Decoherence and the Thouless Crossover in One-Dimensional Conductors

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The temperature and magnetic-field dependences of the resistance of one-dimensional (1D) conductors have been studied in the vicinity of the Thouless crossover. We find that on the weak localization (WL) side of the crossover, these dependences are consistent with the theory of quantum corrections to the resistance, and the phase breaking is due to the quasi-elastic electron-electron interactions (the Nyquist noise). The temperature dependence of the phase coherence time \( \tau_\phi \) does not saturate, and the quasiparticle states remain well defined over the whole WL temperature range.

This fact, as well as observation of the Thouless crossover in 1D samples, argues against the idea of intrinsic decoherence by zero-point fluctuations of the electrons (Mohanty et al., Phys.Rev.Lett. 78, 3366 (1997)). We believe that frequently observed saturation of \( \tau_\phi(T) \) is caused by the external microwave noise.

Recently intrinsic decoherence in disordered conductors has been proposed [1]. It has been noted that many distinct experiments indicate a saturation of the phase coherence length \( L_\varphi \) at low temperatures. The authors of Ref. [1] suggested that this saturation is due to zero-point fluctuations of the electrons.

In this Letter, we present new data on the temperature dependence of \( L_\varphi \) in one-dimensional (1D) conductors in the vicinity of the Thouless crossover. The experimental values of \( L_\varphi \) are very well described by the theory of decoherence due to the quasi-elastic electron-electron scattering [2]. The temperature dependence of \( L_\varphi \) does not saturate down to the crossover temperature, and the maximum experimental values of the phase coherence time \( \tau_\phi \) exceed the limit suggested in [1] by a factor of 50. This fact, as well as previously reported observation of the temperature-driven Thouless crossover in these samples [3,4], contradicts the idea of decoherence by the zero-point fluctuations of the electromagnetic environment. We attribute the frequently observed saturation of \( L_\varphi \) to the phase breaking due to the external high-frequency noise [5]. Our samples are much less "sensitive" to the noise-induced decoherence because of a very high resistance, by a factor of \( \sim 10^4 \) greater than that for the Au wires studied in [1].

The temperature and magnetic-field dependences of the resistance have been measured for sub-micron-wide "wires" fabricated from the \( \delta \)-doped GaAs structures. Similar structures have been used to study the crossover from weak localization (WL) to strong localization (SL) in 1D conductors [6,7]. A single \( \delta \)-doped layer with concentration of Si donors \( N_D = 5 \times 10^{12} \text{cm}^{-2} \) is 0.1 \( \mu \text{m} \) beneath the surface of an undoped GaAs. The 1D wires were fabricated by electron beam lithography and deep ion etching. The samples consist of up to 500 wires connected in parallel; the length \( L \) of each wire is 500 \( \mu \text{m} \). A 50-\( \mu \text{m} \)-thin silver film deposited on top of the structure was used as a "gate" electrode: the electron concentration \( n \) and the resistance of the samples can be "tuned" by varying the gate voltage \( V_g \) (for more details, see [4]).

We discuss the results for a typical sample consisting of 360 wires of effective width \( W = 0.05 \mu \text{m} \). The values of \( W \), obtained from the sample resistance, are in accord with the estimate of \( W \) from the analysis of the WL magnetoresistance; it has been also verified that \( W \) does not depend on \( V_g \) [5]. Parameters of the sample at three different values of \( V_g \) are listed in Table 1. The mean free path of electrons \( l \) increases with \( n \) from 17 nm to 58 nm (\( k_F l \approx 6 \div 30 \)), where \( k_F \) is the Fermi wave number. A relatively high concentration of carriers ensures that the number of occupied 1D sub-bands \( N \) is large (\( \sim 10 \)), and the localization length \( \xi \sim Nl \) is much greater than \( l \). Two-dimensional expressions for the diffusion constant \( D \) and the density of states \( \nu \) are used because the broadening of energy levels due to the elastic scattering is greater than the spacing between the 1D sub-bands.

