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LETTER TO THE EDITOR

Single-particle lifetime in quasi-one-dimensional systems

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Abstract. We report a systematic experimental investigation of single-particle lifetimes in quasi-one-dimensional structures. The lifetimes were measured in GaAs quantum wires of variable width and carrier density. Experimental data show excellent agreement with theoretical estimates that use a single fitting parameter. The data also suggest that the dominant relaxation mechanism for single-particle excitations in these structures at low temperature is remote impurity scattering. Additionally, we find that the electrostatic confining potential along the width of these structures is parabolic in shape, which agrees with existing theoretical predictions.

Single-particle lifetimes (also known as 'quantum lifetimes') in semiconductor low dimensional structures has been a topic of significant current research interest [1–12]. In the past, theoretical and experimental investigations of these lifetimes have dealt mostly with two-dimensional systems (quantum wells) [1–11], with very little attention paid to one-dimensional structures (quantum wires) [12]. In this paper, we report the first systematic experimental investigation of single-particle lifetimes in quasi-one-dimensional (quasi-1D) systems. These studies provide a comprehensive picture of how single-particle excitations decay in quasi-1D quantum wires.

The quasi-one-dimensional structures used in our experiments were realized on a modulation doped heterostructure grown on a p^+ conducting substrate, a cross-section of which is shown in figure 1. The sample was grown by molecular beam epitaxy and was modulation doped using a 600 Å n^+-AlGaAs layer (doped $\sim 10^{18}$ cm^{-3}) separated from the 2DEG by a 200 Å undoped AlGaAs spacer layer. The 1 μm thick undoped i-GaAs layer (with a background doping of 10^{14}–10^{15} cm^{-3}) acts as an insulator at liquid helium temperatures, and was included to reduce the back-gate leakage current. The p^+ conducting substrate allows the carrier concentration in the high mobility two-dimensional electron gas (2DEG) to be varied by the application of an external back-gate voltage. We have earlier reported on the electronic properties of such back-gated heterostructures [10]. The use of a back-gate to change the carrier concentration has several advantages, such as, (a) it allows the carrier density to be varied continuously over a wide range, (b) it eliminates the uncertainties involved in using different samples (which is a more common practice) and (c) it eliminates the complication of changing the impurity scatterer distribution that takes place if the carrier density modulation is achieved through illumination.

First, a number of Hall bars were fabricated using the standard photolithography, mesa etching, ohmic contact definition, metallization, lift-off and annealing steps. Details of the fabrication procedure are presented in [10] and [13]. Next, split-gate devices were fabricated

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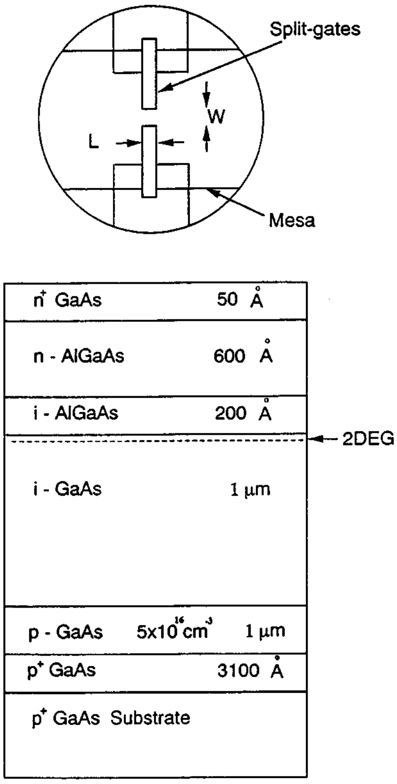

Figure 1. Schematic cross-section of the sample used in the experiments. An ohmic contact to the p^+ substrate forms the back gate. The inset shows the split-gate structure used for realizing quantum wires of variable width.

on the Hall bars using electron-beam lithography, gate metal deposition and the metal lift-off technique. The gate metal used was 50 Å/200 Å layers of Ti/Au. The schematic diagram of a typical split-gate device is shown in the inset of figure 1; the devices used in this research has dimensions of $L = 0.2$ μm and $W = 0.6$ μm. By applying a negative voltage to the split gates with respect to the electron gas underneath, it is possible to continuously constrict the conducting channel located between the split gates thereby realizing a quantum wire of variable width. Similarly, by applying a back-gate voltage, depletion or accumulation of electrons in the wire is obtained thus changing the carrier density continuously. By using these two external voltages *independently*, the width of the quantum wire and the carrier density can be varied over a wide range. This allows the study of the interplay between the degree of quantum confinement and the electron concentration (or Fermi energy).

