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Electron scattering in AlGaN/GaN structures

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We present data on mobility lifetime \( \tau_1 \), quantum lifetime \( \tau_q \), and cyclotron resonance lifetime \( \tau_{\text{CR}} \) of a series of high-mobility two-dimensional electron gases in the AlGaN/GaN system, covering a density range of 1 to \( 4.5 \times 10^{12} \) cm\(^{-2} \). We observe a large discrepancy between \( \tau_q \) and \( \tau_{\text{CR}} (\tau_q - \tau_{\text{CR}}/6) \), and explain it as the result of density fluctuations of only a few percent. Therefore, only \( \tau_{\text{CR}} \)—and not \( \tau_q \)—is a reliable measure of the time between electron-scattering events in these specimens. The ratio \( \tau_1/\tau_{\text{CR}} \) increases with increasing density in this series of samples, but scattering over this density range remains predominantly in the large-angle scattering regime.

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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 \( \tau \) between events and an average scattering angle \( \phi \). Since each scattering event dephases the wave function, the quantum lifetime \( \tau_q \) is very similar to \( \tau \). In contrast, the transport lifetime \( \tau_1 \) deduced from mobility, measures the time for electron backscattering to occur. It depends heavily on \( \phi \) and must always exceed \( \tau_q \) and \( \tau_{\text{CR}} \). For large-angle scattering, \( \phi \) is large and \( \tau_1 \) is very similar to \( \tau_q \) and \( \tau_{\text{CR}} \). If small-angle scattering dominates, then \( \tau_1 \gg \tau_q \), \( \tau_{\text{CR}} \). Hence, the ratio of \( \tau_1 \) and \( \tau_q \), \( \tau_{\text{CR}} \) 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 \textit{et al.}\(^{5} \) measured a \( \tau_1/\tau_q \) 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 \( n_{2\text{D}} = 2.4 \times 10^{12} \) cm\(^{-2} \) and mobility 60 000 cm\(^2\)/V s indicated \( \tau_1/\tau_q \sim 20 \), again suggesting that weak scatterers play the dominant role.\(^{7} \) A common feature of all these studies is the reliance on SdH data to assess the interevent lifetime \( \tau \), 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 \( n_{2\text{D}} < 2 \times 10^{12} \) cm\(^{-2} \), and even in the mid-\( 10^{12} \) cm\(^{-2} \) range, only sparse data exist. Lastly, there are only a few reports on CR lifetime \( \tau_{\text{CR}} \) for such samples. None of them compares the CR lifetime data to values of \( \tau_1 \) or \( \tau_q \) of their specimens.\(^{8-11} \)

Here, we report on data for \( \tau_1 \), \( \tau_q \), and \( \tau_{\text{CR}} \) measured on heterostructures with \( n_{2\text{D}} \) ranging from 1 to \( 4.5 \times 10^{12} \) cm\(^{-2} \). All measurements are performed at ~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 \( \tau_q \) 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, \( \tau_{\text{CR}} \) provides a good measure for this interevent lifetime and we can use it, in combination with \( \tau_1 \), to deduce the average scattering angle \( \phi \). 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 \( \sim 0.5 - 1 \times 10^9 \) cm\(^{-2} \). The 2D density \( n_{2\text{D}} \) 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 \( \tau_t \) from the Drude mo-
ability $\mu = e\tau /m^*$. The quantum lifetime $\tau_q$ 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 lifetime $\tau_{\text{CR}}$ is deduced from the half width at half-maximum ($h/\tau_{\text{CR}}$) of the broadened CR line. The magnetic field was applied perpendicular to the 2DES and the carrier density was measured \textit{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, $\tau_\text{v}$, is roughly constant up to $n_{2D}=2\times10^{12}$ cm$^{-2}$ and then increases as the density rises to $4.5\times10^{12}$ cm$^{-2}$. The CR lifetime $\tau_{\text{CR}}$ is very similar to $\tau_\text{v}$ for $n_{2D}\leq2.5\times10^{12}$ cm$^{-2}$ and then decreases slightly for higher $n_{2D}$. The quantum lifetime $\tau_q$ 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 $\tau_{\text{CR}}$ 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 $\tau$’s.

