циклотронной частоте. При увеличении подвижности осцилляции усиливались с ростом мощности падающей волны, и при низких температурах сопротивление (для холловских образцов) или проводимость (для корбиновских образцов) исчезали [3, 4] в конечных интервалах магнитного поля, рис. 2. Реализация таких «бездиссипативных состояний» вызвала лавину теоретических работ. Предложенные в литературе сценарии позволяют качественно понять ряд важных особенностей обсуждаемых эффектов, но удовлетворительное объяснение в настоящее время отсутствует.

В конце 2003 г. в аналогичной системе обнаружен [5] еще один тип осцилляций магнитосопротивления, индуцированных СВЧ-излучением, рис. 3, и периодических по B, рис. 4, который объяснен возбуждением краевых магнитоплазмонов.

Доклад посвящен обзору полученных в этой области экспериментальных результатов и попыток их теоретического осмысления. Работа поддержана грантами РФФИ и ОФН РАН.

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Puzzles of low-temperature electron dephasing

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As early as in 1984, studying weak localization correction to the conductivity of In_2O_{3-x} films Ovadyahu [1] has found a puzzling behavior of the electron dephasing time τ_φ as a function of the static disorder. Namely, for a given temperature τ_φ^{-1} was scaled with a sample conductivity. This result contradicts the naive considerations that the disorder should lead to an increase of any scattering rate. While the similar behavior was predicted by Schmid [2] for electron-phonon scattering in dirty metals, in the experiments of [1] such a mechanism was ruled out by the observed temperature dependence of τ_φ ($\sim 1/T$ at temperatures about

10 K). To the best of our knowledge, the behavior has not obtained a relevant explanation until now.

Recently the question seems to arise again in relation to the problem of apparent low temperature saturation of the weak localization dephasing rate which has been extensively discussed during last years, for a review e. g. Ref. [3] Namely, the correlation [3, 4] between the "saturated" dephasing rate, τ_φ^{-1}, and the diffusion constant D was reported.

This report aims to show that the correlation mentioned above can be explained within a framework of the model of tunneling states (TS) proposed in Ref [5] and considered in detail in Ref. [6]. According to this model, the dephasing is produced by dynamical structural defects with two (or more) configurations with very close energies. Due to interaction with a thermal bath these defects switch between the above states producing time-dependent fields acting upon the electrons.

There exist two mechanisms of electron dephasing due to dynamic defects. The first one is induced by direct inelastic transitions between the levels of the TS leading to a possibility of determining the actual path of the electron, and consequently to loss of interference. The second one is due to relaxation dynamics of dynamic of TSs, which fluctuate due to interaction with the thermal bath. Time dependence of the electron scattering crossection due to the defects fluctuations leads to violation of the time-reversal symmetry and, as a consequence, to decoherence. The effective Hamiltonian of a TS,

$$\tilde{\mathscr{H}}_{\mathrm{d}} = (\Delta\,\sigma_3 - \Lambda\,\sigma_1)/2\,, \tag{1}$$

is characterized by the asymmetry, Δ, and the tunneling matrix element, Λ. Since these parameters are random, their distribution, $\mathscr{P}(\Delta, \Lambda)$, is crucially important. In crystalline materials, it is naturally to assume that the TSs keep intrinsic crystal symmetry. As a result, the Λ-distribution is limited from above by some value Λ_0. To keep the model simple it is sufficient to assume that $\mathscr{P}(\Delta, \Lambda) \propto \delta(\Lambda - \Lambda_0)$.

To evaluate the distribution over Δ let us assume [5] that the distribution is due to some mesoscopic disorder around a generically symmetric defect and consider adiabatic renormalization of the site energy ε_1 of one of TS component due to conduction electrons scattered by some defect i, [5]

$$\varepsilon_{1i} = V_1 \Re\left[\sum_{\mathbf{k}} \frac{f_i(\theta)}{R_{1i}} \frac{e^{ikR_{1i}(1-\cos\theta)}}{1 + e^{(\varepsilon_{\mathbf{k}} - \varepsilon_F)/k_B T}}\right] .$$

Here $\theta = \angle\{\mathbf{k}, \mathbf{R}_{1i}\}$, f_i is the scattering amplitude by the ith defect, $\mathbf{R}_{1j}$ is the vector connecting the sites 1 and i, while V_1 is the potential of the defect 1. This

correction is due to Friedel oscillations of the electron density induced by the defect i. Assuming that the scattering potentials for the defects 1 and i are the same we get an order-of-magnitude estimate for this quantity as

$$\varepsilon_{1i} \approx -\frac{|V|^2}{\varepsilon_F} \frac{\cos(2k_F R_{1i})}{(k_F R_{1i})^3} .$$

Now let us consider a TS formed by the site 1 and some state 2, such as $R_{12} \ll R_{1i}, R_{2i}$. Then the effective two-level system acquires the diagonal splitting $\Delta_i \equiv (\varepsilon_{1i} - \varepsilon_2)$ given by the expression

$$\Delta(\mathbf{R}_i, \mu) \approx \frac{2|V|^2}{\varepsilon_F} \frac{\sin(k_F R_{12}\mu) \cdot \sin(2k_F R_i)}{(k_F R_i)^3} . \tag{2}$$

