10^6 n^{-1/2} A (T_e^5 - T^5)[K^5]. \quad (2)$$

Here A is the area of the device, and n is the electron concentration. In the opposite case $q_t l < 1$, the so-called hydrodynamic regime [15]:

$$P^*[W] \simeq 7 \times 10^{-2} \frac{e^2 R_\square}{h} A (T_e^4 - T^4)[K^4]. \quad (3)$$

The device is expected to enter the hydrodynamic regime at $T \leqslant 1$ K. However, the experimental accuracy is not sufficiently high to give preference to either of the predictions [14] and [15] over our limited T range.

In the SL regime, a striking similarity of the dependences $P(T)$ obtained in the WL and SL regimes suggests that nonlinearity on the "insulating" side of the crossover is also due to the hot-electron effects rather than the field effects. The hot-electron model describes very well the dependences $R(P)$ in the hopping regime over a wide range of P (see Fig. 4). Observation of identical dependences $P(T)$ on both sides of the WL-SL crossover suggests that the electron-phonon interaction in our samples is not modified in the hopping regime. This might be expected, because the parameter $q_t \xi$ remains of the order of unity even at $T = 50$ mK.

The most important proof of the hot-electron nature of nonlinearity is provided by our observation that the magnitude of P does not depend on ξ. This has been tested by varying the gate voltage or, for a fixed V_g, by applying the magnetic field B strong enough to break the time-reversal symmetry within the localization domain [5]. Despite large variations of ξ, no dependence $P(\xi)$ was observed (the data for $B = 0$ and $B = 2$ T are compared in Fig. 3).

The analysis of the Joule power (instead of the "threshold" electric field) helps to understand the qualitative difference between mechanisms of nonlinearity in systems with large and small ξ. In the model of the electron hop tilting, the critical power $P = (EL)^2/R$ depends strongly on ξ, mostly due to the exponential dependence $R(\xi)$ [7].

With increasing ξ, P grows rapidly, and exceeds the power that can be removed from the electrons due to electron-phonon coupling without substantial electron overheating. Thus, one can expect the crossover from field effects to electron heating in nonlinear hopping transport with increasing ξ.

We have tested that in the hopping regime, P scales with the area of a device over a range $A = 6 \times 10^2 - 4.3 \times 10^4\ \mu\text{m}^2$. Thus, the electron-phonon coupling remains the dominant mechanism of electron cooling over the whole temperature range even in a 6-μm-long sample. We recall that in the micron-size WL samples, the hot-electron outdiffusion becomes a more efficient cooling mechanism at low temperatures than the electron-phonon coupling [9,17]. Of course, outdiffusion is suppressed in the hopping regime. However, the long-range dipole-dipole interactions might create, in principle, unlocalized neutral excitations, which can participate in the thermal conductivity, but do not contribute directly to the charge transfer [18]. This channel of electron cooling, if existing, is less effective than the electron-phonon coupling in our samples with $L > 6\ \mu$m at $T > 70$ mK.

It is worth comparing the hot-electron effects, observed for a 2D system with a large ξ, with behavior of the large-ξ systems of different dimensionality. In 3D, a large ξ can be realized in the vicinity of the metal-insulator transition. The non-Ohmic effects in hopping conductivity of heavily doped Ge samples are well described by the hot-electron model (see [19] and references therein). In comparison with these 3D samples, our 2D structures have two important features that help to attribute the observed nonlinear effects to electron overheating. First, the study of the same sample on *both* sides of the WL-SL crossover allows direct comparison of nonlinear effects in the hopping and diffusive regimes. Second, it is much easier to maintain equilibrium between the heat sink and phonons for a 2D electron gas embedded in bulk GaAs rather than for the 3D uniformly doped samples. In contrast to 2D and 3D, it is difficult to realize the hot-electron nonlinearity in 1D. For 1D "wires" with ξ as large as 1.5 μm, we have observed nonlinear effects at P by 2–3 orders of magnitude *smaller* than the power required for electron overheating [2]. A very low threshold for field effects in 1D is due to the existence of the so-called critical hops [20] with exponentially large resistance, which cannot be "bypassed" in 1D geometry.

To summarize, we have shown that nonlinearity of the resistance of two-dimensional systems with a large localization length is due to the *hot-electron* effects rather than the field effects. When the electrons are removed from equilibrium with phonons, the resistance in the hopping regime depends on the *electron* temperature rather than the phonon one. This observation suggests that electron-electron interactions play an important role in the hopping transport in disordered systems with a large localization length (see also [19,21]).

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