We first address the central result of our work: the huge discrepancy between $\tau_{\text{CR}}$ and $\tau_q$. 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 $\tau_q$ in a very significant way. On the other hand, $\tau_{\text{CR}}$ 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, $\tau_{\text{CR}}$ and not $\tau_q$ is a good measure of the interevent lifetime $\tau$.

In order to model the effect of inhomogeneities, we assume a Gaussian distribution of densities of given width $\Delta n$. 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 $\Delta n$. Figure 2 shows a computer generated SdH trace for a density of $n_{2D} = 4\times10^{12}$ cm$^{-2}$ and a lifetime $\tau_{q}^0 = 1$ ps together with the results of a convolution with $\Delta n = 0.02n_{2D}$. 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 $n_{2D} = 4\times10^{12}$ cm$^{-2}$, but a lifetime $\tau_q = 0.18$ ps, six times lower than the actual lifetime $\tau_{q}^0$. Assuming $\tau_{\text{CR}}$ to reflect the true $\tau$, 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 $4.5\times10^{12}$ cm$^{-2}$. From our SdH simulations, we conclude that the $\tau_q$’s determined from SdH measurements are not the true quantum lifetime of the 2DES. Instead, their relatively low value is caused by small ($\sim 2\%–6\%$) 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

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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 $\mu$ is in $10^3$ cm$^2$/V·s.

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<th>$\mu$</th>
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**FIG. 1.** Experimental results of $\tau_\text{v}$, $\tau_q$, and $\tau_{\text{CR}}$ plotted against $n_{2D}$. The dashed line through each set of $\tau$ 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 $\tau_\text{v}/\tau_{\text{CR}}$.

**FIG. 2.** Data simulation to model inhomogeneity in the 2D electron density. Magnetoresistance calculated for uniform $n_{2D} = 4\times10^{12}$ cm$^{-2}$ (homogeneous). The lifetime was derived from the oscillatory part of the magnetoresistance: $\Delta R = 4R_\text{Q}(\chi/\sinh\chi)\exp(-m^*\omega_c\tau_q)$, with $\chi = 2\pi kT/h\omega_c$, $\omega_c = eB/m^*$ the cyclotron frequency, $m^*$ the effective mass, and $R_\text{Q}$ 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 $\tau_q$ by a factor of 6.
the required $\Delta n$ for a similar suppression of $\tau_2$ is $\sim 11\%$. This is much larger than the observed inhomogeneity (2%) in AlGaAs/GaAs structures.

For the remainder of our discussion, we take $\tau_{\text{CR}}$ to be a good measure of the interevent lifetime $\tau$. We compare it with $\tau_2$ to learn about the average scattering angle and wave vector: $\varphi$ and $q$, respectively. Since the 2DES is degenerate, all scatterings occur at the Fermi energy $E_F$ between states of Fermi wave vector, $k_F = \sqrt{2 \pi n_{2D}}$. Using a simple model pictured as an inset of Fig. 1, we can write $\sin(\varphi/2) = q/2k_F$. Moreover, modeling the electron motion as a random walk, $N^2$ scatterings with average angle $\varphi = 180^\circ/N$ are required for backscattering to occur, and hence $\tau_{\text{CR}} = N^2 \tau \approx (180^\circ/\varphi)^2 \tau_{\text{CR}}$. For $\varphi = 180^\circ$, each scattering event reverses the momentum. In this limit, $q = 2k_F$ and $\tau_{\text{CR}} \approx \tau_{\text{C}}$. For $\varphi \approx 180^\circ$, many scattering events are required for momentum reversal. Hence, $q \ll 2k_F$ and $\tau_{\text{C}} \gg \tau_{\text{CR}}$. Using these expressions just presented and our usage of $\tau_{\text{C}}$ rather than $\tau_2$ would decrease to a range of 73° to 37°. Using the Fermi velocity $v_F = \sqrt{2E_F/m^*}$ 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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12 Simulations yield acoustic-phonon-limited $\tau_{\text{ac}} \approx 1$ ns at 4 K.
13 Even a 10% density fluctuation at $4 \times 10^{12}$ cm$^{-2}$ adds a 1% spread in $m^*$ due to band nonparabolicity, which in turn broadens the CR line also at the 1% level.