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An electrical characterization of a two dimensional electron gas in GaN/AlGaN on silicon substrates

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We present results of transport measurements performed on AlGaN/GaN heterostructures grown on silicon substrates. Variable temperature Hall effect measurements revealed that the temperature dependence of the carrier density and mobility were characteristic of a two dimensional electron gas (2DEG). Carrier densities greater than 1 x 10^{13} cm^{-2} and Hall mobilities in excess of 1500 cm^2/Vs were measured at room temperature. Variable field Hall measurements at low temperatures, and in magnetic fields up to 6 T, indicated that conduction is dominated by a single carrier type in these samples. Shubnikov de-Haas (SdH) measurements were also performed, but no oscillations were observed in fields up to 8 T and at temperatures as low as 1.2 K. Illuminating some of the samples with a blue (λ = 470 nm) light emitting diode (LED) induced a persistent increase in the carrier density. Shubnikov de-Haas measurements were repeated and again no oscillations were present following illumination. However, exposing the samples to radiation from an ultraviolet (UV) (λ = 395 nm) LED induced well defined SdH oscillations in fields as low as 4 T. The observation of SdH oscillations confirmed the presence of a 2DEG in these structures. It is hypothesized that small angle scattering suppressed the oscillations before exposure to UV light. This conclusion is supported by the observed increase in the quantum scattering time, τ_q, with the carrier density and the calculated quantum to transport scattering times ratio, τ_q/τ_c. For instance, in one of the samples the τ_q increased by 32% while the τ_c changed by only 3% as the carrier density increased; an indication of an increase in the screening of small angle scattering. The absence of SdH oscillations in fields up to 8 T and at temperatures as low as 1.2 K is not unique to AlGaN/GaN on silicon. This behavior was observed in AlGaN/GaN on sapphire and on silicon carbide. Shubnikov-de Haas oscillations were observed in one AlGaN/GaN on silicon carbide sample following exposure to radiation from a UV LED.

I. INTRODUCTION

Due to their superior electrical and optical properties, the group III-nitride family, consisting of GaN, AlN, InN, their alloys and heterostructures, primarily AlGaN/GaN and InGaN/GaN, are the subject of intense research activity world wide as they promise to usher in a new era in optoelectronic and electronic devices.[1-4] Characteristics, such as high electron saturation velocity, high-peak velocity, high breakdown voltage, high thermal conductivity, chemical inertness, mechanical stability, and excellent radiation hardness, make the nitride family of semiconductors materials of choice for the fabrication of electronic devices capable of operating at high temperatures, high frequency, and high power densities.[1-3,5] The nitrides can crystallize in either the zinc-blend or the wurtzite form, with the wurtzite structure being the most commonly studied. In this structure, the nitrides all have a direct band gap with energies ranging from 1.9 eV, the commonly cited value,[6] for InN to 6.2 eV for AlN.[1,2] These energies correspond to wavelengths that range from the visible to the ultraviolet; opening the door to a new class of optoelectronic devices.[1-3]

GaN optoelectronic devices are commercially available,[1,2] including light emitting diodes (LEDs), laser diodes, and ultraviolet emitters and detectors. These devices have impacted several industries.[2,4] One area of intense interest is solid state lighting. GaN-based white light sources promise to be cool to the touch, robust, extremely reliable, and use only a fraction of the energy compared to incandescent bulbs.[1,3]

In the field of electronic devices, III-nitrides hold much promise for devices that operate at high frequency, high power, high temperature and in caustic environments.[5,7,8] To appreciate the magnitude of the potential of these materials one need only consider the Baliga and the Johnson figures of merit, which are the two most often used figures for comparing semiconductors with respect to high temperature, high frequency and high power performance.[9] The Baliga figure of merit for GaN is about 100 times that of Si and about 6 times that of GaAs, whereas the Johnson figure of merit for GaN is about 280 times that of Si and about 40 times that of GaAs.[10-12] These numbers unambiguously reflect the superiority of GaN over Si and GaAs in these device areas. GaN based electronic devices are expected to benefit many areas including wireless communications, automotive and aerospace electronics, power conditioning and transmission.

With so much promise, what then is inhibiting the commercialization of III-nitride based electronic devices? As with any developing technology, there are problems that must be overcome before commercial viability is realized.[13-16] Since high quality GaN substrates are not readily available, a key issue is selecting a suitable substrate for GaN epitaxy. The two most commonly used substrates for GaN epitaxial growth are sapphire and silicon carbide. However, there are problems associated with using these substrates that have prevented GaN from establishing a clear pathway to commercialization[17] in the electronic device field and are limiting GaN from realizing its full potential in the optoelectronic device field. GaN is poorly lattice matched to both sapphire and silicon carbide resulting in defects which degrade electronic device performance.[18-22] The current defect density has not prohibited commercial production of LEDs, but has proven to be a major obstacle for reliable performance of electronic devices. In addition, both of these substrates are not available in large diameters and are inhibitively expensive (particularly silicon carbide) making mass production of GaN devices on these substrates not cost effective. For these reasons, several semiconductor research groups have turned to Si as an alternative substrate.[23-29] The ability to successfully deposit device quality GaN on a Si substrate would be a major achievement and holds much promise for electronic device development.

