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Electron scattering in AlGaN/GaN structures

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We present data on mobility lifetime τ_t, quantum lifetime τ_q, and cyclotron resonance lifetime τ_{CR}, of a sequence of high-mobility two-dimensional electron gases in the AlGaN/GaN system, covering a density range of 1 to $4.5\times10^{12}\ \mathrm{cm}^{-2}$. We observe a large discrepancy between τ_q and $\tau_{\mathrm{CR}}(\tau_q\sim\tau_{\mathrm{CR}}/6)$, and explain it as the result of density fluctuations of only a few percent. Therefore, only τ_{CR}—and not τ_q—is a reliable measure of the time between electron-scattering events in these specimens. The ratio $\tau_t/\tau_{\mathrm{CR}}$ increases with increasing density in this series of samples, but scattering over this density range remains predominantly in the large-angle scattering regime. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1655704]

In contrast to the extensively studied two-dimensional electron system (2DES) in AlGaAs/GaAs heterojunctions, the transport properties of 2DES in the more recently developed AlGaN/GaN system remain much less well understood. In particular, the qualitative nature of the scattering mechanisms at low temperatures in this material remain controversial, and the degree to which electron scattering is preferentially large- or small-angle is still under discussion. Electron scattering can be characterized by an average lifetime τ between events and an average scattering angle φ. Since each scattering event dephases the wave function, the quantum lifetimes τ_q deduced from Shubnikov de Haas (SdH) measurement and from cyclotron resonance (CR) measurements τ_{CR} are not expected to depend on φ, and both to be close to τ. In contrast, the transport lifetime τ_t deduced from mobility, measures the time for electron backscattering to occur. It depends heavily on φ and must always exceed τ_q and τ_{CR}. For large-angle scattering, φ is large and τ_t is very similar to τ_q and τ_{CR}. If small-angle scattering dominates, then $\tau_t \gg \tau_q$, τ_{CR}. Hence, the ratio of τ_t and τ_q, τ_{CR} provides insight into the dominant electron-scattering events.[1,2]

A few groups have assessed the significance of one type of scatterers over another in AlGaN/GaN heterostructures.[3–7] Using a sample grown by molecular-beam epitaxy (MBE) on a GaN template, Elhamri *et al.*[3] measured a τ_t/τ_q ratio of $\sim$20, suggesting the dominance of small-angle scattering in their specimen. Data from a single heterostructure grown on single-crystal GaN with $n_{2\mathrm{D}}=2.4\times10^{12}\ \mathrm{cm}^{-2}$ and mobility $60\,000\ \mathrm{cm}^2/\mathrm{V\,s}$ indicated $\tau_t/\tau_q\sim20$, again suggesting that weak scatterers play the dominant role.[7] A common feature of all these studies is the reliance on SdH data to asses the interevent lifetime τ, which, as we will show in this report, can be unreliable in samples with even small density inhomogeneity. In addition, so far there exist no data for $n_{2\mathrm{D}} < 2\times10^{12}\ \mathrm{cm}^{-2}$, and even in the mid-$10^{12}\ \mathrm{cm}^{-2}$ range, only sparse data exist. Lastly, there are only a few reports on CR lifetime τ_{CR}. None of them compares the CR lifetime data to values of τ_t or τ_q of their specimens.[8–11]

Here, we report on data for τ_t, τ_q, and τ_{CR} measured on heterostructures with $n_{2\mathrm{D}}$ ranging from 1 to $4.5\times10^{12}\ \mathrm{cm}^{-2}$. All measurements are performed at $\sim$4 K where, in our specimens, only scattering from static scatterers (defects, interface roughness, residual impurities, etc.) contribute, and scattering by phonons is negligible.[12] Our results from modeling SdH oscillations clearly indicate that τ_q is severely affected by density inhomogeneities. We propose it not to be a good measure for the time between scattering events in our samples. Instead, τ_{CR} provides a good measure for this interevent lifetime and we can use it, in combination with τ_t, to deduce the average scattering angle φ. Our analysis shows that the scattering events in our samples are predominantly large-angle.

