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Single particle and electron–electron scattering rates in coupled quantum wells

Y. Berk [a], A. Kamenev [b], A. Palevski [a,*], H. Shtrikman [b], M. Slutzky [a]

[a] *School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel*
[b] *Department of Condensed Matter, The Weizmann Institute of Science, Rehovot 76100, Israel*

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Abstract

We have studied experimentally single-particle (small angle) and electron–electron scatterings in coupled double-quantum well systems. These scattering rates were determined by analysis of the resistance resonance (RR) effect in the in-plane magnetic field. We have demonstrated that the values for single-particle scattering rate are in fair agreement with Shubnikov–de Haas data, and that electron–electron scattering rates are consistent with theoretical calculations.

Keywords: Electrical transport; Gallium arsenide; Heterojunctions; Quantum effects; Quantum wells; Tunneling

1. Introduction

The resonant coupling of electrons in double quantum wells (QWs) leads to delocalization of electronic states in such systems. It was demonstrated experimentally [1,2] that this quantum mechanical phenomenon strongly influences the electrical resistance of QWs measured in parallel, giving rise to a "resistance resonance" (RR) peak when QWs have different mobilities. Recently, it was demonstrated [3,4] that the in-plane magnetic field suppresses the coupling between electronic states. The microscopic description of the lateral magnetoresistance of the coupled QWs was developed and verified [4] by the experimental data. Some microscopic parameters, namely coupling energy Δ, and single-particle (or small angle) scattering time τ incorporated in the theory were estimated, but not independently experimentally verified, in the above-mentioned investigation. In this paper we present extensive experimental studies of magnetoresistance in double QWs in different limits of quantum mechanical coupling between QWs, mobilities and temperature. These measurements are supplemented by the analysis of Shubnikov–de Haas (SdH) oscillations in a perpendicular magnetic field, which allows us to deduce independently the parameters used in the theory. The main points arising from our studies are:

(1) The in-plane magnetic field destroys the coupling between QWs; the lineshape of the magnetoresistance fits the microscopic formula with a single-particle scattering time being the only fitting parameter.

(2) The width (i.e. the characteristic magnetic field H_c) of the RR is sensitive to the single-electron scattering time, providing a new method of

* Corresponding author. Fax: +972 3 6422979; e-mail: apalev@ccsq.tau.ac.il.

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measuring the small-angle scattering time on the remote impurities.

(3) The dependence of H_c on temperature at elevated temperatures, and on Fermi energy, suggests that the electron–electron scattering rate (intralayer and interlayer) may also be tested.

A detailed diagrammatic calculation, based on the Kubo formula [4] leads to the following dependence of the resonance resistance R on the in-plane magnetic field H (H is perpendicular to the direction of the excitation current j)

$$R^{-1}(H)-R_{\text{off}}^{-1}=(R^{-1}(0)-R_{\text{off}}^{-1})f(H/H_c), \tag{1}$$

where

$$f(x)=\frac{2(\sqrt{1+x^2}-1)}{x^2\sqrt{1+x^2}}, \tag{2}$$

and the characteristic field is given by

$$H_c=\frac{\hbar c}{e}\frac{1}{v_F\tau b}\sqrt{1+\left(\frac{\Delta}{\hbar}\right)^2\frac{\tau_1^{\text{tr}}+\tau_2^{\text{tr}}}{2}\tau}, \tag{3}$$

with $2\tau^{-1}\equiv\tau_1^{-1}+\tau_2^{-1}$. The above relations are valid until $H\approx H_F$, where $H_F\equiv 2\pi\hbar c/(e\lambda_F b)$, and λ_F is the Fermi wavelength. Note also that $H_c \ll H_F$ when $\varepsilon_F\tau/\hbar \gg 1$. Here $\tau_{1,2}$ and $\tau_{1,2}^{\text{tr}}$ are single-particle (small angle) and two-particle (transport) scattering times in the first and the second QWs respectively, v_F is the Fermi velocity, and b is the distance between the centers of the QWs. Note that all the parameters can be measured directly from SdH oscillations of the resistance in perpendicular magnetic field at low temperatures.

2. Experimental

Two sets of double QW structures were grown on a N^+ GaAs substrate by molecular-beam epitaxy and consist of two GaAs wells of width 139 Å separated by 14 and 28 Å $Al_{0.3}Ga_{0.7}As$ barriers. The electrons were provided by remote delta-doped donor layers set back by spacer layers from the top and the bottom well correspondingly. The electron concentration in all samples was about 2.5×10^{11} cm^{-2} in each well. In all our samples the bottom well had lower mobility, due to the rougher GaAs/AlGaAs interface and a partial diffusion of Si into that well. However, slight variation of the growth conditions varies dramatically the extent to which the mobility of the bottom QW is lowered. The microscopic parameters of the samples A–D are presented in Table 1. A schematic cross-section of the device can be found in Ref. [1]. Measurements were done on 10 μm wide and 200 μm long channels with Au/Ge/Ni ohmic contacts. Top and bottom gates were patterned using the standard photolithography fabrication method. The top Schottky gate covered 150 μm of the channel. The data were taken using a lock-in four-terminal technique at $f=37$ Hz. The voltage probes connected to the gated segment of the channel were separated by 100 μm.

