Quantum lifetime of two-dimensional electrons in a magnetic field

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Phys. Rev. B **85**, 115312 — Published 20 March 2012

DOI: 10.1103/PhysRevB.85.115312

Quantum lifetime of 2D electron in magnetic field

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(Dated: March 9, 2012)

Positive magnetoresistance of two-dimensional electrons in GaAs quantum wells placed in weak quantizing magnetic fields is observed. From comparison of the magnetoresistance with theory quantum lifetime of 2D electrons is determined in broad range of temperatures from 0.3 K to 20 K. The temperature variation of the inverse electron lifetime is in good agreement with conventional theory of electron-electron scattering and correlates with the rate of energy relaxation of 2D electrons.

PACS numbers: 72.20.My, 73.43.Qt, 73.50.Jt, 73.63.Hs

I. INTRODUCTION

Transport properties of 2D electrons, placed in quantizing magnetic fields, attract a great deal of attention for its fundamental significance. Despite a long history[1], the research in this direction is still active and very surprising. Significant progress has been made during the last decade in understanding the nonlinear properties of the 2D electrons in crossed electric and magnetic fields. In response to both microwave radiation and *dc* excitations, strongly nonlinear electron transport[2–39] that gives rise to unusual electron states[40–49] has been reported and investigated. Very recent experimental studies of the strongly nonlinear resistance in the low frequency domain[12,24–26] show that the dominant mechanism of the nonlinearity is related to a peculiar quantal heating ("inelastic" mechanism[35]), which may not increase the broadening of electron distribution ("temperature") in systems with discrete spectrum[24,25]. Microwave studies of this nonlinearity[22] indicate the relevance of another nonlinear mechanism: electric field induced variations in the kinematics of electron scattering on impurities ("displacement" mechanism[27,28,34]), which limits the lifetime of an electron in a quantum state.

The electron quantum lifetime τ_q has been measured in many experiments[1] and is an important property of two dimensional systems[50]. The standard transport method to measure the electron lifetime is based on an extraction of the Dingle factor from temperature or magnetic field dependences of the amplitude of Shubnikov-de-Haas (SdH) oscillations. This method works well at low temperatures, at which the Dingle factor is nearly temperature independent. Application of this method to higher temperatures is considered to be problematic, since it involves a separation of unknown, small temperature variations of the Dingle factor from strong variations of SdH amplitude with the temperature. Moreover theoretical investigations indicate that despite the fact that the electron-electron scattering affects the electron quantum lifetime it does not change the amplitude of the quantum resistance oscillations[51–54]. Thus the standard method is not applicable to study the electron-electron scattering, which, as shown below, is the dominant mechanism reducing the electron lifetime with the temperature. Another limitation is the high sensitivity of the standard method to spatial fluctuations of the electron density due to long range variations of the bottom of the conducting band. The density variations induce spatial variations of the period of the SdH oscillations. It decreases the total SdH amplitude, but does not change the electron lifetime. Finally at high temperatures, the SdH oscillations are absent and, thus, the standard method does not work.

Recently several transport methods have been introduced to access the temperature dependence of the quantum electron lifetime τ_q. Electric field[21] and microwave[22] induced magnetoresistance oscillations show that the amplitude of the oscillations depends on temperature. At $T > 2K$ variations of the quantum scattering time τ_q are found to be temperature dependent. At temperature below 2K the dependence saturates, indicating an electric-field-induced overheating. The overheating may create very peculiar electron distributions[24] and is a restriction of this method. The quantum electron lifetime τ_q was recently accessed through the amplitude of magnetophonon resistance oscillations[55,56]. However the method depends on the rate of electron-phonon scattering and, therefore, requires high temperatures.

In another transport experiments[57–59], which are done on multi-subband electron systems, the temperature dependence of the quantum lifetime τ_q was extracted from quantum contributions to the magnetoresistance[34,60,66]. Despite the fact that the magnetoresistance may be affected by other scattering mechanisms (such as classical magnetoresistance, memory effects etc) in multi-subband electron systems the magnetoresistance demonstrates magneto-inter-subband oscillations (MISO)[60], which set a scale of the quantum contributions and, thus, facilitate significantly the interpretation of experimental data. In single subband electron systems the oscillating quantum contribution is absent and the application of this transport method is challenging.

