Quantum and transport lifetimes of two-dimensional electrons gas in AlGaN/GaN heterostructures

P. Lorenzinia and Z. Bougrioua
Centre de Recherche sur l’Hétéroépitaxie et ses Applications, CNRS, rue Bernard Gregory, F-06560 Valbonne, France

A. Tiberj and R. Taek
Groupe d’Etude des Semiconducteurs, Montpellier University & CNRS, place E. Bataillon, F-34095 Montpellier, France

M. Azize
Centre de Recherche sur l’Hétéroépitaxie et ses Applications, CNRS, rue Bernard Gregory, F-06560 Valbonne, France

M. Sakowicz, K. Karpierz, and W. Knap
Groupe d’Etude des Semiconducteurs, Montpellier University & CNRS, place E. Bataillon, F-34095 Montpellier, France

(Received 29 July 2005; accepted 13 October 2005; published online 30 November 2005)

The transport and quantum lifetimes were respectively deduced from low-temperature mobility and Shubnikov–de Haas measurements as a function of carrier density in metal organic vapor phase epitaxy-grown AlGaN/GaN/sapphire heterostructures. We show experimentally that the lifetime ratio varies as a bell curve, qualitatively confirming a recent theoretical prediction. However the experimental ratio varied much less than was theoretically predicted: From 9 to 19 for carrier densities in $1–9 \times 10^{12}$ cm$^{-2}$ range. Moreover, we show the variation of quantum time with carrier density presents some discrepancy with the theoretical study. We also show that transport to quantum lifetime ratio cannot be used alone as a clear figure of merit from AlGaN/GaN heterojunctions. © 2005 American Institute of Physics. [DOI: 10.1063/1.2140880]

The improvement of performances in modern AlGaN/GaN power devices requires the investigation and identification of parasitic scattering mechanisms that are likely responsible for the lack of reliability frequently observed up to now. As pointed out by recent theoretical work,\textsuperscript{1} one of the most efficient ways to identify these scattering mechanisms is the study of transport and quantum scattering lifetimes versus carrier density in the two-dimensional electron gas (2DEG). The quantum lifetimes measure the intercollision time, no differences are made between large and small scattering angles $\theta$, and all scattering events have the same weight. The transport lifetimes measure the time the carrier spent in a particular direction (electric-field direction, for example) so we have to take into account an angular factor $[1–\cos(\theta)]$ which overweight large scattering angle over small angle. This work presents a systematic experimental study of the quantum and transport scattering rates versus carrier density measured in AlGaN/GaN heterojunctions. The results for heterojunctions with different barrier and interface architecture are presented. We show that the experimental data confirm some of the main theoretically predicted trends.\textsuperscript{1} We also point out some discrepancies in theoretical interpretation and discuss their possible origin.

The investigated samples were grown by metalorganic vapour phase epitaxy on sapphire substrates. The AlGaN/GaN structures were deposited on Fe-modulation-doped semi-insulating GaN templates containing a low dislocation density ($3.5–7.8 \times 10^8$ cm$^{-2}$) using a process described elsewhere.\textsuperscript{2} Three different structures—named A, B, and C—were investigated. Table I gives their technological parameters: A, B, and C have a 21, 26, 25 nm AlGaN supply layer with, respectively, 23%, 29%, and 25% of aluminum. Moreover, for A and specimen C, a 1 nm AlN spacer layer was grown at the AlGaN/GaN interface. Typically, all of these as-grown ungated AlGaN/GaN heterostructures present a 2DEG with a carrier density in the range of $6–9 \times 10^{12}$ cm$^{-2}$ and mobility above $2000$ cm$^2$ V$^{-1}$ s$^{-1}$ at 300 K, and in the range of $14\,800–30\,000$ cm$^2$ V$^{-1}$ s$^{-1}$ at 4.2 K.

