Crossover from Weak to Strong Localization in Quasi-One-Dimensional Conductors

M. E. Gershenson* and Yu. B. Khavin
Rutgers University, Department of Physics and Astronomy, Serin Physics Laboratories, Piscataway, New Jersey 08855-0849

A. G. Mikhalchuk and H. M. Bozler
University of Southern California, Department of Physics and Astronomy, Los Angeles, California 90089-0484

A. L. Bogdanov
Swedish Nanometer Laboratory, Chalmers University of Technology, S-412 96 Göteborg, Sweden
(Received 16 December 1996)

The crossover from weak to strong localization in the resistance of quasi-1D conductors is observed for the first time with decreasing the temperature; it occurs when the phase-breaking length becomes comparable with the localization length. The signature of the strong-localization regime is an activation-type temperature dependence of the resistance and exponentially strong negative magnetoresistance. The magnetoresistance is well described by the theory of doubling of the localization length in quasi-1D conductors in strong fields; this provides a direct measurement of the localization length. [S0031-9007(97)03671-5]

PACS numbers: 72.15.Rn, 71.30.+h, 72.20.My

It is widely believed that all electron states in low-dimensional conductors are localized, however weak the disorder [1,2]. The scaling theory of localization makes a distinction between the weak localization (WL) regime and the strong localization (SL) regime. In the WL regime, the broadening of the electron energy levels due to the phase-breaking processes, $\hbar/\tau_\varphi$, is larger than the spacing between the levels, Δ_ξ, within a domain of a size ξ, the localization length. In this regime, the electron scatters inelastically to another state, localized around a different site, before it diffuses over the localization length. With decreasing temperature, the level broadening becomes smaller than the spacing between the levels, and eventually the electron transport can proceed only by hopping (the SL regime). However, within the length scale ξ the electron motion is still diffusive provided ξ is much greater than the mean free path of electrons l. In terms of competition between the length scales, the crossover from WL to SL occurs in low-dimensional conductors at a finite temperature $T = T_\xi$ when the phase-breaking length $L_\varphi(T) = (D\tau_\varphi)^{1/2}$ (D is the electron diffusion constant at the scale L_φ) becomes comparable to the localization length.

From the experimental viewpoint, the crossover from WL to SL has been studied in detail only in two-dimensional (2D) systems [3–7]. For a macroscopically homogeneous 2D conductor, the crossover is observable when the sheet resistance $R_\square$ approaches a universal value of $R_Q = 2\pi\hbar/e^2 \approx 30\ \mathrm{k}\Omega$. The 2D localization length $\xi_{2D} \sim l\exp(R_Q/R_\square)$ is of the order of the mean free path in this case. If $R_\square$ is well below R_Q, the energy level spacing at the length scale ξ decreases exponentially ($\Delta_\xi \propto \xi^{-2}$), and the crossover temperature becomes unattainably low.

The WL-SL crossover in quasi-1D MOSFET structures has been observed as a function of the gate voltage (for a review, see [8]). It would be interesting, though, to explore the transition from diffusive regime to hopping as a function of temperature, when the electron states are the same at the both sides of the crossover (in other words, for a fixed concentration of the carriers and disorder in a conductor). Such crossover has not been demonstrated in 1D conductors with the same clarity as in 2D conductors. Most of the data were obtained for granular or discontinuous narrow metal films, where charging effects can modify substantially the nature of the transition (see, for instance, [9,10]). The choice of *macroscopically homogeneous* quasi-1D conductors suitable for observation of the crossover is rather limited. The localization length in quasi-1D conductors,

$$\xi = \frac{\pi\hbar}{e^2}\frac{W}{R_\square} = 2\pi\hbar\nu D W \tag{1}$$

(ν is the 2D density of electron states), is huge in both the metal wires of any conceivable cross section (very large ν) and high-mobility semiconductor structures (very large D), resulting in the crossover temperatures T_ξ that are inaccessible. However, it is possible to increase T_ξ substantially by exploiting low-mobility semiconductor structures. We report in this Letter the first experimental observation of the crossover from weak to strong localization in quasi-1D conductors with decreasing the temperature and on the study of the activation transport in these conductors in the vicinity of the crossover.

