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Short range scattering effect of InAs quantum dots in the transport properties of two dimensional electron gas

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Short range interaction between two dimensional electron gas (2DEG) and InAs quantum dots embedded in the GaAs/AlGaAs quantum well is investigated as a function of carrier density. At low carrier density the interaction is significantly characterized by a transport to quantum lifetime ratio of less than 5. However, with an increase in carrier density, quantum lifetime is observed to undergo a sharp transition from 0.17 to 0.25 ps. This is attributed to the screening of short range repulsive scattering due to InAs quantum dots by the 2DEG. © 2007 American Institute of Physics. [DOI: 10.1063/1.2720704]

Study of scattering in two dimensional electron gas (2DEG) is important for optimizing the performance of high electron mobility transistors. Extensive studies on the effect of scattering in the transport properties of 2DEG is carried out by measuring transport and quantum lifetime for modulation doped GaAs/AlGaAs heterostructure.^{1,2} Recently owing to the rapid development of quantum dot based devices such as quantum dot field effect transistor, quantum dot memory devices, and single photon detector, scattering effect of quantum dots on the 2DEG is studied with greater interest.³⁻⁷ Some groups have attempted to study the effect of scattering due to InAs quantum dots in the transport properties of 2DEG.⁸⁻¹⁰ In one of such studies, scattering of InAs quantum dots embedded in the vicinity of the GaAs channel is reported to affect the transport properties of the 2DEG such as mobility, transport, and quantum lifetimes when the thickness of the spacing layer between the 2DEG and the quantum dot is reduced.⁹ On the other hand, these transport properties of the 2DEG were enhanced as the InAs dot density was reduced when the thickness of the spacing layer and carrier density is maintained constant.¹⁰ However, there is scarcely any report on the scattering effect of InAs quantum dots of constant density embedded in AlGaAs/GaAs quantum well without any spacing layer.

In this letter, the short range interaction between 2DEG and InAs quantum dots embedded in the quantum well is investigated. The effect of short range scattering due to InAs quantum dots in the transport properties of 2DEG in the quantum well is studied for increasing carrier density. Carrier density is varied by changing the front gate voltage and the ability of 2DEG to screen the short range scattering is analyzed from the variation in transport and quantum lifetime.¹¹

The sample used for this study is a GaAs/AlGaAs single quantum well structure grown by molecular beam epitaxy. The heterostructure is grown on GaAs substrate and consists of an 18-nm-wide GaAs/Al_{0.33}Ga_{0.67}As quantum well that is modulation doped on both sides using a 40 nm spacer layer. InAs quantum dots were then inserted in the quantum well at a distance of 9 nm from the lower half of the quantum well. Hall bars were fabricated using standard photolithographic technique. Shubnikov-de Hass oscillations (SdH) and Hall measurements were performed in a pumped liquid helium cryostat at a temperature of 1.4 K using a superconducting magnet capable of producing a magnetic field of 7 T. During the entire measurement process, the channel current is maintained at 95 nA.

The study is carried out by changing the front gate voltage from -0.2 to 0.76 V to vary the carrier density in the quantum well. With increase in gate voltage, the frequency of SdH oscillation increased as carrier density increases. We observed a single frequency in the SdH oscillations indicating that only one subband is occupied (Fig. 1). Therefore the short range scattering effect of InAs quantum dots can be

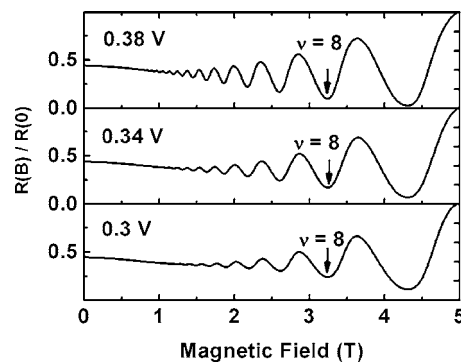


FIG. 1. Normalized SdH oscillations for 0.3, 0.34, and 0.38 V at 1.4 K.

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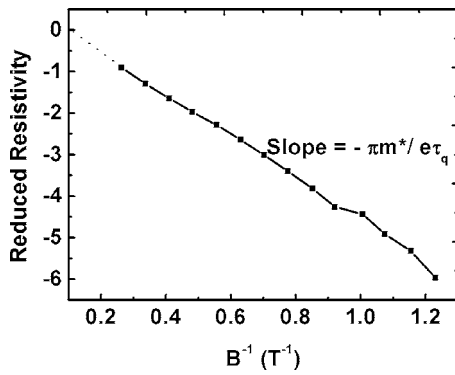


FIG. 2. Dingle plot corresponding to a gate voltage of 0.5 V.

investigated by calculating the quantum lifetime using standard analytical technique. Carrier density measured from the low field (0–0.4 T) Hall slopes was found to increase from 3.07×10^{11} to $6.34 \times 10^{11} \text{ cm}^{-2}$ in the above mentioned gate voltage ranges and the mobility of the sample varied from 1.26×10^4 to $2.22 \times 10^4 \text{ cm}^2/\text{V s}$. These low mobility values are expected for a 2DEG containing InAs quantum dots.⁹ Moreover, longitudinal resistivity of $0.6\text{--}1 \text{ k}\Omega \text{ cm}^{-1}$ at $B=0$ for the range of carrier density studied indicates that repulsive scattering potential of inserted InAs dot structures affects the transport properties of the 2DEG significantly.⁹ However, the influence of the scattering phenomenon on the transport properties can be understood only from the analysis of transport and quantum lifetimes.

