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Quantum and transport lifetimes in a tunable low-density AlGaN/GaN
two-dimensional electron gas

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We experimentally determine the density dependence of the transport lifetime \( \tau_t \) obtained from low-field Hall measurements and the quantum lifetime \( \tau_q \) derived from analysis of the amplitude of Shubnikov–de Haas oscillations in a tunable high mobility two-dimensional electron gas (2DEG) in a Al\(_{0.06}\)Ga\(_{0.94}\)N/GaN heterostructure. Using an insulated gate structure, we are able to tune the 2DEG density from \( 2 \times 10^{11} \) to \( 2 \times 10^{12} \) cm\(^{-2}\), and thus, monitor the evolution of the scattering times in a single sample at \( T=0.3 \) K in a previously unexplored density regime. The transport lifetime \( \tau_t \) is a strong function of electron density, increasing from \( \sim 2.7 \) ps at \( n_e=2 \times 10^{11} \) cm\(^{-2}\) to \( \sim 11 \) ps at \( n_e=1.75 \times 10^{12} \) cm\(^{-2}\). Conversely, we find that the quantum scattering time \( \tau_q \) is relatively insensitive to changes in electron density over this range. The data suggest that dislocation scattering accounts for the density dependence of \( \tau_q \), as well as \( \tau_t \), in our low-density sample. © 2004 American Institute of Physics. [DOI: 10.1063/1.1827939]

In the study of the transport properties of the two-dimensional electron gas (2DEG) it has long been recognized that two distinct relaxation times can be defined.1 The most commonly encountered is the transport lifetime defined as:

\[ \tau_t = \mu m / e \]

where \( \mu \) is the low-field Hall mobility, \( m^* \) is the effective mass of the charge carrier, and \( e \) is the electronic charge. If \( P(\theta) \) is the probability density that an electron is scattered through angle \( \theta \), then \( 1/\tau_t = \int P(\theta) (1 - \cos(\theta)) d\theta \). The inclusion of the angular weighting factor \( 1 - \cos(\theta) \) enhances the contribution of large angle scattering events over small angle scattering. Another relaxation time, the quantum scattering time \( \tau_q \), can be defined as:

\[ 1/\tau_q = \int P(\theta) d\theta \]

As the weighting function \( 1 - \cos(\theta) \) is not included, all scattering angles are counted equally. \( \tau_q \) is a measure of the time that an electron remains in a single momentum eigenstate in the presence of scattering. The quantum scattering time can be related to disorder broadening of the Landau levels of an electron in a magnetic field. At low magnetic fields, it is assumed that each Landau level is broadened by a Lorentzian of width \( \Gamma \), such that \( \Gamma = \hbar / 2 \tau_q ^2 \). The transport and the quantum lifetimes will be substantially different for scattering processes in which the scattering matrix element has significant angular dependence. Consequently, the ratio of the two scattering times \( \tau_q / \tau_t \) has traditionally been used in the study of semiconductor transport to discriminate between various scattering mechanisms and to measure the degree to which carrier scattering is predominantly large or small angle.

Only recently have high mobility 2DEGs in AlGaN/GaN heterostructures become available for study.3-7 In this system, the proper analysis of the quantum scattering time and the degree to which scattering is predominately large or small angle remains controversial.3-8 Recently, Syed et al.8 demonstrated that the amplitude of the Shubnikov–de Haas (SdH) oscillations is severely dampened by relatively small (~3%) density inhomogeneities in AlGaN/GaN 2DEGs. Such inhomogeneities are often observed.9 As a result, naive analysis of the dampened SdH oscillations may result in an artificially low quantum scattering time \( \tau_q \) and therefore an artificially high ratio \( \tau_t / \tau_q \).

In this letter we detail our investigation of the quantum and transport lifetimes of a tunable 2DEG confined in an AlGaN/GaN heterostructure. Using an insulated gate structure we are able to tune the 2DEG density from \( 2 \times 10^{11} \) to \( 2 \times 10^{12} \) cm\(^{-2}\), and thus, monitor the evolution of the scattering times in a single sample at \( T=0.3 \) K in a previously unexplored density regime. A principle advantage of this structure is that \( \tau_q \) and \( \tau_t \) can be measured at several different 2DEG densities while keeping various forms of disorder such as background impurity concentration, dislocation density, alloy disorder, and interface roughness constant. The density dependence of \( \tau_q \) and \( \tau_t \) suggests that scattering from charged dislocations determines both lifetimes in our sample.