In this paper we describe an application of the trans-

port method based on the quantum magnetoresistance to electron systems with the single band occupation and study the quantum positive magnetoresistance[34] at different temperatures. Both positive and negative magnetoresistance were observed in 2D electron systems[61–65], however the quantum contribution to the magnetoresistance has not been identified in those works. In a very recent experiment on a two-subband electron system, the quantum positive magnetoresistance[66] and the classical magnetoresistance were separated[67].

The positive magnetoresitance is induced by the quantized (periodic) motion of electrons in magnetic fields. Due to the circular motion, a scattered electron may return to the same impurity repeatedly, enhancing the total scattering amplitude. The stronger the magnetic field, the larger the probability for the electron to return to the same impurity. Thus, the scattering rate increases with the magnetic field, giving rise to the positive magnetoresistance[34].

We have found good agreement between our experiment and the theory in a broad range of magnetic fields. Comparison with the theory yields the quantum lifetime of 2D electrons τ_q. At small temperatures T the inverse electron lifetime (quantum scattering rate) is found to be proportional to T^2 and deviates from the T^2 above 15 K. The temperature dependence agrees very well with the conventional theory of electron-electron scattering at zero magnetic field in broad range of temperatures from 0.3 K to 20 K. The comparison yields the electron screening vector q_s, which is close to the Thomas-Fermi value q_{TF} for these electron systems. Good agreement is found also between contributions of the electron-electron scattering to the quantum scattering rate $1/\tau_q$ and the rate of inelastic electron relaxation $1/\tau_{in}$, which is obtained on the same sample by different method[24].

II. EXPERIMENTAL SETUP

Our samples are high-mobility GaAs quantum wells grown by molecular beam epitaxy on semi-insulating (001) GaAs substrates. The width of the GaAs quantum well is 13 nm. Two AlAs/GaAs type-II superlattices grown on both sides of the well served as barriers, providing a high mobility of 2D electrons inside the well at a high electron density[68]. One sample was studied with electron density $n = 8.2 \times 10^{15}$ m^{-2} and mobility $\mu =$ 93 m^2/Vs. Another sample with comparable parameters shows similar results. In this paper we show results for the first sample.

The studied 2D electron system is etched in the shape of a Hall bar. The width and the length of the measured part of the sample are $d = 50\mu m$ and $L = 250\mu m$. A 12 Hz alternating current is applied through current contacts formed in the 2D electron layer. The longitudinal *ac* voltage V_{xx} is measured between potential contacts displaced $250\mu m$ along each side of the sample. The Hall voltage V_{xy} is measured between potential contacts displaced $50\mu m$ across the electric current.

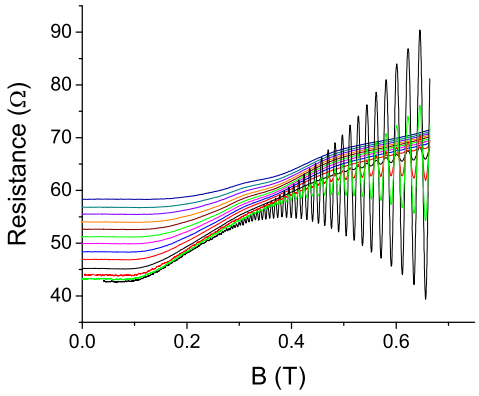

FIG. 1: (Color online) Resistance versus magnetic field at different temperatures from the bottom to the top: 2.25K, 2.98K, 3.75, 4.71K, 5.94, 6.95K, 7.96K, 8.85K, 9.80K, 10.73K, 11.75K, 12.66K, and 13.70K.

The current contacts are sufficiently separated from the measured area by a distance of $500\mu m$, which is much greater than the inelastic relaxation length of the 2D electrons $L_{in} = (D\tau_{in})^{1/2} \sim 1 - 5\mu m$. This ensures that the experiments are done at thermal equilibrium and the distribution of the electric current is uniform across the samples. The longitudinal and Hall voltages were measured simultaneously, using two lockin amplifiers with 10 MΩ input impedances. The potential contacts provided insignificant contribution to the overall response due to small values of the contact resistance (about 1kΩ) and negligibly small electric current flowing through the contacts.

