Transport and Quantum Lifetime Dependence on Electron Density in Gated GaAs/AlGaAs Heterostructures

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In the transport theory one must deal with two different characteristic times—the quantum lifetime \(\tau_q\) which is given by total scattering rate and the transport lifetime \(\tau_t\) which is weighted by the scattering angle \(\theta\). For a short-range scattering potential \(\tau_q\) and \(\tau_t\) are approximately equal, but for GaAs/Ga\(_{1-x}\)Al\(_x\)As heterostructures, where the dominate scattering mechanism is the long-range potential associated with ionized donors which produce predominantly small-angle scattering, \(\tau_q\) can be considerably smaller than \(\tau_t\).

Quantum lifetimes can be determined experimentally from Dingle plots. The amplitude \(\Delta \rho\) of the Shubnikov-de Haas (SdH) oscillation is given by \([1]\)

\[ \Delta \rho = 4 \rho_0 \frac{\chi}{\sinh \chi} \exp \left[ -\frac{\pi}{\omega_c \tau_q} \right] \]

where \(\rho_0\) is the zero-field resistivity, \(\omega_c\) is the cyclotron frequency, and \(\chi = \frac{2 \pi^2 kT}{h \omega_c}\).

Though several studies of \(\tau_q\) in GaAs/Ga\(_{1-x}\)Al\(_x\)As heterostructures with different electron densities have been reported, but to date there seems to have been no systematic studies of transport and quantum lifetime dependence on electron density. It is well known that at liquid helium temperature, the distribution and density of ionized donors remain constant. Therefore by measuring a gated GaAs heterostructure, one can study both the transport and quantum lifetime as a function of electron density at a fixed ionized donors’ distribution and density, and it is the purpose of this paper to report such measurements.

Using the sample with high mobility about 300 m\(^2\)/Vs for the experiments, our results show that the quantum lifetime decreases with decreasing electron density, as shown in Fig. 1. But with decreasing electron density, \(\tau_q\) appears to show an exponential decrease and we get an empirical fit: \(\tau_q = 1.261 \times 10^{-12} + 1.25 \times 10^{-30} \exp(2.85 \times 10^{-14} n_e)\) (sec). Moreover, after studying the transport lifetime dependence on electron density we obtain the results that the ratios of \(\tau_t/\tau_q\) increase from about 45 to 90 as the electron density decreases, as shown in Fig. 2. This figure not only shows the importance of the long-range impurity scattering in our sample, but also strongly proves that the transport (\(\tau_t\)) and quantum (\(\tau_q\)) lifetimes have two different characteristic dependences on electron density.

References:
Fig. 1. The quantum lifetime measured from the Dingle plots is plotted against electron density. The quantum lifetime has an exponential increase as electron density. The exponential fit is \( \tau_q = 1.261 \times 10^{-12} + 1.25 \times 10^{-30} \exp(2.85 \times 10^{-14} n_e) \) (sec).

Fig. 2. The ratios \( \tau_t / \tau_q \) are plotted against electron density.