Silicon offers some very important advantages over sapphire and silicon carbide: High quality, large size wafers, and very low cost (about 1/10 the price of sapphire and about 1/100 the price of silicon carbide wafers).[30] In addition, silicon is a better thermal conductor than sapphire. The development of Si as a substrate has been delayed mainly for two reasons. First, Si is not well matched thermally to GaN.[24] Second, like sapphire and silicon carbide, Si is not well lattice matched to GaN.[31] These mismatches present a major drawback for silicon as a substrate for GaN as they put considerable limitations on the thickness of GaN films due to cracking. Several research groups are actively addressing this problem by using a variety of different growth techniques .[23-31]

To overcome the problems arising from the thermal and lattice mismatch, the Nitronex materials group has developed an (Al)GaN based transition layer between the silicon substrate and the GaN layer. Their approach has led to the growth of crack-free GaN films with total epitaxial thicknesses exceeding 2 μm.[32] Having successfully grown sufficiently thick, crack-free GaN films, the group has moved on to grow device quality AlGaN/GaN heterostructures. In this article, we report the results of our magnetotransport studies on these AlGaN/GaN heterostructures grown on silicon substrates.

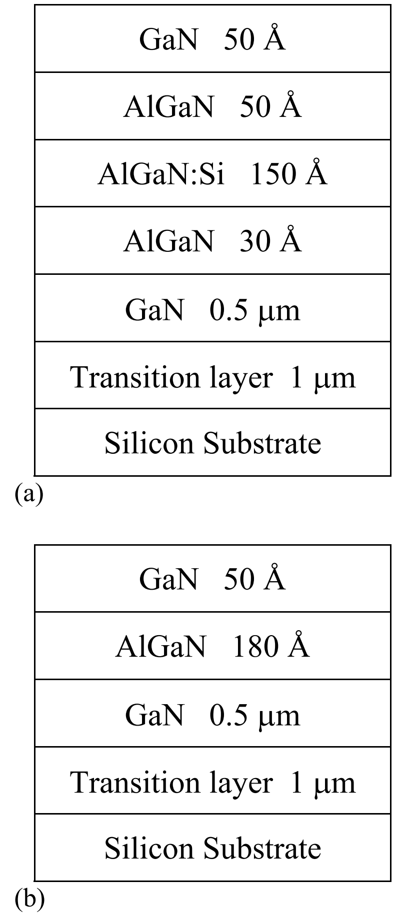

FIG. 1. Schematic of the MOCVD grown sample structures. The Al mole fraction is ~25% for structure (a) and ~20% for structure (b). Samples A and B has the structure shown in (a) and sample C has the structure shown in (b).

II. EXPERIMENT

The AlGaN/GaN heterostructures were grown by Nitronex Corporation on 100 mm Si (111) wafers in a custom-built, cold wall, rotating disc MOCVD reactor. The growth temperature was nominally 1000 ºC. The reactor design enables control of temperature and flow across multiple zones allowing for development of uniform processes. Trimethylgallium (TMG) and trimethylaluminum (TMA) precursors were carried by Pd-diffused hydrogen. Ammonia (NH_3) was used as the N precursor. The aluminum content in the device layer was determined by reflectance measurements. Electrical characterization was performed on 7mm x 7mm van der Pauw samples, which were diced from as grown wafers. A Ti/Al/Ni/Au ohmic contact scheme was electron beam evaporated to the corners of the samples and rapid thermal annealed to complete the metallization. Two sets of samples were investigated. One set, Figure 1a, had an Al mole fraction of ~25% and an AlGaN donor layer that was intentionally doped with 2 x 10^{18} Si atoms. The other set, Figure 1b, had an Al mole fraction of ~20% and was not intentionally doped. The energy band gap of AlGaN varies with the Al content.[1,33,34] For an Al content of 20% and 25% the gaps are determined to be 3.81 eV and 3.92 eV respectively.

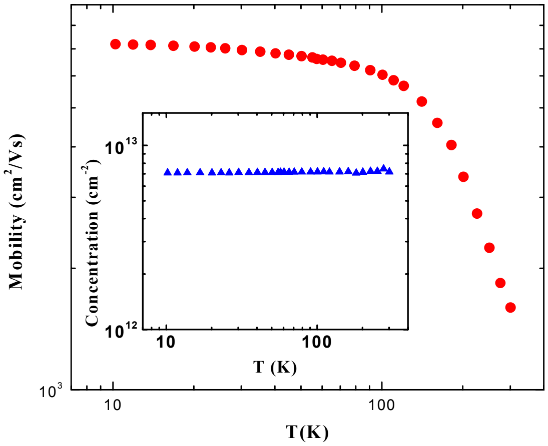

FIG. 2.. Carrier concentration (solid triangles shown in the inset) and mobility (solid circles) as a function of T for one of the samples, sample B, used in this study. The carrier densities at 300 K and 10 K are 7.18 x 10^{12} cm^{-2} and 7.09 x 10^{12} cm^{-2} respectively. The carrier mobilities at 300 K and 10 K are 1598 cm^2/Vs and 7180 cm^2/Vs, respectively.