Measurements were carried out for discrete temperature values in the range of 0.3 to 20 Kelvin in a He-3 insert in a superconducting solenoid. Samples and a calibrated thermometer were mounted on a cold copper finger in vacuum. Magnetic fields were applied perpendicular to the 2D electron layers and sweeps were made at each temperature over the range of zero to 0.7 Tesla.

III. RESULTS AND DISCUSSION

Figure 1 shows the magnetoresitance of 2D electrons taken at different temperatures. All curves demonstrate a similar behavior. At small magnetic fields (B <0.1 T) the curves show extremely weak (unrecognizable in the present scale) dependencies on the magnetic field. At higher magnetic fields, the resistance increases. Not shown in figure 1 is the trace at the lowest temperature T=0.3K, which indicates that the resistance increase correlates with the quantization of the electron spectrum. Namely, the positive magnetoresistance (taken at T >2K) starts at the magnetic field at which the quantum (SdH) oscillations are first observed at T =0.3 K.

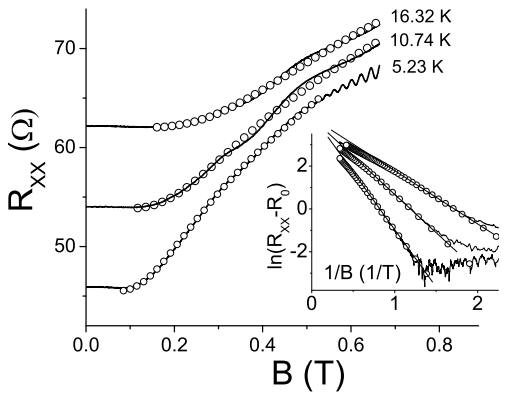

FIG. 2: Comparison between experiment (solid lines) and theory (open circles) at different temperatures as labeled. Insert shows the data plotted vs inverse magnetic field $1/B$, indicating exponential growth of the magnetoresistance at small magnetic fields.

The positive magnetoresistance and its temperature dependence are the main targets of the experiments. Below we compare the resistance increase with the interference enhancement of impurity scattering in the quantizing magnetic fields[34]. At even higher magnetic fields the magnetoresistance shows quantum oscillations, which depend strongly on the temperature. The oscillations are beyond the scope of this paper.

Figure 2 shows the positive magnetoresistance in better detail and demonstrates a comparison with theory[34]. The theory considers 2D electrons, which are moving in magnetic field and scattered by a rigid disordered potential. Due to circular electron motion in magnetic field, electrons scattered by an impurity may return to the impurity again and again, enhancing the total scattering amplitude. The stronger the magnetic field, the more probable it is for the electron to return to the same impurity. A quantitative account of the interference of quantum amplitudes, corresponding to different electrons returns, shows the positive magnetoresistance[34]:

$$R(B) = R_0 \cdot [1 + 2(e^{-\alpha} + e^{-2\alpha}(1-\alpha)^2)] \qquad (1)$$

, where $\alpha = 2\pi/(\omega_c \tau_q)$, ω_c is cyclotron frequency and R_0 is a resistance at zero magnetic field.

Although the theory is developed for a broad range of temperatures, it considers the elastic impurity scattering to be dominant in the electron dynamics. Equation (1) was derived in the absence of electron-electron and electron-phonon interactions ignoring possible temperature effects on the magnetoresistance. Presented in fig.1 data show considerable variations of the magnetoresistance with the temperature. In accordance with eq.1 the electron lifetime τ_q is the leading parameters affecting the shape of magnetoresistance. In comparison with the theory we consider the time $\tau_q(T)$ to be the dominant temperature dependent variable. While the exponential terms will likely contain a simple combination of quantum disorder scattering rate and electron-electron scattering rate, there is a possibility that prefactor α in the last term of Eq. (1) depends only on disorder scattering time. In the paper the parameter α is used as a single fitting parameter for all terms in eq.1. The possible overestimation of the electron lifetime is below 3%.