Table 1

| \( V_g, V \) | \( n \times 10^{-12} \text{cm}^{-2} \) | \( D(10K) \text{ cm}^2/\text{s} \) | \( \xi, \mu \text{m} \) | \( T_0(H = 0) \text{ K} \) |
|---|---|---|---|---|
| +0.7 | 4 | 250 | 1.1 | 0.7 |
| 0 | 2.7 | 90 | 0.35 | 2.2 |
| -0.35 | 2 | 52 | 0.15 | 4.6 |

The temperature dependences of the resistance for different \( V_g \) are shown in Fig. 1. As it will be shown below, behavior of \( R(T) \) at high temperatures is consistent with the theory of quantum corrections to the resistance (for...
a review, see [7]). The crossover from weak to strong localization emerges with decreasing the temperature. The activation-type temperature dependence of the resistance has been observed on the SL side of the crossover [8,9]. The crossover temperature \( T_0 \) that corresponds to the hopping activation energy in the SL regime is shown in Fig. 1 with arrows.

The phase coherence length \( L_\varphi \) has been estimated from the WL magnetoresistance. Experiments with 1D conductors [8] have demonstrated that phase breaking in 1D conductors at low temperatures is governed by the quasi-elastic electron-electron collisions, which is equivalent to decoherence by the equilibrium Nyquist-Johnson noise [2]. The procedure of extraction of \( L_\varphi \) from the WL magnetoresistance in this case has been described in detail in [11]. The high-temperature \(( T > T_0 )\) magnetoresistance has been fitted with the magnetic field dependence of the 1D WL correction to the resistance [11]:

\[
\frac{R(H) - R(0)}{R(0)} = \sqrt{2} \frac{e^2}{\pi \hbar \sigma_1} L_\varphi f \left[ 2 \left( \frac{L_\varphi}{L_{\varphi 0}(H)} \right)^2 \right],
\]

(1)

where \( L_{\varphi 0}(H) = \sqrt{D \tau_\varphi} \) is the magnetic length. However, if \( W \leq l \), \( \tau_H \) is larger than the estimate (2) due to the flux cancellation effect [12,13]. Numerical calculations [13] show that \( \tau_H \) exceeds the estimate (2) by factor 2.5 at \( l = W \) (this case corresponds to \( V_g = 0.7 \) V), by 1.2 at \( l = 0.5W \) \( (V_g = 0 \) V), and the difference is negligible for \( l = 0.3W \) \( (V_g = -0.35 \) V). The observed magnetoresistance is well described by Eq.1 over the whole range of fields where the Eq.1 is applicable, \( L_H > W \) (the insert in Fig.2). For the samples studied, strongly-inelastic decoherence processes can be neglected at \( T < 30K \) \( [L_\varphi << L_{\varphi 0}(H = 0)] \), and the only fitting parameter is the Nyquist length \( L_\varphi \). The temperature dependences of \( L_\varphi \) (Fig. 2) are in a good agreement with the theoretical result [11]:

\[
\tau_{\varphi 0}^{-1} + \tau_H^{-1}.
\]

It is noteworthy that Eq.1 differs from the expression for the 1D WL magnetoresistance [11] which is valid only for the strongly-inelastic phase breaking. The latter expression for the 1D WL magnetoresistance, which is often used for fitting the experimental data (see, e.g. [14]), does not hold if the quasi-elastic Nyquist phase breaking is the dominant decoherence mechanism.

For a “diffusive” \( (W >> l)\) 1D wire in a perpendicular magnetic field [11],

\[
\tau_H = \frac{12L_H^4}{D W^2},
\]

(2)

FIG. 1. Temperature dependences of the resistance at different \( V_g \). The crossover temperatures \( T_0 \) are shown with arrows.

FIG. 2. The phase coherence length versus temperature at different \( V_g \): \( \square - +0.7V; \bigcirc - 0V; \triangle - -0.35V \). Solid lines - Eq.3 calculated for a fixed \( D = D(T \simeq 4T_0) \); the dashed line - Eq.6. The insert shows the magnetoresistance at \( T = 8K \), \( V_g = 0V \); the solid line - Eq.1.
\[ L_\varphi(T) = \left( \frac{\hbar^2 D \sigma_1}{\sqrt{2e^2 k_B T}} \right)^{1/3} \propto T^{-1/3} \]  

(3)

over the whole temperature range that corresponds to the WL regime. The dependences (3) (solid lines in Fig.2) are extended down to the crossover temperature.