The AlGaN/GaN heterostructure used in this study was grown by molecular beam epitaxy (MBE) on a low threading dislocation density (~10\(^8\)) 40-\(\mu\)m-thick GaN template prepared by hydride vapor phase epitaxy. The details of the MBE growth have been reported previously. At \( T=0.3 \) K, the gate leakage is \( \leq 10^{-12} \) A over a voltage range \( \pm 4 \) V. This sample displayed a maximum mobility of 80,000 cm\(^2\) V\(^{-1}\) s\(^{-1}\) with \( n_e=1.75 \times 10^{11} \) cm\(^{-2}\) at \( T=0.3 \) K.

Figure 1(a) displays a typical magnetoresistance measurement at \( T=0.3 \) K. At a gate voltage of \( V_G=-1 \) V, the 2DEG density is \( 9.8 \times 10^{11} \) cm\(^{-2}\) and the mobility is 64 200 cm\(^2\) V\(^{-1}\) s\(^{-1}\), corresponding to a transport lifetime of 8.7 ps. The quantum lifetime is determined in the customary fashion using Dingle plots.10 The amplitude (\( \Delta R \)) of the Shubnikov–de Haas oscillations is given by:

\[ \Delta R = 4 R_0 \chi(T) \exp(-\pi \omega_0 \tau_q) / \sinh(2 \pi \kappa T / \hbar \omega_0) \]

where \( X(T) = (2 \pi \kappa T / \hbar \omega_0) \) and \( R_0 \) is the resistance at zero magnetic field. The logarithm ln(\( \Delta R / 4 R_0 \chi(T) \)) is plotted

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The density is plotted as a function of

\[ \frac{1}{\tau_q} = 2k_F/t_F \]

where \( k_F = (2\pi n_e)^{1/2} \) and \( \tau_F = 2m^* e^2/\hbar^2 \) is the two-dimensional Thomas–Fermi screening wave vector to aid comparison with existing theory of the quantum scattering time in AlGaN/GaN structures. \( e \) is the dielectric constant of GaN. As noted by Syed et al.,\(^8\) the magnitude of the derived quantum scattering time may be suppressed due to density inhomogeneities. Nevertheless, two trends are immediately apparent. First, the transport lifetime displays significant density dependence. The transport lifetime monotonically increases from \( \sim 4.8 \) ps at \( n_e = 4.3 \times 10^{11} \) cm\(^{-2} \) to \( \sim 10 \) ps at \( n_e = 1.47 \times 10^{12} \) cm\(^{-2} \). Second, the quantum lifetime shows a weak dependence on density. \( \tau_q \) increases slightly with increasing density, rising from 0.35 ps at \( n_e = 4.3 \times 10^{11} \) cm\(^{-2} \) to 0.49 ps at \( n_e = 1.47 \times 10^{12} \) cm\(^{-2} \). Nevertheless, this \( \sim 40\% \) increase is modest in comparison with the increase in the transport lifetime.

At low densities, the mobility, and therefore \( \tau_q \), exhibit a power law dependence on density- \( \mu \sim n_e^{\alpha} \), with \( \alpha \sim 1 \), over the range of \( 2 \times 10^{11} \) to roughly \( 1 \times 10^{12} \) cm\(^{-2} \). This power law dependence in the low-density regime is indicative of mobility limited by Coulomb scattering from charged dislocations.\(^7,11\) This behavior can be qualitatively understood with the following simple model. The mobility is most affected by large angle scattering across the Fermi circle. The improved mobility at higher density can be attributed to the increase in the Fermi wave vector \( k_F = \sqrt{2}\pi n_e \) that accompanies the rise in 2DEG density. For a given scattering wave vector \( \mathbf{q} \), established by the spatial configuration of the Coulomb scattering sites, the angle through which the electron is scattered decreases with increasing \( k_F \), and thus, the mobility is increased. However, the fact that \( \tau_q \) increases only slightly with density indicates that the total scattering rate is not decreasing substantially with increasing density and that the dominant scattering mechanism must still contribute significantly to small angle scattering.

Several groups have treated the effects of dislocation scattering.\(^11,14\) Jena et al.\(^12\) recently presented a calculation of the quantum scattering time due to dislocation scattering. In the Thomas–Fermi approximation, the screened matrix element for charged dislocation scattering is

\[ \langle k' | V(q) | k \rangle = \frac{4\pi e}{\varepsilon c} \frac{1}{q (q + q_T)} , \]

where \( q = |k' - k| = 2k_F \sin(\theta/2) \) and \( \theta \) is the scattering angle. \( c \) is the distance between charges along the dislocation. In the Born approximation, the quantum scattering rate is then given by

\[ \frac{1}{\tau_q} = N_{\text{dis}} \frac{m^*}{\hbar^3} \int_0^{2k_F} \frac{dq}{|V(q)|^2 \sqrt{1 - (q/2k_F)^2}} , \]

where \( N_{\text{dis}} \) is the areal density of dislocations. This equation can be reduced to

\[ \frac{1}{\tau_q} = \frac{N_{\text{dis}} m^* 4\pi e^2}{\hbar^3 e^2 c^2 k_F^2} I_q , \]

where
FIG. 3. \( \tau_d/\tau_q \) measured as a function of density. The density dependence of the calculated ratio due to dislocation scattering for three values of cutoff angle \( \theta_c \) are also displayed. The theoretically predicted ratio for remote ionized impurity scattering for a structure with a 20 nm barrier is shown. The density dependence of the ratio for remote ionized impurity scattering is stronger than the experimentally observed dependence.