The devices were first characterized by low field Hall measurements and Shubnikov–de Haas (SdH) measurements in order to obtain the 2DEG characteristics. The measurements were performed in a pumped liquid helium cryostat at a temperature of 1.4 K using an iron core magnet capable of producing magnetic fields of up to 1 tesla (T). The samples were cooled in the dark to avoid the persistent photoconductivity (PPC) effect. SdH and Hall measurements were performed at different back-gate voltages with the top split gate maintained at ground potential. The back-gate bias was applied between a top ohmic contact and the p^+ substrate and was varied between -5 V and +0.5 V, in which range the 2DEG carrier density could be varied by 300%. Over this range, the leakage current was measured to be less than 5 nA, which was deemed small enough to ignore in our calculations. The SdH data shows only one frequency thus indicating that there is only one sub-band populated in this sample. The 2DEG carrier densities obtained from Hall and SdH measurements agreed to within $\pm 3\%$.

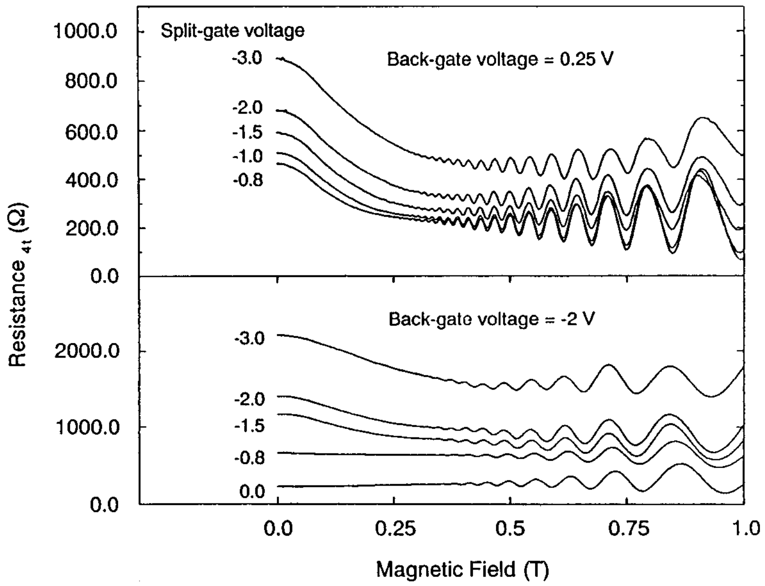

Figure 2. The four-terminal resistance of the quantum wires as a function of magnetic field for typical split-gate and back-gate voltages. Carrier concentrations estimated from the SdH frequency for back-gate voltages of +0.25 and −2.0 V are 3.33×10^{15} m^{-2} and 2.13×10^{15} m^{-2} respectively.

Quasi-1D devices were next formed by applying a reverse bias to the top split gate. Magnetoresistance measurements, up to a magnetic field of 1 T, were performed on the quasi-1D devices at different split-gates and back-gate biases. In this range, it was possible to observe both the low field magnetoresistance and a number of SdH oscillations. The measurements were performed at very low excitation currents to avoid electron heating. For a fixed back-gate voltage, different split-gate biases were used to vary the effective channel width. The set of measurements was then repeated for different back-gate voltages.

Figure 2 shows typical four-terminal magnetoresistance data for various split-gate biases at two different back-gate voltages. All traces show a negative magnetoresistance at low fields and SdH oscillations at higher fields once the quasi-1D channel is formed. The effective channel widths of the wire were estimated from the low field negative magnetoresistance data (0.05 T–0.3 T) following the procedure described in detail in [14]. The negative magnetoresistance arises due to suppression of the geometrical constriction resistance in the ballistic regime by the magnetic field [15]. The two-dimensional (2D) carrier concentration for each scan was obtained from the SdH frequency using data above 0.5 T. It may be noted from figure 2 that the two-dimensional carrier density in our sample depends primarily on the back-gate voltage, and is almost independent of the split-gate voltages, as evidenced by the unchanged frequency of the SdH oscillations. The one-dimensional (1D) carrier concentration can be estimated by multiplying the 2D concentration into the electrical width. The single-particle lifetimes were obtained from the slope of the Dingle plots [16], the procedure for which is described in more detail in [10]. The linearity of the Dingle plots observed for these samples indicates that for all back-gate biases, the carrier density was uniform throughout the sample.