Our heterostructures are grown by MBE on GaN templates prepared by hydride vapor-phase epitaxy on sapphire substrates. These templates have a typical dislocation density of $\sim0.5\text{–}1\times10^9\ \mathrm{cm}^{-2}$. The 2D density $n_{2\mathrm{D}}$ was established during growth by controlling the thickness and Al% of the barrier layer. The sample parameters are listed in Table I. Evaporated Ti/Al contacts were used to perform van der Pauw, low-field Hall, and SdH measurements in the same cooldown. The first two measurements were used to determine the classical transport lifetime τ_t from the Drude mo-

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TABLE I. Parameters of samples discussed in this work. The density n_{2D} is in units of 10^{12} cm^{-2} and the mobility μ is in 10^3 cm^2/V s.

Sample no.	Al%	n_{2D}	μ
1	5	1.38	16
2	5	1.48	17.9
3	6	1.6	12
4	5	2.35	17
5	5	2.4	18
6	5	2.74	16
7	9	3.4	27
8	10	3.9	36
9	12	4.36	41

bility $\mu = e\tau_t/m^*$. The quantum lifetime τ_q was derived from SdH data using the customary expression[1] for the oscillatory part of the magnetoresistance. CR experiments using a Fourier transform spectrometer were performed in a separate cooldown. The CR carrier lifetime τ_{CR} is deduced from the half width at half-maximum ($\hbar/\tau_{CR}$) of the broadened CR line. The magnetic field was applied perpendicular to the 2DES and the carrier density was measured *in situ* from the SdH oscillations.

Figure 1 shows the three lifetimes plotted against 2D electron densities. In spite of the sample-to-sample scatter in the data, there are several important observations that can be made. In this series of samples, the mobility lifetime, τ_t is roughly constant up to $n_{2D} \sim 2 \times 10^{12}$ cm^{-2} and then increases as the density rises to 4.5×10^{12} cm^{-2}. The CR lifetime τ_{CR} is very similar to τ_t for $n_{2D} < 2.5 \times 10^{12}$ cm^{-2} and then decreases slightly for higher n_{2D}. The quantum lifetime τ_q is found to be the shortest over the entire density range studied. The dashed lines drawn through the lifetimes are guides for the eyes and are used for parameterization. The parameterizations are required since τ_{CR} was measured in cooldowns separate from those for SdH and mobility measurements. This produces slightly different densities, as seen in Fig. 1, and a parameterization of the data helps us compare the τ's.

We first address the central result of our work: the huge discrepancy between τ_{CR} and τ_q. Since we have observed shifts in SdH oscillations recorded at different contacts at the sample periphery, there is strong evidence that our specimens are inhomogeneous. Different local densities contributing slightly shifted oscillations in SdH can affect the deduced τ_q in a very significant way. On the other hand, τ_{CR} is practically immune from density inhomogeneities across the specimen. The position of the CR resonance line $\omega_c = eB/m^*$, depends only on the electron mass m^*, which is largely density independent.[13] The line broadening is caused almost exclusively by carrier scattering. Hence, τ_{CR} and not τ_q is a good measure of the interevent lifetime τ.

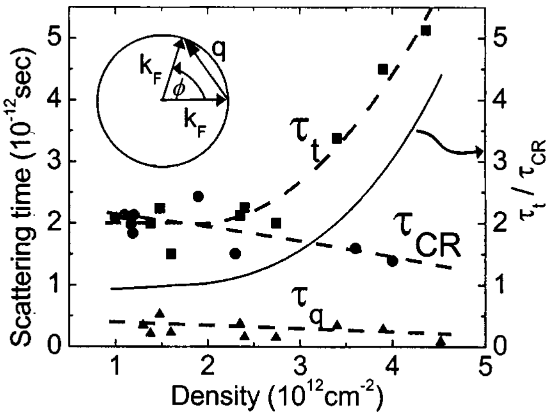

FIG. 1. Experimental results of τ_t, τ_q, and τ_{CR} plotted against n_{2D}. The dashed line through each set of τ is a guide for the eye. It also serves as a parameterization of the data and is used to produce the solid line representing the ratio τ_t/τ_{CR}.

