Microwave-Induced Dephasing in One-Dimensional Metal Wires

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We report on the effect of monochromatic microwave (MW) radiation on the weak localization corrections to the conductivity of quasi-one-dimensional (1D) silver wires. Due to the improved electron cooling in the wires, the MW-induced dephasing was observed without a concomitant overheating of electrons over wide ranges of the MW power $P_{MW}$ and frequency $f$. The observed dependences of the conductivity and MW-induced dephasing rate on $P_{MW}$ and $f$ are in agreement with the theory by Altshuler, Aronov, and Khmelnitsky [1]. Our results suggest that in the low-temperature experiments with 1D wires, saturation of the temperature dependence of the dephasing time can be caused by an MW electromagnetic noise with a sub-pW power.

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The processes of dephasing of electron wave function are central to the electronic transport in mesoscopic systems [2]. The dominant low-temperature dephasing mechanism in low-dimensional conductors is the scattering of an electron by equilibrium fluctuations of the electric field in the conductor, i.e. the Nyquist (Johnson) noise [3]. The Nyquist dephasing time $\tau_\varphi$ increases with decreasing temperature as $T^{-2/3}$ in the quasi-one-dimensional (1D) conductors with the cross-sectional dimensions much smaller than the dephasing length $L_\varphi = \sqrt{D\tau_\varphi}$ ($D$ is the electron diffusion constant) [4]. In the 1D metallic wires, this mechanism typically governs the dephasing at $T < 1$K [4, 5, 6].

Recently, the interest in the fundamental limitations on $\tau_\varphi$ was invigorated by the reports on the saturation of $\tau_\varphi(T)$ dependences in one- and zero-dimensional systems at ultra-low temperatures (see, e.g. [7, 8]). The experiments [7, 9, 11] demonstrated that, at least in some studied 1D wires, this saturation could be attributed to the presence of localized spins in a small concentration undetectable by analytical methods. However, the problem of $\tau_\varphi(T)$ saturation in the most “clean” samples remained open [9, 7]. One of the “extrinsic” mechanisms that might lead to the saturation of $\tau_\varphi(T)$ is the dephasing by the external microwave (MW) electromagnetic noise [1]. Detection of a very weak MW noise that is sufficient to destroy the phase coherence at ultra-low temperatures is a challenge. Indeed, the MW-induced dephasing may occur without an easily-observable electron overheating if the electrons in a wire can efficiently dissipate their energy in the environment [10, 12, 13, 14]. The possibility of “noise-dephasing-without-overheating” has not been ruled out in the experiments [9, 7, 11].

In this Letter, we study the dephasing by monochromatic microwave radiation in 1D wires. By optimizing the sample design, we minimized electron overheating and observed for the first time the microwave-induced dephasing in 1D wires without a concomitant overheating of electrons. The dependences of the MW-induced dephasing rate on the MW power and frequency are in agreement with the theoretical predictions [1]. Our results suggest that the $\tau_\varphi(T)$ dependence in a 1D wire may be significantly affected by a sub-pW power of an external microwave noise absorbed in the sample.

The challenging aspect of the experiments on MW-induced dephasing is the separation of this effect from a trivial MW-induced electron overheating, which also leads to the dephasing enhancement [12, 13, 14]. An efficient cooling of the electrons is crucial for this separation. The amplitude of the MW electric field $E_{MW}$ that leads to a strong MW-induced dephasing within the optimal frequency range $\omega\tau_\varphi \sim 1$ can be estimated from the condition $eE_{MW}L_\varphi \sim \hbar$. The corresponding MW power is proportional to the wire length $L$:

$$P_\varphi \equiv (E_{MW}L)^2/R = \frac{\hbar^2 L}{D\tau_\varphi^2 R_1 e^2}. \quad (1)$$

FIG. 1: WL magnetoresistance measured at $T = 0.2$K for different values of the microwave power $P_{MW}$ of radiation with $f = 1$GHz. The solid lines correspond to the power range $P_{MW} < 5 \cdot 10^{-12}$W where electron overheating is negligible; the dashed lines - to the power range $P_{MW} > 5 \cdot 10^{-12}$W where electron overheating by MW radiation becomes significant. The microphotograph of a portion of the sample is shown in the inset.
in our samples) is much greater than the raphy and thermal evaporation of Ag (purity 99.9999%).