We measured the temperature and magnetic-field dependences of the resistance of submicron-wide channels in Si δ-doped GaAs structures. A single δ-doped sheet of Si donors with concentration $\sim(3-5)\times10^{12}\ \mathrm{cm}^{-2}$ was placed 0.1 μm below the surface of an undoped GaAs layer which was molecular-beam epitaxy (MBE)-grown on a semi-insulating GaAs substrate. Narrow channels of different widths between 0.3 and 15 μm were defined by e-beam lithography, followed by ion etching. Because of side depletion the effective width W of the samples is smaller than the "geometrical" one by ~ 0.2 μm, and the narrowest samples studied had an effective width $W \approx 0.1$ μm. The mean free path of electrons in the δ-doped layers is small ($l \sim 20$ nm) due to the strong electron-ionized impurity scattering. The relatively high concentration of carriers ensures that the number of the occupied 1D subbands $N_{1\mathrm{D}} = k_F W/\pi \geq 10$ even in the narrowest samples. The electron motion along the width of the channels is diffusive; on the other hand, with respect to the quantum interference effects the samples are one dimensional at low temperatures $[W < \xi, L_\varphi(T)]$.

We report here the results from two samples (A and B). The samples comprise five "wires" 40 μm long which are connected in parallel; the effective width of the wires was 0.1 μm (sample A) and 0.2 μm (sample B). As will be shown below, all the samples with $W \leq 0.3$ μm demonstrate the crossover from weak to strong localization; wider samples with $W > 1$ μm remain in the WL regime down to the lowest $T \approx 50$ mK. Parameters of samples A and B are listed in Table I. A standard ac lock-in technique was used for resistance measurement; however, the measuring frequency was limited to 0.5 Hz to avoid errors due to parasitic capacitances because of the high sample resistance at low temperatures. We performed I-V measurements at a series of temperatures to make sure all data presented were taken at excitation voltages low enough to be in a linear I-V regime.

Temperature dependence of the resistance of sample A is shown in Fig. 1. At $T \gg T_\xi$, it is consistent with the theory of quantum corrections due to the weak localization and electron-electron interaction (EEI) effects [11]. For instance, at $T = 10$–70 K, where sample A is two dimensional with respect to the quantum effects ($W > L_\varphi, L_T$), its resistance can be fitted with the dependence

$$\frac{R(T) - R(30\ \mathrm{K})}{R(30\ \mathrm{K})} = C\,\frac{e^2 R_\square(30\ \mathrm{K})}{2\pi^2\hbar}\,\ln\!\left(\frac{30}{T}\right), \qquad (2)$$

$C \cong 4$, which is in accord with previously reported data on GaAs heterostructures with a high concentration of carriers [12].

Below the crossover temperature, the dependence $R(T)$ becomes exponential and can be fit with a simple activation law:

$$R(T) = R_0 \exp(T_0/T) \qquad (3)$$

TABLE I. Parameters of the samples.

Sample	$R_\square(T = 30\ \mathrm{K})$ (kΩ)	W (μm)	$T_0(H = 0)$ (K)	ξ (μm)	Δ_ξ (K)
A	3.5	0.1	1.47	0.37	1.1
B	4.2	0.2	0.39	0.61	0.34