The best correspondence with the theory is obtained for the following fitting function:

$$R(B,T) = R_0(T) + 2R_D(e^{-\alpha} + e^{-2\alpha}(1-\alpha)^2) \qquad (2)$$

, where the resistance at zero magnetic field $R_0(T)$ and a "Drude" resistance R_D are additional fitting parameters. The resistance R_0 takes into account all scattering events responsible for the conductivity, whereas resistance R_D accounts only the scattering, which is responsible for the quantum positive magnetoresistance. Thus the fitting procedure excludes effects of electron-phonon scattering, which reduce the electron transport scattering time τ_{tr} at zero magnetic field and, most likely, do not change the quantum interference enhancement of the impurity scattering in strong magnetic fields [34]. The parameter R_0 absorbs also all other scattering processes, which do not contribute to the quantum positive magnetoresistance. Figure 2 demonstrates the comparison with the theory at three different temperatures. Good agreement is obtained in a broad range of magnetic fields. The insert shows the magnetoresistance plotted against inverse magnetic field $1/B$, indicating the exponential growth of the resistance, which is consistent with eq.1 at $\alpha \gg 1$. The exponentially strong enhancement of the scattering rate at the small magnetic fields provides an immunity of the utilized procedure with respect to possible smooth resistance variations of yet unidentified origin.

Presented in figure 2, comparison with the theory yields the quantum scattering time (electron lifetime) τ_q. Figure 3 shows the temperature dependence of the quantum scattering rate $1/\tau_q$. The dependence is plotted vs the square of the temperature. The plot indicates quadratic variations of the quantum scattering rate $1/\tau_q$ with the temperatures below 15 K. Shown in the figure the dashed straight line approximates the T^2 dependence:

$$1/\tau_q(GHz) = 201 + 1.05 \cdot T^2(K^2) \qquad (3)$$

The T^2 dependence suggests that the electron-electron scattering is the dominant mechanism, reducing the electron lifetime. In accordance with conventional theory[71–73] at zero magnetic field the $e-e$ scattering rate is

$$\frac{1}{\tau_{ee}} = \frac{\pi(kT)^2}{4\hbar E_F} \cdot ln(\frac{\hbar q_s v_F}{kT}) \qquad (4)$$

, where k is Boltzmann's constant, E_F and v_F are Fermi energy and velocity and q_s is screening wave vector. A

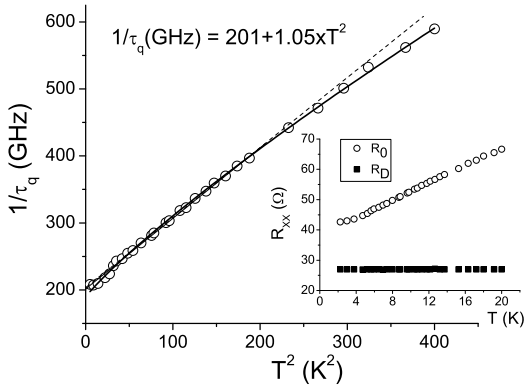

FIG. 3: Temperature dependence of the quantum scattering rate $1/\tau_q$ (open circles) plotted vs T^2. Dashed line presents a linear fit of the temperature dependence at $T < 15$K. Solid line presents expected temperature dependence due to electron-electron scattering (see eq.(4)). Insert shows parameters $R_0(T)$- open circles and $R_D = 27$ (Ohm)- black squares, which are used to compare data shown in fig.1 with eq.(2).

comparison of the temperature dependence of the $1/\tau_q$ with the theory is shown in figure 3 by the solid black line. The comparison utilizes the screening wave vector q_s as the only fitting parameter. The screening waver vector is found to be $q_s = 1.82 \cdot 10^8$ (1/m), which is very close to the Thomas-Fermi screening wave vector in 2D, given by $q_{TF} = 2me^2/(\epsilon\hbar^2) = 1.96 \cdot 10^8$ (1/m), where $\epsilon = 12.9$ is the GaAs lattice dielectric function. Thus variations of the electron lifetime with the temperature are in good agreement with the theory of electron-electron scattering at zero magnetic field[71–73].