\[ \Delta R_{EEI}(T) = \frac{e L_{\varphi} R_1}{\pi h} \left( T_e^2 - T^2 \right) \] (2)

is inversely proportional to 1. Thus, in sufficiently short wires, 1 can be dissipated without overheating. However, short wires with a small total resistance are more susceptible to the overheating by external electromagnetic noise. Also, a large amplitude of universal conductance fluctuations in short wires reduces the accuracy of extraction of 1 from the weak localization (WL) magnetoresistance. We resolved this dilemma by attaching the cooling fins to a long wire (L=1200 μm) wire (see the inset in Fig. 4). These fins provide the heat sinks for the hot electrons in the wire and improve significantly the electron cooling. At the same time, the cooling fins do not affect the 1D WL correction to the conductivity provided the spacing between them (L*≈30 μm in our samples) is much greater than L_{\varphi} (≈ 4.5μm at T = 0.05K for the studied wires).

The 1D silver wires were fabricated by e-beam lithography and thermal evaporation of Ag (purity 99.9999%). Similar results have been obtained for several samples; below the data are presented for a wire with the width W = 69 nm, thickness d = 20 nm and the diffusion constant D = 110 cm²/s. The resistance was measured by the ac resistance bridge at the frequency 13 Hz over the temperature range 0.05 – 1K. Special care was taken to reduce the MW noise level in the dilution refrigerator by installing low-pass filters in all lines at the top of the cryostat and at the cold finger near the sample. The central and outer conductors of the broad-band (f = 0 – 26 GHz) coaxial cable were coupled to the sample via 5-nF DC block capacitors. For suppressing the external MW noise and room-temperature thermal radiation, the cable was interrupted by two 20-dB attenuators at T = 4K and 1K.

The evolution of the WL magnetoresistance with 1, measured at a fixed bath temperature T = 0.2K, is shown in Fig. 4. The positive magnetoresistance observed in weak magnetic fields for the studied wires is due to the field-induced suppression of the WL corrections to the resistivity in the presence of strong spin-orbit scattering (the so-called weak antilocalization, see, e.g., [20]). Over a wide range of 1 (∼ 20dB), the only observable change in the MR is a decrease of the amplitude of the B = 0 “dip” associated with an increase of the dephasing rate. Within this range, the dependences R(B) outside the dip are not affected by radiation, which indicates that the electrons remain in equilibrium with the bath. The electron overheating at 1 > 10^{-11}W leads to the decrease of R in strong magnetic fields (L_H ≪ L_{\varphi}(T), where L_H = √h/(2eH) is the magnetic length), which is associated with the temperature dependence of the electron-electron interaction correction to the conductivity 2:

\[ \frac{\Delta R_{EEI}(T)}{R} = \frac{e^2 L_T R_1}{\pi h} \] (3)

where \( L_T = \sqrt{hD/k_B T} \).

We have used the measurements of ∆R_{EEI}(T, P) [Fig. 2] for an estimate of the electron temperature T_e [21]. The dependence ∆R_{EEI}(T) was also used for calibration of the microwave power dissipated in the wire. In these measurements the electrons were overheat a fixed bath T either by the dc current I_{dc} or by the MW radiation. The decrease of the resistance, ∆R, was recorded (a) as a function of the dc power P_{dc} = I_{dc}^2 R at P_{MW} = 0 and (b) as a function of P_{MW} at P_{dc} = 0 (see the inset in Fig. 2). Assuming that the heating by the total current is the same as that by MW radiation in the limit \( f ≪ (2\pi\tau)^{-1} \) (\( \tau ≈ 10^{-15} \) s is the momentum relaxation time in our wires), one can estimate the MW power dissipated in the sample [22].