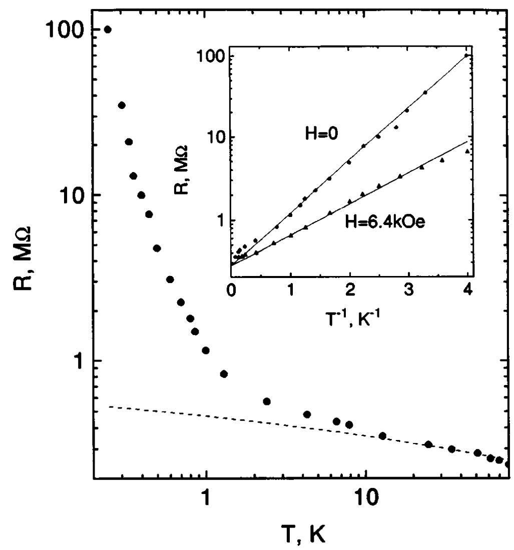

FIG. 1. The temperature dependence of the resistance of sample A in zero magnetic field. The dashed curve—the sum of the WL and EEI corrections to the resistance of a 2D sample with the same sheet resistance $R_\square = 3.5$ kΩ as that of sample A at $T = 30$ K [Eq. (2)]. The inset shows $\ln R$ versus $1/T$ for sample A at $H = 0$ (▲) and at $H = 6.4$ kOe (●). The straight lines correspond to the dependences $R(H = 0) = 0.28$ MΩ $\exp(1.47\ \mathrm{K}/T)$ and $R(H = 6.4\ \mathrm{kOe}) = 0.28$ MΩ $\exp(0.86\ \mathrm{K}/T)$.

(see the inset in Fig. 1). The values of T_0 at $H = 0$ are listed in Table I. For all the samples studied, the magnitude of the resistance at $T = T_0 \cong T_\xi$, calculated for a segment of wire of the length of ξ $[5R_0(\xi/L)$ for five wires connected in parallel] turns out to be 25 ± 3 kΩ, which is consistent with the resistance $\sim h/e^2$ expected of a 1D conductor of the length ξ in the vicinity of the crossover [1]. Below $T \sim 0.1$ K the increase of the resistance saturates, probably, because of the heating of electrons by the rf noise, which is difficult to avoid with high-resistance samples.

The magnetoresistance of our quasi-1D samples is negative over the whole temperature range. It is very anisotropic; we observed no magnetoresistance due to the H component parallel to the plane of the δ layer. The magnetoresistance becomes large exponentially in the SL regime (see the inset in Fig. 1); the activation energy $k_B T_0$ decreases in strong fields by a factor of ~ 2. In strong fields we also observe aperiodic fluctuations of the magnetoresistance whose amplitude increases with decreasing the temperature (see the inset in Fig. 2).

We address the question of whether our experiment agrees with the Thouless' requirement that the crossover to activated conductivity occurs at $L_\varphi(T_\xi) \cong \xi$. The temperature range, where the crossover is observed, agrees with the requirement. The phase-breaking length can be estimated at high temperatures ($T \geq T_\xi$) by fitting the magnetoresistance with the theory of suppression of the WL corrections by magnetic field [11]. (The detailed analysis of the high-temperature magnetoresistance will

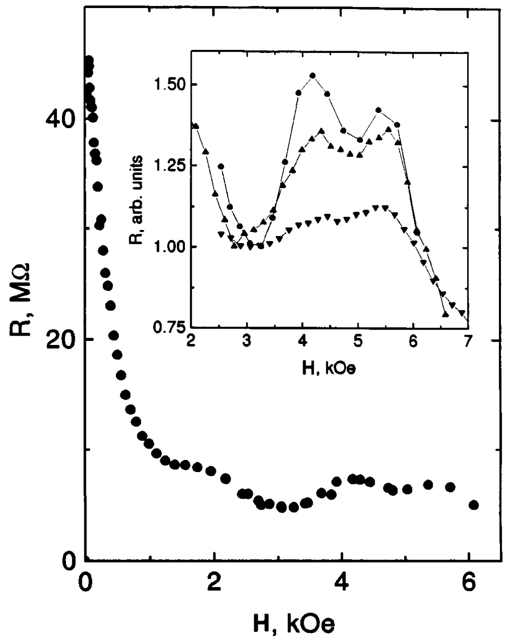

FIG. 2. The magnetic field dependence of the resistance of samples A at $T = 0.3$ K. The inset shows aperiodic fluctuations of the resistance in strong magnetic fields at different temperatures: ●—0.3 K, ▲—0.4 K, ▼—0.6 K.

be published elsewhere.) For example, the phase-breaking length L_φ for sample A increases from 0.05 ± 0.01 μm at 30 K to 0.2 ± 0.05 μm at 3 K. The high-temperature fit becomes progressively worse approaching the crossover, and the accuracy in estimating of L_φ decreases. Nevertheless, it is possible to conclude that at the crossover L_φ becomes comparable to the value of ξ calculated from Eq. (1) or estimated from the SL magnetoresistance (see below).