As \( T \) approaches \( T_0 \), the dependence \( L_\varphi(T) \) is flattened out. For all the samples studied, \( L_\varphi \) at the crossover temperature is 2-3 times smaller than the 1D localization length \( \xi = \pi h \sigma_1/e^2 \). The scaling theory of localization [4] predicts that the crossover occurs when \( L_\varphi \) becomes comparable with \( \xi \). However, one should not expect to observe the exact equality \( L_\varphi = \xi \) at \( T_0 \), because the crossover is due to both localization and interaction effects. The resistance of a wire segment of a length of \( \xi \) for this sample is \( \sim 20 \) k\( \Omega \) at \( T = T_0 \), which is also consistent with the quantum resistance \( h/e^2 \) expected at the crossover [3].

The temperature dependences of the resistance in the WL regime are also well described by the theory of quantum corrections. Figure 3 shows \( R(T) \) for \( V_g = +0.7 V \) in two cases: \( a) \) at \( H = 0 \), when both localization and interaction effects contribute to \( R(T) \), and \( b) \) at \( H = 17 \) kOe, when the temperature dependence of the WL correction is completely suppressed (\( L_H < l \)). The theoretical expression for \( R(T) \) due to the first-order quantum corrections can be written for \( H = 0 \) as follows [3]:

\[
\frac{R(T) - R_0}{R_0} = \frac{e^2}{\pi^2 h \sigma_1} \left[ \sqrt{2\pi} \cdot 1.37L_\varphi(T) + 4.91\alpha L_T(T) \right].
\]  

(4)

The first term in the square brackets is the asymptotic form of the WL correction (for our samples \( L_\varphi \ll L_{\varphi 0}(H = 0) \) at \( T < 30 \) K, and \( f(x) \approx 1.37 \) in Eq.1), the second term is the interaction correction, \( L_T = \sqrt{\hbar D/k_B T} \) is the thermal length. Two parameters have been used for fitting the experimental data at \( H = 0 \): \( R_0 = 16.5 \) k\( \Omega \) and the screening factor \( \alpha = 0.37 \). In strong fields, only the interaction term in Eq.4 with the same value of \( \alpha \) has been used for fitting \( R(T) \) [3]: we do not expect modification of \( \alpha \) in this magnetic field because the Zeeman splitting \( g \mu_B H \ll k_B T \) at \( T > 1K \) (\( g \)-factor is \( \sim 0.4 \) for the conduction band in GaAs). The best agreement with experiment at \( H = 17 \) kOe was obtained with a larger \( R_0 = 17.5 \) k\( \Omega \). We believe that the increase of \( R_0 \) is due to the classical positive magnetoresistance: \( (\omega_c \tau)^2 = 0.1 \) at \( H = 17 \) kOe (\( \omega_c \) is the cyclotron frequency, \( \tau \) is the elastic scattering time).

An excellent agreement with the theory of quantum corrections is observed down to \( T \approx 3T_0 \); at lower temperatures, the higher-order terms of both localization and interaction contributions to \( R(T) \) must be taken into account. As it has been shown earlier [3], the shift of the Thouless crossover toward lower temperatures in strong magnetic fields (\( L_H \ll \sqrt{\xi W} \)) is accompanied with doubling of the localization length [15], and halving of the hopping activation energy in the SL regime.

The observed dependences \( L_\varphi(T) \) oppose the idea of the decoherence due to zero-point fluctuations of the electrons. Indeed, the following expression for the "cut-off" decoherence time \( \tau_0 \) has been obtained for a 1D wire fabricated from a two-dimensional electron gas (2DEG) [1]:

\[
\tau_0 = \left( \frac{\pi \hbar^2}{m^* \sigma_1} \frac{\sigma_1 W}{e^2 \nu_{1D} D} \right)^2,
\]  

(5)

where \( m^* \) is the effective electron mass. The corresponding length scale \( L_0 \) coincides with the width of the wire:

\[
L_0 = (D\tau_0)^{1/2} = \frac{\sigma_1 W}{e^2 \nu_{1D} D} = W.
\]  

(6)