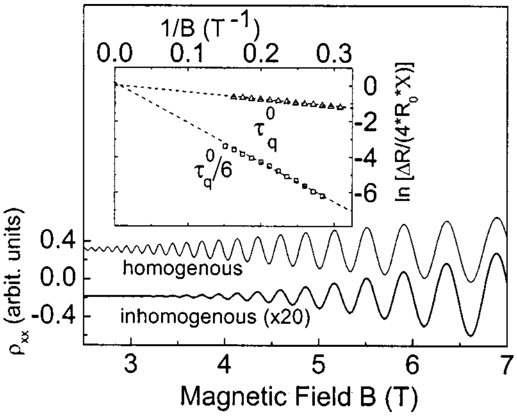

FIG. 2. Data simulation to model inhomogeneity in the 2D electron density. Magnetoresistance calculated for uniform $n_{2D} = 4 \times 10^{12}$ cm^{-2} (homogeneous). The lifetime was derived from the oscillatory part of the magnetoresistance: $\Delta R = 4R_0\,(X/\sinh X)\exp(-\pi/\omega_c\tau_q)$, with $X = 2\pi^2 kT/\hbar\omega_c$, $\omega_c = eB/m^*$ the cyclotron frequency, m^* the effective mass, and R_0 the resistance at $B=0$. Convolution of these oscillations with a Gaussian of width $\Delta n/n_{2D} = 2\%$ (inhomogeneous) yields a heavily damped set of SdH oscillations. Inset: Quantum lifetimes extracted from the oscillations of the homogeneous and the inhomogeneous 2DES. The 2% density inhomogeneity reduces the original τ_q by a factor of 6.

In order to model the effect of inhomogeneities, we assume a Gaussian distribution of densities of given width Δn. The "total SdH oscillations" are then modeled as the sum of the distribution of all "partial SdH oscillations." Mathematically, this amounts to a convolution of the magnetoresistance for the central density with a Gaussian of width Δn. Figure 2 shows a computer generated SdH trace for a density of $n_{2D} = 4 \times 10^{12}$ cm^{-2} and a lifetime $\tau_q^0 = 1$ ps together with the results of a convolution with $\Delta n = 0.02 n_{2D}$. Note that the convoluted trace is heavily damped but free of "beating." This demonstrates that the absence of beating in data from such high-density specimens does not guarantee a homogeneous electron density. Interpreting the convoluted trace as single-density experimental data yields the correct average electron density of $n_{2D} = 4 \times 10^{12}$ cm^{-2}, but a lifetime, $\tau_q = 0.18$ ps, six times lower than the actual lifetime τ_q^0. Assuming τ_{CR} to reflect the true τ, we performed simulations on all our specimens and deduced density inhomogeneities that decrease from $\Delta n = 6\%$ to 2% of n_{2D} as the density increases from $n_{2D} = 1$ to 4.5×10^{12} cm^{-2}. From our SdH simulations, we conclude that the τ_q's determined from SdH measurements are not the true quantum lifetime of the 2DES. Instead, their relatively low value is caused by small (~2%–6%) density modulations in our samples. We emphasize that the 2DES in AlGaN/GaN is particularly susceptible to this effect due to its comparatively high electron density. In AlGaAs/GaAs systems, typically $n_{2D} \sim 2 \times 10^{11}$ cm^{-2} and the required Δn for a similar suppression of τ_q is $\sim$11%. This is much larger than the observed inhomogeneity ($<$2%) in AlGaAs/GaAs structures.