Transport lifetime (τ_t) is determined by using the classical equation $\tau_t = m^* / \rho n_s e^2$, where m^* is the effective mass, ρ is the zero field resistivity, and n_s is the electron carrier density. Quantum lifetime (τ_q) is calculated by using the equation

$$\Delta\rho = 4\rho_0 X(T) \exp\left(\frac{-\pi}{\omega_c \tau_q}\right) \hbar, \quad (1)$$

where ρ_0 is the zero field resistivity, ω_c is the cyclotron frequency, and the thermal damping factor $X(T)$ is given by

$$X(T) = \frac{2\pi^2 kT / \hbar \omega_c}{\sinh(2\pi^2 kT / \hbar \omega_c)}. \quad (2)$$

To obtain the Dingle plot, logarithm of $\Delta\rho / 4\rho_0 X(T)$ is plotted against $1/B$ for various carrier densities. The resulting graph is linear and has an intercept at zero for infinite magnetic field which is a characteristic of a good Dingle plot, as shown in Fig. 2.²

Figure 3 shows the variation of transport and quantum lifetimes with carrier density. As carrier density is increased, the transport lifetime increased steadily from 0.3 to 0.8 ps.

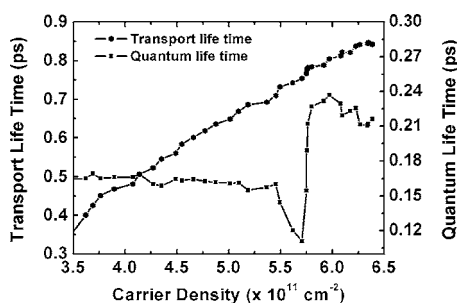


FIG. 3. Transport and quantum lifetime as a function of carrier density.

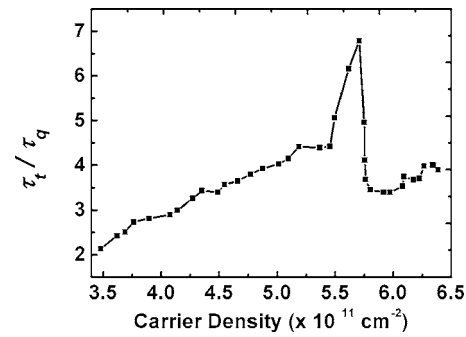


FIG. 4. Ratio of transport to quantum lifetime as a function of carrier density.

This behavior is typical for modulation doped heterostructure in which an increase in carrier density effectively screens the potential due to remote ionized donors. This screening of potential subsequently increases the transport lifetime and hence the mobility of the 2DEG also increases as carrier density is increased.¹² Quantum lifetime, on the other hand, exhibits an interesting behavior. It remains almost constant at 0.17 ps until a carrier density of $5.5 \times 10^{11} \text{ cm}^{-2}$ is reached and then decreases to 0.13 ps. Thereafter, there is a sharp increase in quantum lifetime attaining saturation at 0.25 ps as carrier density is increased, as shown in Fig. 3. The ratio between τ_t and τ_q is found to vary within a range of 2–7, indicating that the dominant scattering mechanism is short range (Fig. 4). From the observed characteristics of transport and quantum lifetime, we hardly notice any correlation between them. In a recent investigation by Russ *et al.* on the nature of interaction between the 2DEG and InAs quantum dots separated by a tunnel barrier demonstrates that quantum dots act as uncorrelated scattering centers and enhance scattering due to resonant interaction with the 2DEG.¹³ The potential from uncorrelated scattering centers cannot be treated by standard approximation methods to predict the variation in two dimensional density of states and hence the behavior of quantum lifetime.¹⁴ Therefore the absence of correlation between the two lifetimes observed in our study needs further detailed theoretical and experimental investigation.

On either side of the sharp transition region, quantum lifetime almost remains constant (Fig. 3). These observations suggest that the scattering rate due to short range potential can be controlled by varying the carrier density with the help of gate voltage to optimize our device performance. We present a plausible explanation for the abrupt change in the quantum lifetime with gate voltage observed in our sample. The potential candidate for the origin of short range scattering in our sample is the electrons in the quantum dots. Therefore by modeling the electrons as scattering centers the resultant screened potential can be approximated by the equation¹⁵

$$\langle U(q) \rangle^2 = N_{\text{qd}} \left(\frac{2\pi e^2}{\kappa q} \right)^2 F(q, d)^2, \quad (3)$$

where N_{qd} is the density of electrons in the quantum dots, q is the scattering wave number, κ is the dielectric constant of GaAs, and $F(q, d)$ is the form factor which takes into account the finite extension of the 2DEG and the distance d between the plane of the quantum dot and the 2DEG.¹⁵ We further assume that all parameters except $F(q, d)$ in Eq. (3) to remain constant. The validity of our assumption is supported