Figure 3 shows the single-particle lifetimes as a function of the measured wire width for various carrier concentrations as obtained from the experimental data. It may be observed

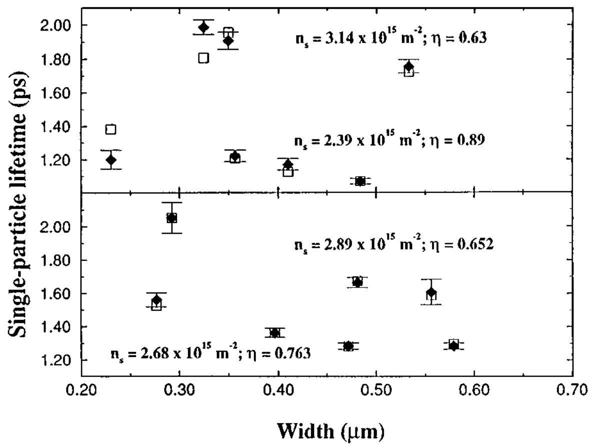

Figure 3. The single-particle lifetimes as a function of measured electrical width for various measured two-dimensional carrier concentrations n_s. The closed diamonds (♦) are experimental data and the open squares (□) represent the theoretical fits. The screening parameters η required to fit the data for various carrier concentrations are displayed alongside the concentration. Data corresponding to four different carrier concentrations are shown in this figure in two separate frames for clarity. Data for other carrier concentrations show the same trend and have similar agreement with theoretical calculations. Note that though the compressed scale gives the impression of excessive scatter, it is still used to indicate the impressive agreement between theory and experiment.

from the figure that the lifetimes increase with decreasing width of the wire (increasing degree of quantum confinement) and increasing carrier concentration. The increase of the lifetime with decreasing width is due to the decrease in the available phase space for scattering. As the wire becomes narrower, the allowed range of scattering angles (allowed by momentum and energy conservation) becomes more and more restricted, which reduces the density of final states available for scattering. This decreases the scattering rate and increases the lifetime. It is precisely this effect that is invoked to predict that quantum wires could in principle exhibit very high mobility at low temperatures.

The increase in the lifetime with increasing carrier concentration, on the other hand, is due to *two* different and independent effects. Increased carrier concentration leads to increased screening and also increased velocity (Fermi) of electrons. Both of these effects are expected to reduce the scattering cross-section if remote impurity scattering is the dominant relaxation mechanism for single-particle excitations.

Before we discuss the comparison of experimental data with theoretical estimates, we address an interesting question. The Fermi velocity corresponding to the 2DEG carrier concentration is about 3×10^7 cm s^{-1}. Multiplication of that by the measured quantum lifetime results in a mean free path of $\sim$0.3 μm which is slightly larger than the length of the structure pinched between the split gates. Hence the structure must be quasi-ballistic. Does it make sense then to describe a quantum scattering lifetime τ if the structure is quasi-ballistic? We believe that the answer is affirmative since quasi-ballistic transport does not mean that every carrier traverses the structure without suffering a collision. Most of them do; however some do not. It is the vestigial scattering of the unlucky carriers that gives rise to an ensemble averaged effective τ in the quasi-1D channel, which is the quantity we measure.

To compare the experimental data with theory and also to ascertain whether remote impurity scattering is indeed the dominant relaxation mechanism, we have calculated the single-particle lifetime in quasi-one-dimensional structures for remote impurity scattering and compared the results with experimental data. Since we are working in the linear response regime (low temperature and low bias), the lifetime that we need to calculate is that of electrons at the Fermi energy E_F since only the Fermi electrons carry current. The lifetime of these electrons in the n_ith sub-band is given by

$$\frac{1}{\tau_s(E_F,n_i)} = \frac{m^* n_I e^4}{2\pi^2 \overline{h}^3 \epsilon^2}\left[\sum_{n_f \neq n_i} \frac{A(E_F,n_i,n_f)}{\sqrt{2m^*(E_F - E^0_{n_f})/\overline{h}^2}} + \sum_{n_f} \frac{B(E_F,n_i,n_f)}{\sqrt{2m^*(E_F - E^0_{n_f})/\overline{h}^2}}\right] \qquad (1)$$

where n_I is the linear impurity concentration (per unit length), ϵ is the dielectric constant, n_i is the subband index for the initial state, n_f is the subband index for the final state, m^* the effective mass, e the electron charge, $E^0_{n_f}$ is the subband energy of the n_fth subband (which depends on the nature of the confining potential, i.e. whether it is parabolic or square well etc) and

