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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 (τ_t) obtained from low-field Hall measurements and the quantum lifetime (τ_q) derived from analysis of the amplitude of Shubnikov–de Haas oscillations in a tunable high mobility two-dimensional electron gas (2DEG) in a $\mathrm{Al}_{0.06}\mathrm{Ga}_{0.94}\mathrm{N}/\mathrm{GaN}$ heterostructure. Using an insulated gate structure, we are able to tune the 2DEG density from 2×10^{11} to 2×10^{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 τ_t is a strong function of electron density, increasing from $\sim$2.7 ps at $n_e=2\times10^{11}$ cm^{-2} to $\sim$11 ps at $n_e=1.75\times10^{12}$cm^{-2}. Conversely, we find that the quantum scattering time τ_q is relatively insensitive to changes in electron density over this range. The data suggest that dislocation scattering accounts for the density dependence of τ_q as well as τ_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 μ 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 θ, 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 τ_q, can be defined as: $1/\tau_q=\int P(\theta)d\theta$. As the weighting fuction $(1-\cos\,\theta)$ is not included, all scattering angles are counted equally. τ_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 Γ, 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 τ_t/τ_q 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.[3,4,8] Recently, Syed *et al.*[8] demonstrated that the amplitude of the Shubnikov–de Haas (SdH) oscillations is severely dampened by relatively small $(\sim3\%)$ 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 τ_q and therefore an artificially high ratio τ_t/τ_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 2×10^{11} to 2×10^{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 τ_q and τ_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 τ_q and τ_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 $(\sim10^8$ cm$^{-2})$ 40-μm-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 $\leqslant10^{-12}$ A over a voltage range ±4 V. This sample displayed a maximum mobility of 80 000 cm^2/V s with $n_e=1.75\times10^{12}$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 9.8×10^{11} cm^{-2} and the mobility is 64 200 cm^2/V s, corresponding to a transport lifetime of 8.7 ps. The quantum lifetime is determined in the customary fashion using Dingle plots.[10] The amplitude (ΔR) of the Shubnikov–de Haas oscillations is given by: $\Delta R=4R_0X(T)\exp(-\pi/\omega_c\tau_q)$ where $X(T)=(2\pi kT/\hbar\omega_c)/\sinh(2\pi kT/\hbar\omega_c)$. $\omega_c=eB/m^*$ and R_0 is the resistance at zero magnetic field. The logarithm $\ln(\Delta R/4^*R_0X(T))$ is plotted

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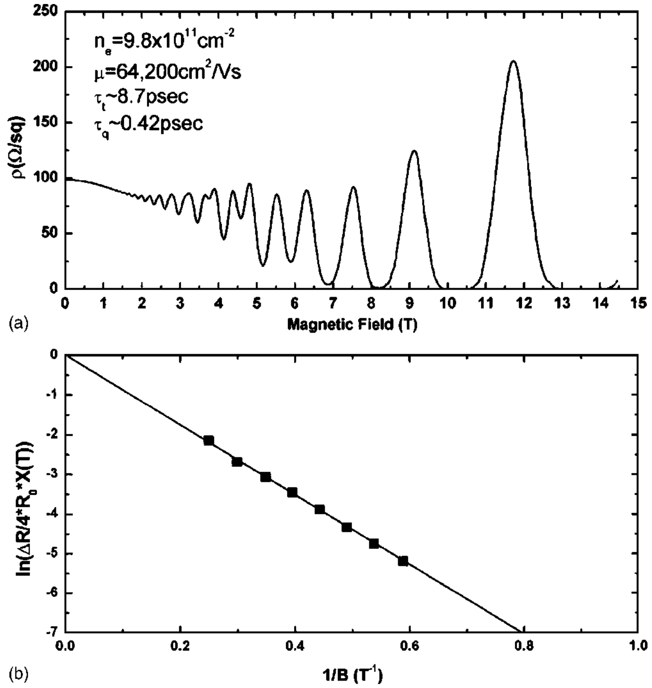

FIG. 1. (a) Magnetoresistance at $V_G=-1$ V and $n_e=9.8\times10^{11}$ cm^{-2} at $T=0.3$ K. The mobility of 64 200 cm^2/V s corresponds to a transport lifetime of 8.7 ps. (b) Dingle plot generated from analysis of the Shubnikov–de Haas oscillations observed in (a). The black squares correspond to the measured points. The solid black line is linear fit to the data which yields a quantum scattering time $\tau_q=0.42$ ps.

against $1/B$. The slope of this plot determines $1/\tau_q$. Figure 1(b) is a Dingle plot generated from the data in Fig. 1(a). The black squares correspond to the experimentally determined points. The black line is generated by a least-squares fit subject to the constraint that the fit intercepts zero at $1/B=0$. Analysis of this data set yields a quantum lifetime of 0.42 ps at $n_e=9.8\times10^{11}$ cm^{-2}. This procedure is repeated at eight different gate voltage settings to establish the density dependence of the transport and quantum lifetimes.

The transport and quantum lifetimes as a function of 2DEG density are plotted in Fig. 2. The density is plotted as a function of the dimensionless parameter $\zeta=2k_F/q_{TF}$ where $k_F=(2\pi n_e)^{1/2}$ and $q_{TF}=2m^*e^2/\varepsilon\hbar^2$ is the two-dimensional Thomas–Fermi screening wave vector to aid comparison with existing theory of the quantum scattering time in AlGaN/GaN structures. ε 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 ~4.8 ps at $n_e=4.3\times10^{11}$ cm^{-2} to ~10.6 ps at $n_e=1.47\times10^{12}$ cm^{-2}. Second, the quantum lifetime shows relatively weak dependence on density. τ_q does increase slightly with increasing density, rising from 0.35 ps at $n_e=4.3\times10^{11}$ cm^{-2} to 0.49 ps at $n_e=1.47\times10^{12}$ cm^{-2}. Nevertheless, this ~40% increase is modest in comparison with the increase of the transport lifetime.