For the remainder of our discussion, we take τ_{CR} to be a good measure of the interevent lifetime τ. We compare it with τ_t to learn about the average scattering angle and wave vector: φ and q, respectively. Since the 2DES is degenerate, all scattering occurs at the Fermi energy E_{F} between states of Fermi wave vector, $k_{\mathrm{F}}=\sqrt{2\pi n_{2\mathrm{D}}}$. Using a simple model pictured as an inset of Fig. 1, we can write $\sin(\varphi/2)=q/2k_{\mathrm{F}}$. Moreover, modeling the electron motion as a random walk, N^2 scatterings with average angle $\varphi=180°/\mathrm{N}$ are required for backscattering to occur, and hence $\tau_t\approx N^2\tau\approx(180°/\varphi)^2\tau_{\mathrm{CR}}$. For $\varphi=180°$, each scattering event reverses the momentum. In this limit, $q=2k_{\mathrm{F}}$ and $\tau_t\approx\tau_{\mathrm{CR}}$. For $\varphi\ll 180°$, many scattering events are required for momentum reversal. Hence, $q\ll 2k_{\mathrm{F}}$ and $\tau_t\gg\tau_{\mathrm{CR}}$. Using these expressions, we can deduce φ and q from our data. To this end, we have parameterized the data of Fig. 1 and show their ratio $\tau_t/\tau_{\mathrm{CR}}$ in Fig. 1 (see solid line). The variation of $\tau_t/\tau_{\mathrm{CR}}\approx 1$ to 4.5 reveals that the average scattering angle φ varies from $\approx$180° to $\approx$90° as $n_{2\mathrm{D}}$ increases from 1 to $4.5\times 10^{12}\ \mathrm{cm}^{-2}$. It indicates that large-angle scattering dominates in the density regime of our samples. This observation is contrary to most reports on AlGaN/GaN and is a result of our usage of τ_{CR} rather than τ_q as a measure for the time between scattering events. Had we used τ_q instead, the average φ would decrease to a range of 73° to 37°. Using the expressions just presented and our $\tau_t/\tau_{\mathrm{CR}}$ data, we can also derive the density dependence of the wave vector q. Beyond $n_{2\mathrm{D}}\approx 2.5\times 10^{12}\ \mathrm{cm}^{-2}$, where the parameterization of our data is quite reliable (see Fig. 1), we find q not to vary significantly. This indicates that scattering events of approximately constant q value, whose average angle, and hence effectiveness, decreases with increasing density, are dominant throughout this regime.

Finally, we compare our data with available theoretical results. From Fig. 3 of the work of Hsu and Walukiewicz,[14] we can estimate that for $\sim$10% Al, τ_t/τ increases from $\sim$10 to $\sim$20 as $n_{2\mathrm{D}}$ increases from 1 to $2\times 10^{12}\ \mathrm{cm}^{-2}$, and drops as the density increases further. In contrast, we measure much smaller lifetime ratios that rise continuously from $\sim$1 to $\sim$4.5 as $n_{2\mathrm{D}}$ increases from 1 to $4.5\times 10^{12}\ \mathrm{cm}^{-2}$ (see our Fig. 1). The discrepancies may be due to the fact that large-angle scatterers such as interface roughness and dislocations were not considered in Ref. 14. Lifetime ratios limited by charged dislocations calculated by Jena and Mishra[15] are found to be $<$10 (Ref. 15, Fig. 3 with $\theta_c=\pi/10$) and monotonically increasing for up to $n_{2\mathrm{D}}\sim 10\times 10^{12}\ \mathrm{cm}^{-2}$. The similarities between our data and these calculations support our model in which large-angle scattering dominates. In fact, the average spacing of dislocations in our specimens is $\sim$400 nm as determined from atomic force microscope measurements. The mean free path deduced from the τ_{CR} and the Fermi velocity $v_{\mathrm{F}}=\sqrt{2E_{\mathrm{F}}/m^*}$ values ranges between 200 and 300 nm. This suggests dislocations to be a major contributor to the overall low temperature scattering.

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