$$A(E_F,n_i,n_f) = \left| \int_{-W_y/2}^{W_y/2} \mathrm{d}y\, \varphi^*_f(y)\varphi_i(y)\chi^-(E_F,n_f,n_i) \right|^2$$

$$B(E_F,n_i,n_f) = \left| \int_{-W_y/2}^{W_y/2} \mathrm{d}y\, \varphi^*_f(y)\varphi_I(y)\chi^+(E_F,n_f,n_i) \right|^2 \qquad (2)$$

where

$$\chi^\pm(E_F,n_f,n_i) = K_0\left(\left(\sqrt{\frac{2m^*(E_F - E^0_{n_f})}{\overline{h}^2}} \pm \sqrt{\frac{2m^*(E_F - E^0_{n_i})}{\overline{h}^2}}\right)\sqrt{y^2+d^2}\right) \qquad (3)$$

where W_y is the width of the quantum wire, φ_i and φ_f are the initial and final state wavefunctions along the width, d is the average distance of the electrons from the impurities (which is approximately equal to the spacer layer thickness) and K_0 is the modified Bessel function of the second kind.

The average lifetime that is measured in our experiments is obtained by averaging over subbands

$$\left\langle \frac{1}{\tau_s(E_F)} \right\rangle = \frac{1}{M}\sum_{n_i=1}^{M} 1/\tau_s(E_F,n_I) \qquad (4)$$

where M is the number of occupied subbands. The value of M depends on the width of the wire, the carrier concentration and also the nature of the confining potential (i.e. whether it is parabolic, square well etc). This value can be estimated experimentally by dividing the measured conductance by the quantum conductance $2e^2/h$.

The above theoretical result for the lifetime is derived rigorously from Fermi's golden rule [17] and the details will be published elsewhere. Its two shortcomings are that it does not account for screening explicitly and it neglects correlations between impurity scattering events. In modulation doped structures, screening is remote in nature and is difficult to treat exactly, especially for one-dimensional confinement [18]. Screening reduces the scattering rate and we can include its effect phenomenologically in the theory by multiplying the scattering rate with an arbitrary constant η less than unity. This constant is the only fitting parameter in our theory. With this modification, our theoretical estimate of the lifetime is $\tau_s = \tau_s/\eta$ where τ_s is given by equation (4).

In figure 3, we have plotted the theoretical estimate τ_s, alongside the experimental data. The fitting parameter η which accounts for screening at various carrier concentrations is also shown in the figure. In order to calculate τ_s, the subband energies $E^0_{n_i}$ and $E^0_{n_l}$ appearing in equations (1)–(4) were computed assuming a parabolic confining potential along the width of the wire. The curvature of the parabola ω_0 is obtained from the measured electrical width W using the relation [19]

$$W = (2\pi)^{3/2}(n_s)^{1/2}\left[\frac{2\hbar}{3\pi m^*\omega_0}\right] \tag{5}$$

where n_s is the 2D carrier concentration. The theoretical result exhibits singularities at the subband edges (associated with the 1D density of states), which leads to an inaccurate comparison. Hence we show the theoretical estimate only at discrete values of the electrical width in order to maintain clarity.

The screening parameter η, required to fit the data, decreases with increasing electron concentration as expected. It may be noted from figure 3 that the experimental data and the theoretical estimates agree very well. The theoretical result deviates at two points since the calculated Fermi levels in these cases are close to the bottom of the calculated subbands. When this happens, the theoretical result is somewhat inaccurate since the density of state has singularities at the subband bottoms. The good agreement between experimental and theoretical data can be obtained *only if we assume the confining potential along the width of the wire to be parabolic, rather than square well in shape*. Attempts to match the data assuming a square well potential were not successful; the disagreement was more than an order of magnitude. Moreover, the number of occupied subbands M, estimated from the experiments, agrees with the theoretical estimate only if we assume parabolic confinement. This suggests that the confining potential, at least within the range of carrier concentration encountered in this experiment, is primarily parabolic. This agrees with both previous and recent theoretical results [20].

In conclusion, we have systematically measured the single-particle lifetimes in quasi-1D quantum wires. The lifetimes increase with decreasing wire width and increasing carrier concentration. This indicates increasing suppression of remote impurity scattering in one-dimensional systems with decreasing wire width, increasing screening and increasing electron velocity. The results presented will be helpful in the design of high mobility electronic devices such as quantum wire field effect transistors [21] and quantum interference devices [22]. Effects of the suppression of impurity scattering on noise in one-dimensional structures were observed previously [23], but our experiments are the first direct measurements of the impurity scattering lifetime.

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