Table 1
Microscopic parameters of samples A–D

Sample	d (Å)	Δ (meV)	$(\tau_1^{\text{tr}})^{-1}$ (meV)	$(\tau_2^{\text{tr}})^{-1}$ (meV)	τ^{-1} (meV)	$\tau(0)^{-1}$ (meV)
A	28	1.1	0.02	0.38	0.8	0.6
B	28	1.1	0.04	0.07	0.5	0.18
C	14	2.27	0.02	0.39	0.9	0.84
D	14	2.27	0.02	0.05	0.34	0.16

Variation of the top gate voltage V_g allows us to sweep the potential profile of the QWs through the resonant configuration. The resistance versus top gate voltage for the sample with the 28 Å barrier at $T=4.2$ K is plotted in the inset of Fig. 1. The resistance resonance is clearly observed at $V_g\approx0.28$ V. A similar procedure allows us to determine resonance values for V_g for structures with a 14 Å barrier. Next we fix the gate voltages corresponding to the exact resonance position, and measure the resistance as a function of the in-plane magnetic field perpendicular to the direction of the current, $H\perp j$. Fig. 1 shows the behavior of the RR for two structures with 14 and 28 Å barriers, respectively.

3. Results and discussion

The experimental data clearly demonstrate the suppression of the RR by the magnetic field, as well as the expected broadening for stronger cou-

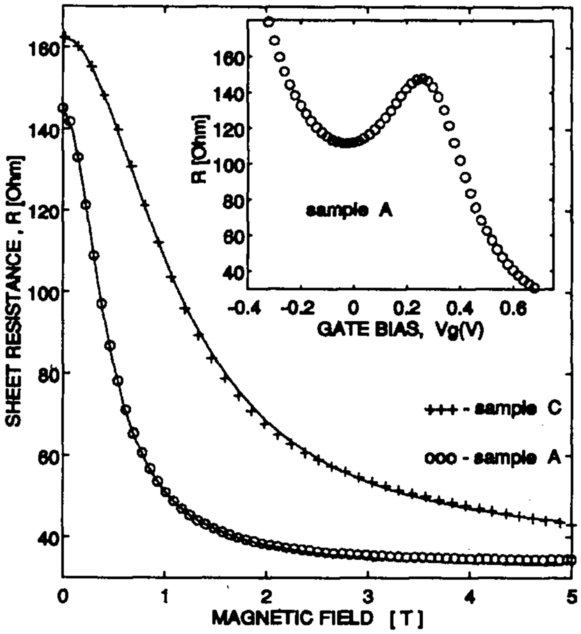

Fig. 1. The resonance resistance (RR) versus magnetic field at 4.2 K (solid lines are the theoretical curves). Inset: lineshape of the RR versus top gate voltage.

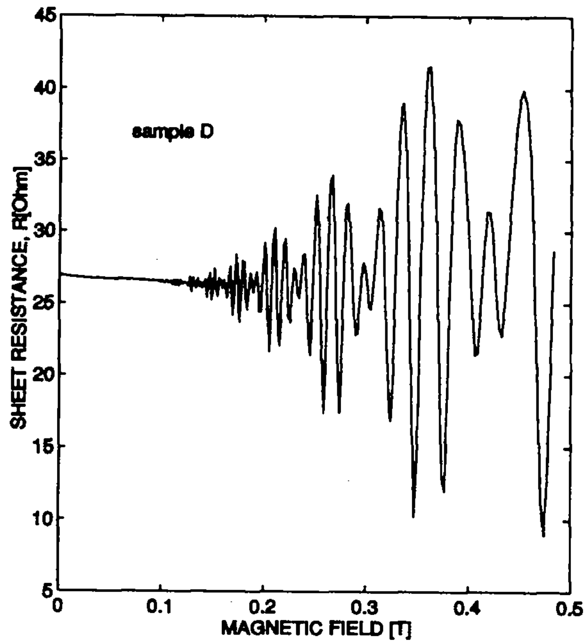

Fig. 2. Shubnikov–de Haas oscillations for sample D.

pled structures (i.e. the resistance decreases more slowly for samples with smaller barrier width). In order to establish the microscopic parameters employed in the theoretical description, we perform an analysis of SdH oscillations of the resistance for the samples with applied gate voltage corresponding to RR. Fig. 2 shows beats of the resistance, which are an indication of two sub-bands with different E_F present at resonance [5].

The distance between the nodes of the curve allows us to find the separation between the subbands $\Delta = E_{F1} - E_{F2}$. For the samples with 14 and 28 Å barriers we obtain $\Delta = 2.3$ and 1.1 meV, respectively. These values are in a good agreement with theoretical estimates. In addition to the parameter Δ we extract for each sample a small-angle scattering time τ, which is assumed to be equal for both bands. Their values are shown in Table 1. The complementary measurements of the Hall effect and the sample resistance versus gate voltage [6] provide us the rest of the parameters entering into the definition of H_c, namely $\tau_{1,2}^{tr}$.