The activation energy $k_B T_0$ of the exponential dependence $R(T)$ is very close to the estimated values of the spacing between the energy levels of the localized electron states within the segment of a wire of the length ξ,

$$\Delta_\xi = (\nu \xi W)^{-1} \tag{4}$$

(see Table I). This suggests that the nearest-neighbor hopping between *strongly overlapping* electron states becomes the dominant transport mechanism in this "moderate" insulating regime (a segment of the wire of a size of $\xi x W$ is "shared" among $\sim 10^3$ localized electrons). It is worth mentioning that in the case of hopping between strongly overlapping electron states, charging effects should not play any significant role (in contrast to the case of granular films [10]). The experimental proof for that is provided by the study of nonlinear effects in the resistance of our samples; the nonlinear regime will be discussed elsewhere.

The available temperature range was too narrow to distinguish clearly between the activation law (3) and the variable-range hopping (VRH) law

$$R(T) \sim \exp(T_M/T)^{1/2}. \tag{5}$$

However, we believe that the VRH is irrelevant in the vicinity of the crossover. Fitting the experimental data with Eq. (5) gives the values of T_M an order of magnitude larger than the level spacing Δ_ξ. The activation energy for the hopping between spatially overlapping localized states cannot exceed Δ_ξ, unless there is a Coulomb gap in the density of states at the Fermi level. The estimate of the localization length from Eq. (5), $\xi = 4/\nu W k_B T_M$, also gives the values of the localization length 2–4 times smaller than that obtained from Eq. (1). It is noteworthy that the simple activation law (3) can be also expected for a long quasi-1D wire ($L \gg \xi$) deeply in the insulating regime, where fluctuations in the distribution of levels should result in exponentially strong fluctuations of the resistance of different hops [8,13,14].

All the features of the magnetoresistance observed in the SL regime are in accord with the theory of doubling of the localization length in quasi-1D conductors in strong magnetic fields [15–17]. The magnetoresistance is negative, as expected for quasi-1D conductors with weak spin-orbit scattering. The theory should apply to the moderate insulating regime where electrons move diffusively over a large distance $\sim\xi$, and the reason for the increase of ξ is the elimination of the coherent backscattering within the localization domain by the magnetic field (the same as for the suppression of the interference corrections in the WL regime).

Note that the prefactor R_0 in the experimental temperature dependence of the resistance (3) *is not affected* by the magnetic field (see the inset in Fig. 1). Hence we can interpret the observed magnetoresistance as the result of the magnetic-field dependence of the activation energy $T_0(H)/T_0(H = 0) = (T/T_0)\ln[R(H)/R_0]$. The dependences $T_0(H)/T_0(H = 0)$ measured for samples A and B at different temperatures below T_ξ are shown in Fig. 3. For each sample, the dependences collapse onto the same universal curve; deviations from this universal behavior, observed at low temperatures in strong fields, are due to

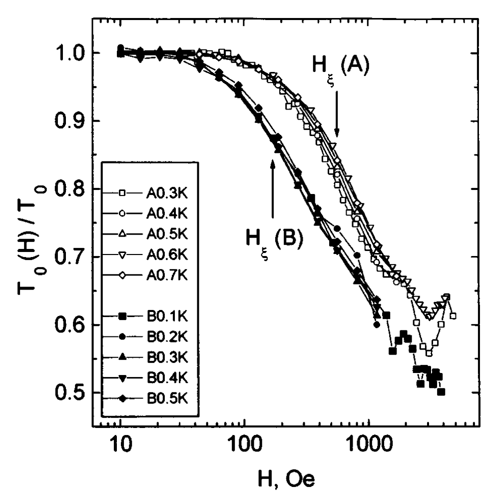

FIG. 3. The magnetic field dependences of the activation energy for samples A and B at different temperatures.

the mesoscopic fluctuations (see below). The doubling of the localization length should result in halving the activation energy for the nearest-neighbor hopping ($T_0 \sim \Delta_\xi \propto 1/\xi$), which is in accord with our data.