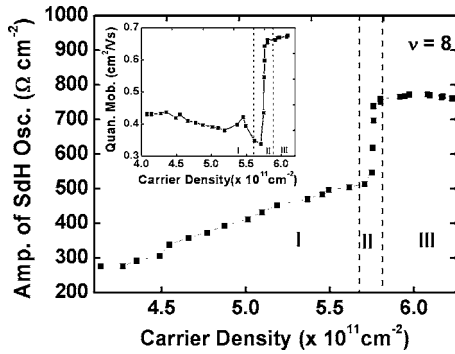


FIG. 5. Amplitude of SdH oscillation as a function of carrier density corresponding to filling factor $\nu=8$. The inset shows the variation of quantum mobility with carrier density.

by the fact that the sharp increase in quantum lifetime is observed for a narrow range of gate voltage during which number of electrons in the dots is not expected to vary much. Secondly, for two dimensional systems the screening is independent of q for the entire range of scattering wave vectors ($0 \leq q \leq 2k_F$). As the front gate voltage is gradually increased, the wave function of the 2DEG localized around the quantum dots shifts toward the barrier interface. Neglecting finite extension of the 2DEG, the form factor is given by¹⁶

$$F(q, d) = e^{-2qd}. \quad (4)$$

The form factor undergoes an abrupt transition from 1 to 0.025 as the wave function shifts from the quantum dots ($d=0$) to the edge of the barrier ($d=9$ nm) when gate voltage is increased from 0.3 to 0.4 V. This sharp reduction in $F(q, d)$ in turn decreases the scattering time in accordance with the equation (Stern-Howard model)¹⁵

$$\frac{1}{\tau_i} = \frac{1}{2\pi\hbar\epsilon_F} \int_0^{2k_F} dq \frac{q^2}{\sqrt{4k_F^2 - q^2}} \frac{\langle |U(q)| \rangle^2}{\epsilon(q)^2}. \quad (5)$$

This decrease in scattering time enhances the quantum lifetime (τ_q), which is related to the imaginary part of the single particle self-energy function (Γ_s) by

$$\Gamma_s = \frac{\hbar}{\tau_q}, \quad (6)$$

Γ_s determines the broadening of the Landau levels due to the interaction between the 2DEG and the quantum dots.¹ Therefore the increase in quantum lifetime reduces the broadening of Landau levels. This has the effect of increasing the resolution of SdH oscillation in the low magnetic field region.¹⁰ Careful investigation of Fig. 1 in our sample shows that as gate voltage is progressively increased from 0.32 to 0.38 V, SdH oscillations begin to develop at fields less than 1 T. Hence the sharp increase in quantum lifetime is attributed to the screening of short range scattering by the 2DEG due to its increased distance from the scattering centers. This explains the transition of quantum lifetime from 0.17 to 0.11 ps as carrier density is varied from 5.5×10^{11} to $5.65 \times 10^{11} \text{ cm}^{-2}$ (0.3–0.38 V) (Fig. 3).

To gain further insight into this phenomenon, a plot of change in amplitude of SdH oscillation corresponding to filling factor $\nu=8$ is plotted against the carrier density in Fig. 5. This graph is characterized by three regions, namely, I, II, and III. In region I, there is a gradual increase in amplitude with increase in carrier density and in region II there is a

sharp increase in amplitude for fractional change in carrier density followed by region III where the amplitude almost remains constant with moderate increase in carrier density.

The gradual increase in amplitude observed in region I is due to the increase in carrier density of the sample. As the carrier density is increased, eigenstates corresponding to higher Landau levels get filled up which tends to increase the fluctuation in the density of states. Therefore, the observed increase in amplitude in region I corresponding to filling factor $\nu=8$ in Fig. 5 is attributed to the increase in carrier density. The inset in Fig. 5 gives a clear picture of this scenario. We can observe that quantum mobility in region I decreased gradually in contrast to the amplitude of SdH oscillation. This indicates that the increase in amplitude is not due to the screening of short range scattering of InAs quantum dots.

The onset of screening of short range scattering by the 2DEG is characterized by sharp increase in amplitude for a fractional increase in carrier density in region II. The screening effect is also evident from Fig. 1, where the amplitude of SdH oscillations is found to increase even though the frequency of oscillations remains almost constant. As already explained, this is due to the gate voltage induced screening of short range scattering potential. In region III, the slight decrease in amplitude of SdH oscillation may be attributed to the increase in interface roughness scattering as 2DEG gets closer to the edge of the quantum well.

In conclusion, the scattering effect of InAs quantum dot embedded in GaAs quantum well is investigated. For a particular narrow range gate voltage and carrier density, the amplitude of SdH oscillations and quantum lifetime increased significantly. This is attributed to the screening of scattering potential due to InAs quantum dots by the 2DEG. These observations suggest that the short range interaction between InAs quantum dots and the 2DEG can be controlled by varying the gate voltage.

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