\[
I_q = \frac{1}{2} \left( \frac{\xi}{\pi} \right)^{1/2} \int_0^1 \frac{du}{u^2 (u + 1)^2 \sqrt{1 - u^2}},
\]

\( \xi = 2k_e/q_{TF} \), and \( u = q/2k_e = \sin(\theta/2) \). The analytic expression for \( 1/\tau_q \) is precisely the same as for \( 1/\tau_q \) except that an additional factor of \( 2u^2 \) appears inside the integral. The importance of small-angle scattering from dislocations is immediately clear upon examination of \( I_q \). This integral formally diverges as \( u \to 0 \), or as the scattering angle \( \theta \) approaches 0. Clearly this divergence must be removed to make comparison with the data, as it would imply that dislocation scattering infinitely broadens the Landau levels and no SdH oscillations should be observed. Nevertheless since dislocation scattering makes significant contributions to small-angle scattering, one can expect that the total scattering rate due to dislocations does not change significantly with increased electron density. In Ref. 12 an arbitrary cutoff angle \( \theta_c \) below which small-angle scattering is not included was introduced to make \( I_q \) finite. One can argue that very small-angle scattering that does not deflect an electron significantly during a cyclotron orbit will not destroy coherence of the SdH oscillations, removing any singularity in \( \tau_q \). A very rough approximation would yield \( \theta_c \sim 1/\sqrt{\nu} \), where \( \nu = \hbar n_e/eB \) is the filling factor, resulting in \( \theta_c \sim 0.3 \) rad in the regime of interest. In addition, it is known from the study of the AlGaAs/GaAs system\(^{10,11} \) that multiple small-angle scattering events are correlated in such a way that small-angle scattering is suppressed. One might expect that such multiple small-angle scattering events would result in an approximate

\[
\theta_c = 2 \sqrt{\frac{\pi N_{\text{dis}}}{n_e}}.
\]

Based on this criterion, \( \theta_c \) should roughly be 0.1 rad.

The experimentally determined ratio of \( \tau_d/\tau_q \) is plotted in Fig. 3. The ratio for our sample varies from \( \sim 10 \) at \( \xi = 0.375 \) to \( \sim 24 \) at \( \xi = 0.63 \). The calculated ratio of \( \tau_d/\tau_q \) due to dislocation scattering with cutoff angles \( \theta_c = 0.05 \), 0.1, and 0.25 rad are also displayed. The calculated weak density dependence of \( \tau_d/\tau_q \) is suggestive that dislocation scattering determines \( \tau_q \) as well as \( \tau_q \) in our sample, but we must be careful not to push the approximation too far. As we have described, the cutoff angle is not constant as the electron density and magnetic field are varied.

In addition to dislocation scattering we must also consider other scattering sources that may contribute to the determination of the quantum scattering time.\(^8\) Remote ionized impurity scattering may also contribute to the determination of \( \tau_q \). Nevertheless we have excluded remote ionized impurities as the dominant source of scattering in our low-density sample. Both the power law dependence of mobility (\( \tau_q \) on density - \( \mu \sim n_e^{\alpha} \), with \( \alpha \sim 1.0 \) and the peak mobility value \((80 \, 000 \, \text{cm}^2/\text{V s})\) are consistent with dislocation scattering rather than remote ionized impurity scattering.\(^7\) Furthermore the \( \tau_d/\tau_q \) ratio for remote ionized impurity scattering has been calculated\(^1,12\) and shows a much stronger dependence on density than is seen in our data. In Fig. 3, the calculated \( \tau_d/\tau_q \) for remote ionized impurity scattering for an AlGaN/GaN heterostructure with a 20 nm AlGaN barrier is shown. This plot is reproduced from Fig. 2 of Ref. 12.

In conclusion, we have presented a study of the density dependence of the transport and quantum lifetimes in a gate tunable high mobility AlGaN/GaN 2DEG in the previously unexplored density regime \( \leq 1.5 \times 10^{12} \text{cm}^{-2} \). The data suggest that dislocation scattering determines both \( \tau_q \) and \( \tau_q \) in our sample.

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