Current accuracy of the experiment at T <15 K does not allow to distinguish the exact T^2 dependence of the quantum scattering rate $1/\tau_q$ from the one given by eq.(4). The T^2 dependence is predicted theoretically for the rate of inelastic relaxation $1/\tau_{in}$ of non-equilibrium electron distribution at low temepratures $T < \hbar\omega_c(\omega_c\tau_{tr})^{1/2}$ (see eq. (37) and eq.(42) in Ref.[35]). Observed temperature dependence of the inelastic relaxation rate[24] is in agreement with the theory. The T^2 behavior of the inelastic relaxation is the result of a modification of electron screening in strong magnetic fields at a distance $d \sim (D/\omega_c)^{1/2}$, where $D = (v_F)^2/(2\omega_c^2\tau_{tr})$ is the diffusion coefficient in strong magnetic fields. At this scale there is a change in the dynamics of electron propagation from a ballistic motion at short distances $r < d$ to a "ballistic diffusion" at long distances $r > d$[35]. Shown in figure 3 agreement between experiments and theory at zero magnetic field (see eq.(4)) indicates that possible variations of electron lifetime τ_q due to the change of the electron dynamics in weak quantizing magnetic fields are small.

The insert in figure 3 presents dependences of the parameters R_0 and R_D on the temperature. The parameter R_0 is very close to the actual resistance $R_{xx}(T)$ at zero magnetic field. The parameter R_D was found to be temperature independent fluctuating at $R_D = 27$ Ohm. Data shown in figure 3 are obtained at fixed $R_D = 27$ Ohm[74].

On a qualitative level the temperature dependence of the electron-electron scattering rate is consistent with results obtained by other research groups. All recent experiments demonstrate the T^2 dependence of the $e-e$ scattering rate: $1/\tau_{ee} = \lambda T^2/E_F$, where coefficient $\lambda \sim 1$ varies between research groups, methods and/or samples. Physical parameters (E_F, v_F, q_s) affecting the e-e scattering rate in eq.(4) may vary from sample to sample. In addition Fermi liquid corrections to the $e-e$ scattering rate may be essential. In this sense the variation of the parameter λ between samples and different methods are expected. Below we compare the obtained electron-electron scattering rate $1/\tau_{ee}$ with the rate of the inelastic relaxation $1/\tau_{in}$ obtained by a different method on the same sample[24]. We also compare these results with theory. In the comparison theoretical expressions for $e-e$ scattering rate have the same physical parameters and one should expect a correlation between electron-electron scattering rates obtained by different experimental methods and corresponding theoretical estimations.

In accordance with eq.(3),(4) the rate of the electron-electron scattering at low temperatures is $1/\tau_{ee} = 1.05 \cdot T^2$(GHz). Measured on the same sample the inelastic relaxation time τ_{in} is shown in fig.6a of Ref.[24]. The inelastic relaxation rate follows the T^2 dependence. The particular value of the rate depends on the form of the density of states (DOS) used for a comparison with the theory[35]. For Gaussian DOS the inelastic rate is found to be $1/\tau_{in}^G = (0.56 \pm 0.05) \cdot T^2$ (GHz) whereas for SCBA density of state the rate is $1/\tau_{in}^{SCBA} = (0.96 \pm 0.15) \cdot T^2$ (GHz). A theoretical evaluation of the inelastic relaxation rate $1/\tau_{in}$ uses eq.(42) and eq.(37) in Ref.[35]. At magnetic field B=0.15 (T) and $q_s = 1.82 \cdot 10^8$ (1/m) the estimated value $1/\tau_{in}^{th} = 0.88 \cdot T^2$(GHz). Thus the experimental and theoretical values of the inelastic relaxation rate $1/\tau_{in}$ are consistently smaller than the rate of electron-electron collisions $1/\tau_{ee}$ limiting the electron lifetime.

Figure 4 shows the temperature dependence of transport scattering rate $1/\tau_{tr}$. The dependence is obtained from the resistivity at zero magnetic field. At all temperatures the transport scattering rate $1/\tau_{tr}$ is much smaller than the quantum scattering rate $1/\tau_q$. The functional form of the temperature dependence of the transport scattering rate $1/\tau_{tr}$ is different from the T^2 dependence of the quantum scattering rate $1/\tau_q$, shown in figure 3. The main reason for the difference is that electron-electron collisions preserve the total momentum of electron system and do not contribute directly to the resistance. Electron collisions, nevertheless, transfer an electron from one quantum state to another states, decreasing the lifetime of the electron in a given quantum state.