Here \( \nu_{1D} = m^* W / \pi \hbar^2 \) is the 1D density of electron states. The existence of the "cut-off" phase coherence length \( L_0 = W \) would imply that \( a) \) narrow channels fabricated from 2DEG cannot demonstrate 1D quantum corrections to the conductivity, and \( b) \) the localization-induced crossover should not be observed in such channels (in this case \( L_\varphi \) is always much smaller than \( \xi \gg W \)). This would also preclude observation of the interaction-driven 1D crossover with decreasing the temperature. Indeed, as soon as \( \tau_0 \) approaches \( \tau_0 \), the broadening of the electron energy levels, \( \hbar/\tau_0 \), becomes temperature-independent. The Fermi-liquid description of quasiparticle states should also break down at \( \hbar/\tau_0 > k_B T \).
Both consequences of Eq.6 contradict our data: we observe the Thouless crossover in 1D conductors with the ratio $\xi/W$ as large as 16, and the temperature dependence of $L_\varphi$ does not saturate down to $T_0$. The phase coherence length near the crossover exceeds the estimate (6) by a factor of $\sim 7$ for $V_0 = 0.7$ V; hence $\tau_\varphi$ exceeds $\tau_0$ by a factor of 50. Similar discrepancy between $\tau_\varphi$ and estimate (6) has been observed recently in Ref. 10.

What is the reason for frequently observed saturation of $L_\varphi(T)$? We believe that this saturation is due to phase breaking by the external microwave electromagnetic noise. The phase coherence is destroyed most efficiently by spectral components of this noise with the frequency $\omega \sim \tau_\varphi^{-1}$1117. The field amplitude $E_\varphi$, which is sufficient for phase breaking at the time scale $\sim \tau_\varphi$, can be estimated as $E_\varphi \simeq \hbar/eL_\varphi \tau_\varphi \propto \tau_\varphi^{-3/2}$1117. The electric field $E_\varphi$ is a linear function of $T$ for 1D conductors with the dominant Nyquist phase breaking. The following noise power is required for saturation of the $\tau_\varphi(T)$ dependence below some temperature $T$: 

$$P_\varphi = \frac{(L \cdot E_\varphi)^2}{2R} = R \left(\frac{e_k B T}{\hbar}\right)^2.$$  

(7)

This power is proportional to the total resistance $R$ of a wire. The Nyquist time is very short ($< 5 \cdot 10^{-12}$ s) in our highly-resistive samples ($R(4K) \approx 9 M\Omega$ for a single wire at $V_0 = 0.7$ V). As a result, the noise power required for phase breaking at this time scale is rather large: $P_\varphi \approx 10^{-9} \div 10^{-8}$W. However, for 1D Au wires with much smaller $R \simeq 0.3 \div 1.8 k\Omega$1117, $P_\varphi$ is only $1 \cdot 10^{-15} \div 1 \cdot 10^{-14}$W at $T = 0.1$K. This $P_\varphi$ is smaller than the power dissipated by the dc measuring current ($4 \cdot 10^{-14} \div 7 \cdot 10^{-13}$W), which has been experimentally proven not to heat the Au wires down to $T = 40 mK$1117. As it is shown in Ref. 19, balancing of the incoming microwave power $P_\varphi$ by the outcoming power due to the hot-electron outdiffusion into the ”cold” leads should result in a negligible rise of the electron temperature for any 1D conductor with $R \ll h/e^2 = 25.8 k\Omega$. In this situation, the microwave noise can efficiently destroy the phase coherence of the electron wavefunction without heating the electron gas. This explains why a well-pronounced temperature dependence of the resistance (due to the interaction effects) has been observed at temperatures where the dependence $L_\varphi(T)$ was already completely saturated 1117.

To summarize, we show that both the temperature and magnetic field dependences of the resistance of 1D conductors are well described by the theory of weak localization and interaction effects on the ”metallic” side of the Thouless crossover. The observed temperature dependence of the phase coherence length is consistent with the Nyquist decoherence mechanism 1117 and does not saturate down to the crossover temperature $T_0$. Our data indicate that the quasiparticle description holds over the whole WL temperature range. In the vicinity of $T_0$, the experimental values of $\tau_\varphi$ exceed $\tau_0$ by a factor of 50. This fact, as well as observation of the Thouless crossover in our 1D samples, argues against the idea of decoherence by zero-point fluctuations of the electrons 1117. Frequently observed low-temperature saturation of the $L_\varphi(T)$ dependence can be attributed to decoherence due to the external electromagnetic noise.

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