The dephasing time \( \tau_{\varphi} \) was extracted from the magnetoresistance (MR) using the theoretical expression for the 1D WL MR modified for the case of strong spin-orbit scattering. 

\[ S(T, B) = S_0 \left( 1 + \beta T_e^2 / T^2 \right) \] (4)
FIG. 3: Dependences of the conductivity \(\Delta \sigma/\sigma(B = 0)\) on the normalized MW power \(\alpha\), measured at 0.5 K at different frequencies [1GHz (○), 0.5GHz (▲), 0.2GHz (■)]. The theoretical dependences (Eq 7) calculated for these frequencies are shown by the solid curves. The inset shows the dependences \(\tau_\varphi(T)\) measured with no intentionally applied monochromatic MW radiation for the wire coupled to the coaxial cable with one “cold” 20dB attenuator (○) and two “cold” 20dB attenuators connected in series (▲). The dashed line shows the T-dependence of the Nyquist dephasing time (Eq 6), the solid curves - fitting by Eq. 5 with \(\alpha = 15\)ns (3.8ns) for 20dB (40dB) attenuation.

\[
\Delta R_{WL} = \frac{e^2 L_2 R_1}{\pi h} \left[ \frac{3}{2} \text{Ai}(\tau_\varphi/\tau_H) - \frac{1}{2} \text{Ai}(\tau_\varphi/\tau_H) - \frac{1}{2} \text{Ai}(\tau_\varphi/\tau_H) \right].
\]

(4)

Here \(\tau_H = \frac{12 L_2}{2 \pi e^2} \), \((\tau_\varphi^{-1})^{-1} = \tau_\varphi^{-1} + \frac{3}{2} \pi^2 \), \(\text{Ai}(x)\) is the Airy function. The temperature dependences of \(\tau_\varphi\) measured with no intentionally applied monochromatic MW radiation are shown on the inset in Fig. 3. These dependences can be fitted with the expression

\[
\tau_\varphi^{-1} = \tau_\varphi^{-1} + \tau_0^{-1},
\]

(5)

where \(\tau_\varphi\) is the Nyquist dephasing time.

\[
\tau_0 = \frac{h^2}{e^2 k_B T R_1 \sqrt{D}}.\]

(6)

We have observed that the \(T\)-independent “cut-off” term \(\tau_0\) increased from 1.5 ns to 3.8 ns with the attenuation in the MW line being increased from 20dB to 40dB. Presumably, this \(\tau_0\) increase reflects suppression of the MW noise delivered to the sample by the MW line (see below).

On Fig. 3 we compare the observed \(P_{MW}\)-induced increase of \(\sigma(B = 0)\) with the theoretical prediction [1]:

\[
\Delta \sigma = \frac{2 e^2 \sqrt{D}}{h \sqrt{\pi \omega}} \int_{\omega r}^\infty \frac{dx}{\sqrt{x}} \exp[-\alpha f(x)] - \frac{2x}{\omega \tau_\varphi} |I_0(\alpha f(x))| (7)
\]

Here \(\alpha = \frac{2 e^2 D (E_{MW})^2}{h^2 c^2} \), \(\omega = 2\pi f\) is the angular frequency of MW radiation, \(I_0\) is the Bessel function of an imaginary argument. In calculating the theoretical dependences \(\Delta \sigma(\alpha, \omega, \tau_\varphi)\) in Fig. 3 we took into account that the electron overheating at large \(P_{MW}\) e.g., \(P_{MW} > 10^{-11}\) W at \(T = 0.2 K\) leads to the decrease of \(\tau_\varphi\): \(\tau_\varphi(P_{MW})\) was calculated from the measured dependences \(\tau_\varphi(T, P_{MW} = 0)\) (the inset in Fig. 3) and \(T(P_{MW})\) (Fig. 2). Our experimental data are in quantitative agreement with the theory [1] over a broad range of \(P_{MW}\). Note that after the electric field in the wire has been determined experimentally, no fitting parameters are involved in the comparison between the data and the theory.