It is accepted that the electron-phonon interaction is

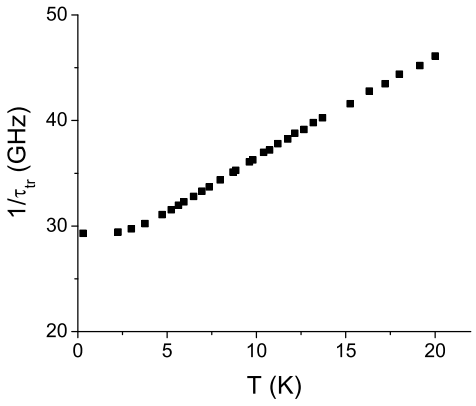

FIG. 4: Temperature dependence of transport scattering time τ_{tr}.

the dominant mechanism of the temperature dependence of the transport scattering time τ_{tr} in GaAs quantum wells[55,75]. Figure 4 shows that at T =20 K the phonon contribution to the electron scattering rate is about 15 GHz. This value is significantly smaller than the rate of electron-electron scattering $1/\tau_{ee}(T = 20K) \approx 370$ GHz shown in figure 3. The comparison emphasizes ones again the dominant contribution of the $e-e$ scattering to the electron lifetime at low temperatures.

IV. LIMITATIONS OF THE METHOD

The comparison presented above indicates very good agreement between experiment and theory[34]. Extracted from analysis, the quantum scattering rate $1/\tau_q$ is consistent with measurements by other methods[24]. The temperature variations of the electron-electron scattering rate are in accord with the conventional theory[71–73].

Below we discuss reasons for complimentary agreement between experiment and the theory of the positive magnetoresistance as well as possible limitations of the method. A difficulty of the practical implementation of the method to general systems is a contribution of other mechanisms to the magnetoresistance, which are beyond the theory[34]. The theory considers the disordered potential in Self-Consistent Born Approximation (SCBA)[76]. Within the SCBA the scattering events are uncorrelated.

Different theories, accounting for correlations in electron scattering (non-markovian or memory effects) indicate a wide-ranging variety of possible behavior of the magnetoresistance[77–79]. A quantitative account of all possible effects may create difficulties for applications of the presented method, since some parameters significant for these theories may not be known *a priori*. A good practical indication of the small contribution of such effects to the electron transport is the absence of the magnetoresistance at small magnetic fields, at which Landau levels are not formed yet ($\omega_c\tau_q \ll 1$). In accordance with classical (Drude) theory, which ignores correlations in electron scattering, the magnetoresistance must be absent in one valley conductors[80]. This is the case for our samples (see figure 5). Indeed, the magnetoresistance is very small at B <0.07 Tesla at which the electron spectrum is not quantized.

In contrast recently a giant negative magnetoresistance is found in high mobility electron systems[81–85]. The origin of this effect is not completely understood. A presence of two types of disorder (non-Gaussian disorder[79]) is considered as a possible explanation of the phenomenon[82]. Additional investigations are required to separate different mechanisms of the magnetoresistance, which are expected in a general case.