Here $\mathbf{R}_i = \mathbf{R}_{1i} \approx \mathbf{R}_{2i}$, $\mu = \cos\angle\{\mathbf{R}_{12}, \mathbf{R}_i\}$. The probability to find a TS with the splitting Δ is then

$$W(\Delta) = 2\pi n_d \int R^2\, dR \int_{-1}^{1} d\mu\, \delta\left[\Delta - \Delta(\mathbf{R}, \mu)\right] . \tag{3}$$

Here n_d is the density of defects, while $\Delta(\mathbf{R}, \mu)$ is given by Eq. (2). The density of TSs is given as $\mathscr{P}(\Delta) = N_{TS} W(\Delta)$ where N_{TS} is the density of TSs. Note that the integral in Eq. (3) is determined by $R \lesssim N_D^{-1/3}$ since the contributions of different defects have quasi-random signs, the main contribution being due to the nearest defect.

A straightforward analysis shows that there is a characteristic energy

$$E^* = \frac{|V|^2 n_d}{\varepsilon_F k_F^3} \approx \frac{1}{2\pi} \frac{\hbar}{\tau_{el}} \sim \frac{\hbar v_F^2}{D} \tag{4}$$

where τ_{el} is the elastic mean free time. At $\Delta \gg E^*$ the probability $W(\Delta)$ decays $\propto E^*/\Delta^2$, while at $\Delta \lesssim E^*$ the function $W(\Delta)$ is smooth. As a result, we arrive to the model for the density of TSs adopted in Ref. [6],

$$\mathscr{P}(\Delta, \Lambda) \approx (N_{TS}/E^*)\, \delta(\Lambda - \Lambda_0) . \tag{5}$$

As shown in Ref. [6], the two of the contributions to the dephasing rate τ_φ^{-1} can be estimated in the relevant temperature region as

$$\tau_{\varphi,in}^{-1} \sim \tau_\Lambda^{-1} = \nu_{TS}(\Lambda_0/E^*) \tag{6}$$

for "inelastic" channel and

$$\tau_{\varphi,e}^{-1} \sim \tau_{\Lambda}^{-1}(T\tau_{\Lambda}/\hbar)^{1/3} \tag{7}$$

Thus the resulting rate can be written as an interpolation

$$\tau_{\varphi}^{-1} = \tau_{\Lambda}^{-1}\left[\alpha(T\tau_{\Lambda}/\hbar)^{1/3} + \zeta\right]. \tag{8}$$

Here ν_{TS} is the effective collision frequency with the tunneling defects, α and ζ are constants of the order 1. Since $\tau_{\Lambda}^{-1} \propto D$ we conclude that for a fixed number of tunneling defects the "saturated" dephasing rate *increases* with the diffusion constant D, the corresponding dependence of τ_{φ}^{-1} tends to direct proportionality when the two items in Eq. (8) are comparable.

To make estimated we rewrite the expression for ν_{TS} in the form

$$\nu_{TS} = \sigma_e^{\mathrm{d}} v_F n_d \tag{9}$$

where σ_e^{d} is the cross-section of elastic electron scattering by a dynamic defect. Correspondingly, the key parameter of our theory, τ_{Λ}, is given as

$$\tau_{\Lambda}^{-1} = \Lambda_0 P_d \sigma_{\mathrm{in}} v_F \tag{10}$$

where $P_d = n_d/E^*$ is the density of states of the dynamic defects.

The density of states P_d can be, in principle, estimated for a given material on the base of point contact measurements. Namely, metallic point contacts are known to exhibit, first, telegraph resistance noise[7] and, second, zero-bias anomalies [8]; both effects are expected to be associated with the dynamic defects [7, 8, 5].

Although we appreciate that the material preparation procedure can significantly affect the defect system, we believe that such experiments can provide more or less reasonable estimates for P_d. The telegraph noise studies [7] for Cu nanoconstriction with a size of $\sim$ 10 nm revealed a presence of about several dynamic defects at energies less than 10 mV. This would give us the value $P_d \sim (3{-}5) \times 10^{32}$ erg^{-1}cm^{-1}. However, the telegraph noise is related to TLS with rather slow relaxation rates ($\lesssim 10^3$ s^{-1}) while we are interested in the defects with switching times of the order of 10^{-9} s. Consequently, these estimates most probably significantly *underestimate* P_d. What is more instructive, the magnitude of the resistance noise revealed rather large defect asymmetry corresponding to the estimate $\sigma_{\mathrm{in}} \sim \sigma_e^{\mathrm{d}} \sim 10^{-15}$ cm^2.

We believe that the zero bias anomalies can give more reliable information concerning P_d. The magnitude of these anomalies for Cu nanoconstrictions[8]

of the same type as mentioned above corresponds to a presence of several tens of TLS at the energy region about 1 meV [8, 5]. Correspondingly, one obtains $P_d \sim (3-5) \times 10^{34}$ erg^{-1}cm^{-3}.