The geometry used for precise transport experiments was gated Hall bars, defined by classical photolithography technology\textsuperscript{2} (see Hall bar in the inset of Fig. 1). Hall effect and resistivity experiments were performed at 4.2 K with a

\[ \Delta \rho \Delta \rho_0 \]

\begin{figure}[h]
\centering
\includegraphics{fig1}
\caption{SdH oscillations measured on a AlGaN/GaN gated Hall bar (shown in the inset; Sample A). Fitting results of the envelope of SdH oscillations are shown in dashed lines.}
\end{figure}
magnetic field swept up to 10 T. We measured the Shubnikov–de Haas (SdH) effect versus the applied magnetic fields \( B \) for different carrier densities modulated by the applied gate voltages. A typical trace of the SdH oscillations of the longitudinal resistivity for Specimen A is shown in Fig. 1. The transport lifetime \( \tau_t \) was derived using the Drude model from the Hall mobility (\( \mu=\sigma t/m^* \)) taking the GaN conduction effective mass equal to 0.24\( m_0 \). The quantum scattering time \( \tau_q \) was determined by fitting the envelope of SdH oscillations with the classical formula:

\[ \tau_q = \frac{R_{\text{SdH}} - R_0}{R_0} \frac{4A}{\sinh A} \exp\left(-\frac{\pi}{\omega_c \tau_q}\right) \cos\left(\frac{\pi \Delta E_Z}{\hbar \omega_c}\right), \]

where \( \Delta E_Z, \ \omega_c = eB/m^* \), and \( A = 2\pi^2kT/\hbar \omega_c \) are, respectively, the spin splitting, the cyclotron resonance, and the damping factor for SdH oscillations. One should note that this formula contains an additional term (the last one) taking into account the spin splitting.3

Figure 2(a) summarizes the mobility and transport lifetime \( \tau_t \) evolutions obtained on the three measured samples by modulating the carrier density \( n_c \) with an applied gate voltage varying in the range from +0.5 V to −4 V (from open to almost pinched-off channel). For the three samples, the mobility (the transport lifetime) versus carrier density exhibits a classical bell shape. At low electron density, the mobility rapidly increases for increasing density. The mobility peaks around \( 4 \times 10^{12} \) cm\(^{-2} \) for Samples A and C, and at a slightly higher carrier density in Sample B \( (5.5 \times 10^{12} \) cm\(^{-2} \)). The maximum of mobility reaches 33 000 cm\(^2\) V\(^{-1}\) s\(^{-1}\) for Sample C with an AlN spacer, and around 20 000 cm\(^2\) V\(^{-1}\) s\(^{-1}\) for Samples A and B. The rise in mobility with increasing carrier density for densities below \( 5–6 \times 10^{12} \) cm\(^{-2} \) is due to the more efficient screening of Coulomb scattering centers. Then, the mobility decreases with a further increase in carrier density. This mobility decrease with increasing \( n_c \) is known to be a consequence of increasing efficiency of alloy and interface roughness scattering mechanisms.4 To validate this interpretation, the mobility at a low temperature was calculated taking into account the classical scattering mechanisms, including threading dislocations,4 alloy disorder,5 interface roughness,6,7 and remote and background impurities.8 The results of the fit are plotted as solid lines in Fig. 2(a), and the component mobilities for the most important mechanisms are shown for Sample A in Fig 2(b). The fitting parameters needed for roughness contribution to the mobility fit (Table I) are practically identical for the three samples. This is consistent with the fact that most of the epitaxy parameters were the same for the three heterostructures. The lower mobility obtained in Sample B can be interpreted by a higher concentration of background impurities (GaN template dependent). For Sample C, the incorporation of an AlN spacer—in order to reduce alloy disorder scattering—is successful as this 2DEG has the best mobility for almost all \( n_c \) ranges. Our calculation confirms that at low temperatures, background impurities and threading dislocations are the dominant sources of scattering at low 2DEG density. It also stresses that for a higher \( n_c \) range (here, \( >6 \times 10^{12} \) cm\(^{-2} \)), the interface roughness and alloy disorder play key roles.