Below we estimate contributions of effects of the correlated scattering and correlated disorder to the magnetoresistance in our samples. As a first step we have to evaluate the correlation length of the disorder ξ. In high mobility samples the electrically charged donors are displaced from conducting layer by a distance l. Inside the conducting layer the displaced electric charges create a weak and smooth fluctuating electric potential with correlation length $\xi \approx l$. The potential induces the small angle scattering of electrons. An electron needs many scattering events to relax (randomize) it's original momentum. As a result the transport scattering time τ_{tr}, describing the relaxation of the electron momentum, is much longer than the quantum scattering time τ_q, which is an average time between two successive scattering events. Due to the scattering the direction of electron momentum performs a diffusive like motion with a typical step $\theta_0 \sim \hbar/(p_F\xi) \ll 1$, where p_F is electron momentum. During the transport scattering time τ_{tr} an electron scatters about $N = \tau_{tr}/\tau_q$ times by the disorder potential and changes it's direction by $(\Delta\theta)^2 = \theta_0^2 \cdot N \sim 1$. Thus $\tau_q/\tau_{tr} \approx \theta_0^2 = (\hbar/(p_F\xi))^2$[34]. The ratio of these two times provides an estimation for the correlation length of the disordered potential ξ. In our samples the quantum scattering time at T=2K is about 5 (ps)(see fig.3), whereas the sample conductivity at zero magnetic fields yields transport scattering time of τ_{tr} =32 (ps). Thus the disorder correlation length is about $\xi \sim (\hbar/p_F) \cdot (\tau_{tr}/\tau_q)^{1/2} = 11$ (nm).

Figure 5 presents effects of correlated disorder and correlated scattering on the magnetoresistance in our sample. In accordance with the theory a smooth disorder provides two distinct contributions to the resistivity[79]:

$$\frac{\Delta\rho_{xx}}{\rho_0} = -(\frac{\xi}{R_c})^2 + \frac{2\zeta(3/2)}{\pi}(\frac{\xi}{l_{tr}})^3(\frac{l_{tr}}{R_c})^{9/2} \qquad (5)$$

, where l_{tr} is mean free path of electrons moving in the smooth disorder and R_c is cyclotron radius. In eq.(5) the first term is due to a bending of electron trajectories within the correlation length ξ. The second term is associated with a classical memory effect due to the circular motion of electrons in a magnetic field[86]. In fig-

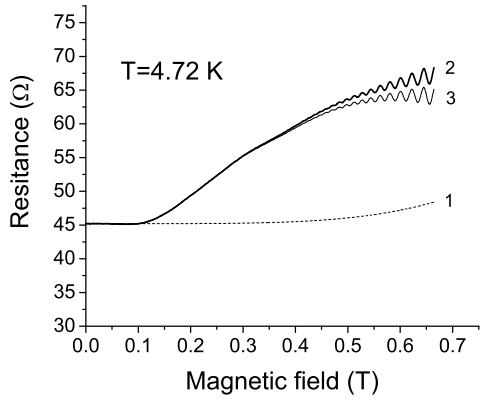

FIG. 5: Thin curve (1) shows contributions of correlated disorder and scattering to magnetoresistance. The curve (1) is plotted in accordance with eq.(5). Curve (2) presents experimental data for the magnetoresistance at T =4.72 K. Curve (3) in difference between curve (2) and curve (1), indicating negligibly small effect of the correlated disorder on the magnetoresistance below 0.3 Tesla.

ure 5 the line (1) shows the contributions of correlated disorder to classical magnetoresistance, which is plotted in accordance with eq.(5) for correlation length $\xi = 11$ (nm). A thick solid line (2) shows experimental results at T=4.72K. The thin solid line (3) is a difference between upper (2) and lower (1) curves, demonstrating the magnetoresistance without contribution of the classical memory effects. Below B=0.3 T curves (2) and (3) are indistinguishable, indicating very small contribution of the correlated disorder to the resistivity.

At B=0.15T the magnetic length $\lambda = 66$ (nm) is considerably longer the correlation length of the disorder $\xi = 11$ (nm) and SCBA works well for most part of scattering events. Thus the theory[34], accounting for the interference contribution of returning paths near this magnetic field, provides the leading contribution to the magnetoresistance.

V. CONCLUSION

The paper presents a simple transport method to access the electron lifetime τ_q of two-dimensional electrons in quantizing magnetic fields in broad temperature range. For two-dimensional electrons in GaAs quantum wells, the temperature variations of the quantum scattering rate $1/\tau_q$ are found to be proportional to the square of the temperature at T <15 Kelvin and are in very good agreement with the theory taking into account electron-electron interactions in 2D systems.

Acknowledgments

S. A. Vitkalov thanks Science Division of CCNY, CUNY Office for Research and NSF (DMR 1104503) for the support of the experiments. A. A. Bykov thanks the Russian Foundation for Basic Research, project no. 11-02-00925.

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