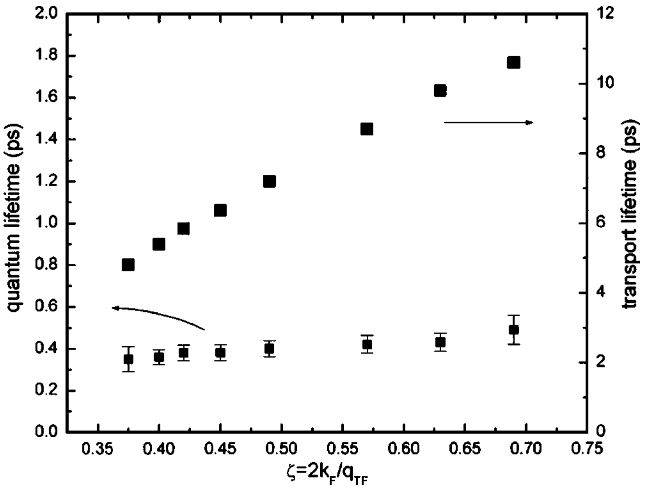

FIG. 2. The measured transport lifetime τ_t and quantum lifetime τ_q plotted as a function of density measured in a single sample at $T=0.3$ K. The density is plotted as the dimensionless parameter $\zeta=2k_F/q_{TF}$. The transport lifetime increases monotonically over the entire density range while the quantum lifetime exhibits much weaker density dependence.

At low densities, the mobility, and therefore τ_t, exhibit a power law dependence on density- $\mu\sim n_e^{\alpha}$, with $\alpha\sim1.0$, over the range of 2×10^{11} to roughly 1×10^{12} cm^{-2}.[7] 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 τ_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

$$\langle k'|V(q)|k\rangle = \frac{4\pi e}{\varepsilon c}\frac{1}{q(q+q_{TF})},$$

where $q=|k'-k|=2k_F\sin(\theta/2)$ and θ 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

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

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

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

where

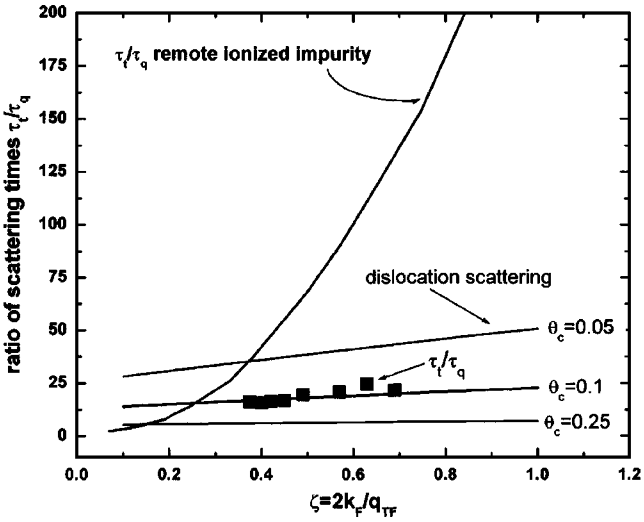

FIG. 3. τ_t/τ_q measured as a function of density. The density dependence of the calculated ratio due to dislocation scattering for three values of cutoff angle θ_C are also displayed. The theoretically predicted ratio for remote ionized impurity scattering for a structure with a 20 nm barrier is also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

$$I_q = \frac{1}{2}\zeta^2 \int_0^1 \frac{du}{u^2(u\zeta+1)^2\sqrt{1-u^2}},$$

$\zeta = 2k_{\mathrm{F}}/q_{\mathrm{TF}}$, and $u = q/2k_{\mathrm{F}} = \sin(\theta/2)$. The analytic expression for $1/\tau_t$ 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 $u \rightarrow 0$, or as the scattering angle θ 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 θ_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 τ_q. A very rough approximation would yield $\theta_C \approx 1/\sqrt{\nu}$, where $\nu = hn_e/eB$ 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[10,15] 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

$$\theta_C \approx 2\sqrt{\frac{2\pi N_{\mathrm{dis}}}{n_e}}.$$

Based on this criterion, θ_C should roughly be 0.1 rad.

The experimentally determined ratio of τ_t/τ_q is plotted in Fig. 3. The ratio for our sample varies from ~ 16 at $\zeta = 0.375$ to ~ 24 at $\zeta = 0.63$. The calculated ratio of τ_t/τ_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 τ_t/τ_q is suggestive that dislocation scattering determines τ_q as well as τ_t 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.[16] Remote ionized impurity scattering may also contribute to the determination of τ_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 (τ_t) on density- $\mu \sim n_e^{\alpha}$, with $\alpha \sim 1.0$ and the peak mobility value $(80\,000\ \mathrm{cm}^2/\mathrm{V\ s})$ are consistent with dislocation scattering rather than remote ionized impurity scattering.[7] Furthermore the τ_t/τ_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 τ_t/τ_q for remote ionized impurity 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 $\leqslant 1.5 \times 10^{12}\mathrm{cm}^{-2}$. The data suggest that dislocation scattering determines both τ_t and τ_q in our sample.

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