The observed difference in the characteristic magnetic fields for samples A and B is also in a good agreement with the theory [15–17]. The doubling of ξ occurs for $H \gg H_\xi$, where

$$H_\xi = \Phi_0/\xi W \tag{6}$$

is the field scale for breaking of the time-reversal symmetry within the area occupied by a localized state (Φ_0 is the magnetic flux quantum). The values of H_ξ calculated for samples A and B are shown as arrows in Fig. 3. Though it is obvious that the theory predicts the correct value of the characteristic field, it would be interesting to obtain the theoretical dependence $\xi(H)$ for all magnetic fields (only limiting values of ξ are available now). In this case the magnetoresistance experiment would give the direct and very accurate measurement of the localization length in quasi-1D conductors.

The experiment discussed above provides the first evidence of the doubling of the localization length in quasi-1D samples with weak SOS in strong magnetic fields. Previously the idea of the universal change of ξ in magnetic fields has been used for interpretation of the magnetoresistance of several 2D and 3D systems with variable-range hopping (see, for instance, [17–19]). Although the effects in higher dimensionalities could be qualitatively similar, the doubling of ξ could be expected only in the quasi-1D geometry; the scaling theory predicts the absence of a universal relation between $\xi(H = 0)$ and $\xi(H \gg H_\xi)$ for $d \geq 2$ [20].

We believe that observation of the magnetoresistance fluctuations in strong magnetic fields does not substantially change the proposed picture of the moderate insulating regime in quasi-1D conductors. Fluctuations of the resistance of different segments of wire are unavoidable on the insulating side of the crossover in 1D geometry. The length of our samples is much greater than the localization length, and far from the crossover, the resistance, probably, is dominated by a few "long" hops. However, the scattering of the resistances of individual hops is not exponentially large in the moderate insulating regime [21]. In addition, the importance of such anomalous hops is reduced by parallel connection of five "wires." As the result, the activation energy for all the samples turns out to be very close to the spacing between the electron energy levels Δ_ξ, and the amplitude of fluctuations $\Delta R/R(H \gg H_\xi)$ does not exceed ~ 0.5 even at low temperatures (see the inset in Fig. 2). With the increase of the magnetic field, the resistances of all the hops decrease exponentially due to the increase of the localization length. "Switching" between leading hops in strong fields results in fluctuations of the magnetoresistance [22], the "period" of fluctuations is comparable with the characteristic field H_ξ. This effect is similar to the switching of the leading hops with variation of the gate voltage V_g in experiments with gated 1D semiconductor channels (see [8,23], and references therein). In the last case, however, the resistance of each hop fluctuates exponentially with V_g, the resistance of a sample is dominated by a single hop in the strongly insulating regime, and switching between the leading hops results in the orders-of-magnitude fluctuations of the resistance.

This work has been supported in part by Russian Foundation for Basic Research Grant No. 96-02-18613, INTAS Grant No. 94-3862, and NSF Grant No. DMR-9623716 (H. M. B., A. G. M.). It is our pleasure to thank B. L. Altshuler, I. Aleiner, M. E. Raikh, and B. I. Shklovskii for helpful discussions. We thank B. K. Mikhailov for fabrication of the δ-doped GaAs layers. One of us (M. E. G.) would like to acknowledge the hospitality of Chalmers University of Technology where the e-beam patterning of the samples has been done.

*Electronic address: gersh@physics.rutgers.edu

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