The theoretical expression (Eq. (1)) fits perfectly

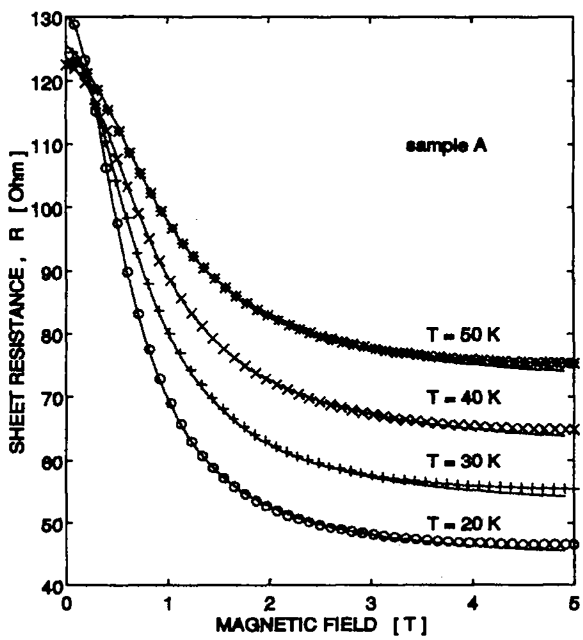

Fig. 3. The resistance versus magnetic field for different temperatures (solid lines are the theoretical curves).

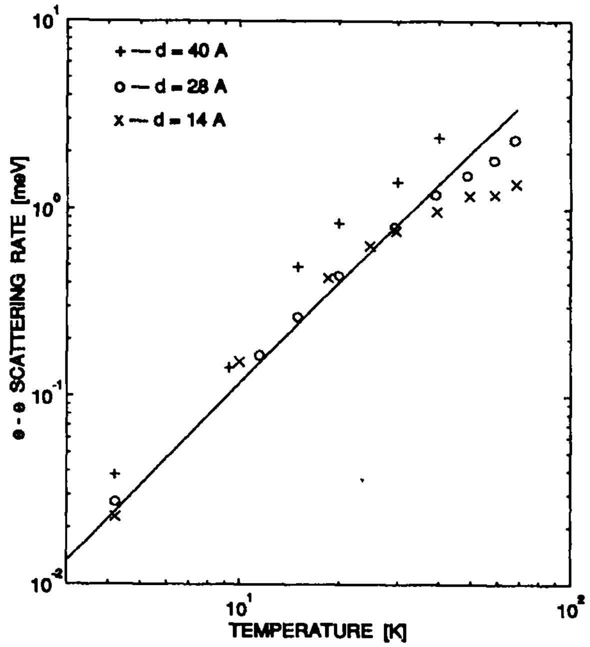

Fig. 4. Electron–electron scattering rate versus temperature.

the experimental data shown in Fig. 1 (solid line is the theoretical curve) and the values of τ used as the only fitting parameter are shown in Table 1. The agreement between values of τ obtained from RR and SdH measurements is fair for samples with low mobilities of one of the wells, and rather poor for the high-mobility samples.

We follow an identical fitting procedure for the RR versus H curves obtained at elevated temperatures (see Fig. 3). As the temperature is increased, the experimental curves become broader and therefore $\tau(T)$ obtained in the fitting procedure attains smaller values. The correction of τ^{tr} due to increase in temperature is measured by the method mentioned above.

The values of the scattering rate $\tau(T)^{-1}$ are temperature-independent (within experimental resolution) below 4.2 K for low-mobility samples, and below 2.2 K for high-mobility samples. These saturated values, which we denote as $\tau(0)^{-1}$, are subtracted from $\tau(T)^{-1}$, and the variation of $\tau(T)^{-1}-\tau(0)^{-1}$ versus temperature is plotted in Fig. 4 for samples with different barrier width d. The data for sample with $d=40$ Å is taken from Ref. [4]. The solid line represents the theoretical expression [7] for $\tau^{-1}(T)$ in a clean 2D gas

$$\frac{\hbar}{\tau_{ee}}=\frac{1}{\pi}\frac{(k_{\mathrm{B}}T)^2}{\epsilon_{\mathrm{F}}}\left(1+\ln 2+\ln\frac{\lambda_{\mathrm{F}}}{\lambda_{\mathrm{TF}}}-\ln\frac{k_{\mathrm{B}}T}{\epsilon_{\mathrm{F}}}\right), \qquad (4)$$

where $\lambda_{\mathrm{TF}}=276$ Å is Thomas–Fermi screening length in GaAs.

The agreement between the experimental points and the theoretical curve is quite remarkable. Eq. (4) is valid only in the limit $k_{\mathrm{B}}T \gg \epsilon_{\mathrm{F}}$. Therefore the deviations of the experimental points from the theory at high temperatures are not surprising. Thus we believe that the RR in two coupled QWs with different mobilities provides a powerful and relatively simple method of measuring small-angle and electron–electron scattering rates.

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