Figure 3(a) shows measured quantum lifetimes \( \tau_q \) versus carrier density for our samples. First, we observe that the better the mobility, the larger the quantum lifetime [compare with Fig. 2(a)]. For Sample B, we note a much lower quantum time (a factor of 2) than could be expected from the mobility value. For two samples (A and B), the quantum time has a well-defined bell shape but with a maximum at higher \( n_c \) than that of the transport lifetime. This bell shape is different from the concave shape predicted by theory.1 As the experimental transport and quantum lifetimes for Samples A and B have a similar bell-like shape, we assume that this

<table>
<thead>
<tr>
<th>Sample</th>
<th>GaN thickness (µm)</th>
<th>Dislocations (cm(^{-2} ))</th>
<th>% Al</th>
<th>Thickness (nm)</th>
<th>Background impurities (cm(^{-3} ))</th>
<th>Roughness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.7</td>
<td>( 7.8 \times 10^6 )</td>
<td>21</td>
<td>23</td>
<td>( 7 \times 10^{16} )</td>
<td>0.22</td>
</tr>
<tr>
<td>B</td>
<td>9.0</td>
<td>( 3.5 \times 10^6 )</td>
<td>26</td>
<td>29</td>
<td>( 1.3 \times 10^{17} )</td>
<td>0.2</td>
</tr>
<tr>
<td>C</td>
<td>7.3</td>
<td>( 4.7 \times 10^6 )</td>
<td>25</td>
<td>25</td>
<td>( 9 \times 10^{16} )</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Note: rms R. = Root-mean-square roughness; and corr. L = correlation length.

![Figure 2](image-url)
similar behavior of both lifetimes can be interpreted as the interplay and balance between carrier screening and interface and alloy scattering. We would like to stress that for Sample C, where the alloy disorder scattering is eliminated by the introduction of an AlN spacer, the quantum time saturates at high \( n_i \) instead of decreasing, which confirms high interface quality and/or reduced alloy disorder scattering.

Figure 3(b) shows the lifetime ratio \( \tau_q/\tau_q \) for the three AlGa\textsubscript{N}/GaN heterostructures. As predicted in Ref. 1, the maximum is obtained for higher density when the Al composition is increased. Though a bell shape is obtained as in Ref. 1, the highest value of the ratio is around 19, two times smaller than the theoretical\textsuperscript{1} value calculated for a similar Al compound. However, surprisingly, the maximum value we find is equivalent to the value already reported in a 2DEG with a very high mobility (\( >60,000 \, \text{cm}^2 \, \text{V}^{-1} \, \text{s}^{-1} \)) confined in a heterostructure grown on bulk GaN substrate.\textsuperscript{9} In our case, this maximum \( \tau_q/\tau_q \) is obtained for Sample B that has the lowest mobility of the series (\( <20,000 \, \text{cm}^2 \, \text{V}^{-1} \, \text{s}^{-1} \)) or lowest transport lifetime. Actually, though the mobility is the lower, it appears that the quantum time is more strongly degraded by defects (background, electrical, or morphological) which results in a higher lifetime ratio \( \tau_q/\tau_q \). As a consequence, one can anticipate that transport to the quantum lifetime ratio, alone, cannot be a clear figure of merit. Further theoretical investigations, taking into account the contribution of all scattering centers, are underway in order to interpret the evolution of the quantum lifetime versus carrier density.

In conclusion, we have measured the transport and quantum lifetimes for AlGa\textsubscript{N}/GaN heterostructures. We report quantum lifetime measurements for a large range of carrier densities. It is found that both quantum and transport lifetimes have the same bell shape behavior versus carrier density, contrary to theoretical predictions. Also, we note that quantum time is very sensitive at high \( n_i \) to interface scattering. Finally, when \( \tau_q \) is strongly degraded (by Coulomb scattering and/or interface scattering), one can get a large \( \tau_q/\tau_q \) ratio even if the mobility is low. The ratio \( \tau_q/\tau_q \), alone, cannot be a clear figure of merit for AlGa\textsubscript{N}/GaN heterojunctions.

Partial support by Polish Ministry of Scientific Research and Information Technology Grant No. 3T11B04528 is acknowledged.

\textsuperscript{1}L. Hsu and W. Walukiewicz, Appl. Phys. Lett. 80, 2508 (2002).