A more intuitive (though less rigorous [2]) way to interpret the MW-induced change in the WL contribution is to associate it with the MW-induced increase of the dephasing rate (see, e.g., [11, 12]):

\[
\tau_\varphi^{-1}(P_{MW}) = \tau_\varphi^{-1}(T_e, P_{MW}) - \tau_\varphi^{-1}(T_e).
\]

(8)

Here \(\tau_\varphi^{-1}(T_e)\) and \(\tau_\varphi^{-1}(T_e, P_{MW})\) are the dephasing rates at \(P_{MW} = 0\) and \(P_{MW} \neq 0\), respectively. When the electron overheating becomes significant at large \(P_{MW}\), \(\tau_\varphi(T_e)\) rather than \(\tau_\varphi(T)\) should be used in Eq. 8. Figure 4 shows the dependence of the MW-induced dephasing rate on the normalized MW power \(\alpha\) at \(f = 1 GHz\). It is worth mentioning that for the studied wires with optimized electron cooling, the difference between the values of \(\tau_\varphi^{-1}(P_{MW})\) calculated with \(\tau_\varphi(T_e)\) and \(\tau_\varphi(T)\) remains small even at high MW power levels: e.g., this difference does not exceed 30% at \(\alpha = 50\) (\(P_{MW} = 10^{-8}\) W at \(f = 1 GHz\). The dependence \((2\pi f\tau_\varphi)^{-1})\) shown in Fig. 4 is in good agreement with the estimate for \(\tau_\varphi^{-1}(P_{MW})\) obtained for optimal frequency \(f \sim \tau_\varphi^{-1}\) at \(\tau_\varphi(P_{MW}) \ll \tau_\varphi(T_e)\): [3]

\[
\tau_\varphi(P_{MW}) = \omega^{-1} \left\{ \begin{array}{ll}
(45/2\alpha)^{1/5}, & \alpha \gg 1 \\
\alpha^{-1}, & \alpha \ll 1.
\end{array} \right.
\]

(9)

In particular, at \(\alpha \gg 1\), the observed dependences approach the asymptotic behavior \((2\pi f\tau_\varphi)^{-1} \propto \alpha^{-1/5}\). The inset in Fig. 4 shows how the range of \(P_{MW}\), where the MW-induced dephasing is observed without electron overheating, depends on the MW frequency at \(T = 0.2 K\). \(\Delta P_{MW}\) represents the ratio of \(P_{MW}\) that causes a measurable increase of dephasing rate (5 \(\Omega\) increase of \(R\) at \(B = 0\), see Fig. 1) to \(P_{MW}\) that caused a noticeable increase of \(T_e\) (5 \(\Omega\) decrease of \(R\) at \(B = 3 \) kG). Note that the ratio is independent of the (frequency-dependent) coupling of the wire to MW radiation. The “MW-induced-dephasing-without-overheating” was observed over \(\sim 1.7\) decades of \(P_{MW}\) within the range \(f = 0.5 - 1 GHz\). “Shrinking” of the \(\Delta P_{MW}\) range for both higher and lower \(f\) is consistent with the prediction [3] that the MW-induced dephasing is most efficient at \(f \sim \tau_\varphi^{-1}(T)\). Note that the characteristic fre-
The MW noise power dissipated in the wire is of the order of $10^{-13}$ W when the wire is connected to the coaxial cable with two 20-dB attenuators (this power is equivalent to $P_{ac} = 3nA$), see Fig. 2. Assuming that the MW noise spectrum is peaked within the frequency range most efficient for dephasing ($f \sim \tau_{\phi}^{-1} \sim 1\text{GHz}$), one can estimate the noise-induced “cut-off” of the dephasing time $\sim 10\text{ ns}$. This cut-off is close to the value of $T$-independent term $\tau_0$ in Eq. 5. Thus, we conclude that the saturation of dephasing time observed in our experiment at $T \leq 0.1\text{ K}$ may be caused by an insufficient screening of the sample from the external microwave noise, including the Nyquist noise from all elements of the measuring set-up.

In summary, we observed for the first time the microwave-induced dephasing in 1D metal wires without a concomitant overheating of the electrons. The key requirement for observation of this effect is the optimization of electron cooling in 1D wires. The observed dependences of the weak-localization correction to the conductivity on the microwave power and frequency are in a quantitative agreement with the theory 4. Our experiments demonstrate that an ultra-low-noise environment is essential for the experiments on fundamental limits of dephasing time at low temperatures.

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