Basing on these estimates and taking $P_d \approx 10^{34}$ erg^{-1}cm^{-3}, $\sigma_{\text{in}} \approx 10^{-15}$ cm^2, $v_F \approx 10^8$ cm/s, and $\Lambda_0 \approx 10$ mK we obtain $\tau_\Lambda \approx 10^{-9}$ s. Equations (9) and (10) yield $T_\Lambda \simeq \Lambda_0$. Thus at temperatures larger than $T_\Lambda \approx \Lambda_0 \approx 10$ mK one expects, according to Eq. (8), temperature-independent contribution of resonant processes.

For the relaxation channel, one obtains $T_\alpha \approx T_\beta \approx 10$ mK. Consequently, at $T \gtrsim T_\alpha \approx T_\Lambda \approx 10$ mK one expects that dephasing rate obeys Eq. (8) with $\tau_\Lambda \approx 10^{-9}$ s.

Now let us check if our assumption $\Lambda_0 \approx 10$ mK realistic. We will exploit a crude estimate

$$\Lambda_0 \simeq \frac{\hbar\omega_0}{\pi} \exp\left(-\frac{2}{\hbar}\int_0^a dr\,\sqrt{2MU(r)}\right) \tag{11}$$

where $U(r)$ is a potential relief between the two stable defect positions separated by a distance a, and M is the defect mass. Taking as an example $U(r) = (U_0/2)\,[1-\cos(2\pi r/a)]$ one obtains for the exponent $(2a/\pi\hbar)\sqrt{2U_0M}$. Taking for a light defect $\omega_0 \approx 10^{14}$ s^{-1} and assuming $a \approx 10^{-8}$ cm, $U_0 \approx 0.2$ eV one estimates that the value $\Lambda = 10$ mK is achievable for $M \approx 2 \times 10^{-23}$ g which corresponds to atomic weight ≈ 10.

Summarizing our estimates, we can conclude that for realistic parameters of the dynamic defects one can indeed expect a slow temperature dependence of the dephasing rate given by Eq. (8) crossing over to a rapid decrease at low temperatures. The crossover temperature, as well as the behavior below than that temperature, depends on the distribution of Λ. For a delta-like distribution of Λ the TLS spectrum has a gap of Λ_0. Thus the TLS contribution to dephasing rate is exponentially frozen out at for $T < \Lambda_0$, and we are left with the "standard" mechanisms like electron-electron scattering. However for the Gaussian distribution of Λ with the variance $\bar{\lambda} \gg 1$ the situation is different. In this case the cut-off temperature is given by the renormalized tunneling coupling, $\Lambda_0 e^{\bar{\lambda}}$ while for lower temperatures one deals with rather flat distribution of λ within the region $\lambda \leq \lambda_0 + \bar{\lambda}$. Correspondingly, at these temperatures one deals with a glass-like TLS distribution for which $\tau_\varphi \propto T^{-1}$.

One notes that the correlation between the dephasing rate and diffusion coefficient does not depend on the fact of "saturation" of dephasing. It depends only on the two assumptions: (1) the density of dynamic defects is given, (2) the density of states is proportional to $1/E^*$ where the scatter of the defect energies E^* is controlled by the disorder. Consequently, if the two factors mentioned above are at the stage, the correlation between τ_φ^{-1} and the diffusion constant D should

exist not only in the region of "saturated" dephasing. Here we return to the results obtained for three-dimensional low-resistivity In_2O_{3-x} films [1] where the observed temperature behavior of τ_φ corresponded to $\tau_\varphi^{-1} \propto T$. We would like to note that the systems in question, first, exhibited rather strong disorder (the elastic mean free times as small as $(2-5)\cdot 10^{-15}$ s), second, some particular disorder was expected to be related to oxygen non-stoheometry distribution. These systems are expected to be some different from the ones where the saturation of dephasing was typically studied (see e.g. [3, 4]) and which we mostly had in mind in our paper [6]. First, in the case of In_2O_{3-x} there is a probable candidate to the role of the mobile defects — oxygen atoms, the number of relevant ones is expected to be fixed for a given x. Then, the large degree of disorder makes it possible to expect that the barriers for the "mobile" defects are also affected. In particular, the expected magnitude of the Friedel oscillations is also expected to be much larger than for typical metallic crystals and their effect on the barriers can be significant. As a result, the potential for the "mobile" atoms can be equivalent to the "glassy" one allowing in particular "soft" configurations with weak barriers. If so, the relaxation rates for the TLS are expected to have a temperature behavior typical for glasses — $\tau^{-1} \propto T$ — although at the same time the density of states is still scaled with a degree of disorder. These considerations explains the experimental results by Ovadyahu [1].

To conclude, we have demonstrated that the model of tunneling states formed by light defects in crystalline conductors and affected by electronic mesoscopic disorder can explain both of the puzzles mentioned above — that is low temperature saturation-like behavior of the dephasing and the correlation between the dephasing rate and the static disorder.

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