For the electrical characterization of these AlGaN/GaN heterostructures, we performed three types of electromagnetic measurements. Variable temperature Hall effect measurements were carried out between 10K and 300K at a magnetic field of 0.5 T using DC guarded measurements. A calibrated AlGaAs diode thermometer was used to measure the temperature. These measurements allowed us to study how the carrier density, the mobility, and the resistivity varied with the temperature. To investigate the possibility of multicarriers contributing to conduction in the samples, and to determine if parallel conduction was significant at low temperature, magnetic field dependent Hall effect measurements were performed. Shubnikov-de Haas measurements were performed to investigate the presence and the quality of a two dimensional gas (2DEG) in these samples. Both the variable field Hall effect and the SdH experiments were performed in a ^{4}He cryostat equipped with a 9 Tesla superconducting magnet. The sample was immersed in liquid helium and the pressure was varied to change the temperature from 4.2 K to 1.2 K. For higher temperatures, a heater was used to warm the sample to the desired temperature while the sample was immersed in flowing He vapor. A calibrated thermometer was used to measure the sample temperature. The standard four probe ac method was used to gather data. The sample current was kept low to avoid self heating.

III. RESULTS AND DISCUSSION

Figure 2 plots the carrier concentration, shown in the inset, and the mobility as a function of temperature, T, for one of the three samples, sample B, used in this study. The carrier densities and mobilities for samples A, B, and C at three different temperatures are summarized in Table I. Note that n and μ are relatively insensitive to T below about 100 K. This type of T dependence for n and μ is largely the same for all samples investigated in this work. This kind of T dependence is expected from a sample that exhibits a two dimensional electron gas.[35] A flat mobility versus T at low temperatures suggests the presence of a 2DEG. Also note in

Table I. Carrier density, n, given in (10^{12} cm^{-2}) and carrirer mobility, μ, given in (cm^2/Vs) at 300 K, 80 K and 10 K for samples A, B, and C.

	A	B	C
n 300 K	9.22	7.18	10.49
μ 300 K	1185	1598	1400
n 80 K	8.39	7.16	8.21
μ 80 K	6135	6351	6246
n 10 K	8.30	7.09	8.16
μ 10 K	7011	7180	6980

Figure 2 that there is no rapid increase in n at high temperatures; a phenomenon that is usually associated with parallel conduction. The observed T dependence is similar to that observed in AlGaN/GaN structures grown on either silicon carbide or sapphire.[35,36] Another salient point to mention here is that the values of the mobility recorded in these samples are comparable to those observed in AlGaN/GaN structures grown on other substrates. While much higher mobilities (in excess of 70 000 cm^2/Vs at low temperatures) have been reported for AlGaN/GaN structures,[37-39] it is important to note that these high mobility values were recorded in samples with much lower carrier concentrations and Al mole fraction than reported here. However, for equivalent carrier densities and Al mole fraction, the mobilities reported here are comparable to what is commonly reported for AlGaN/GaN grown on substrates other than Si;[40-45] indicating the proportionate quality of GaN on Si, with respect to GaN on sapphire or SiC.

To investigate the presence of any appreciable parallel conduction, low temperature, variable magnetic field measurements were performed on multiple samples. The reduced conductivities, X and Y as a function of B are plotted in Figure 3 for a typical sample. The reduced conductivities, X and Y, are, respectively, σ_{xx} and $2\sigma_{xy}$ divided by the zero field conductivity. The solid lines are the fit to the data, as in the analysis of Kim *et al.*[46] According to Kim *et al.* when the reduced conductivities are plotted as presented in Figure 3, and only a single carrier type is present, then at a magnetic field B, X takes on the value of 0.5 and Y peaks with a magnitude of 1. According to this analysis, it is clear from the data presented in Figure 3 that only a single carrier type is present in these samples at this temperature, with a carrier density of 7.58 x 10^{12} cm^{-2} and a mobility of 6965 cm^2/Vs. (The dashed lines in Figure 3 are provided for reference.) A multicarrier fit to the data exhibited the same results as the single carrier fit confirming that a single carrier type dominates conduction.

To confirm the presence of a 2DEG in the investigated structures, SdH effect measurements were performed on several samples as a function of temperature between 4.2 K and 1.2 K in fields ranging from 0 T to 8.5 T. The Shubnikov-de Haas effect, a quantum mechanical oscillation in the longitudinal resistance as a function of the magnetic field, is a standard technique for characterizing

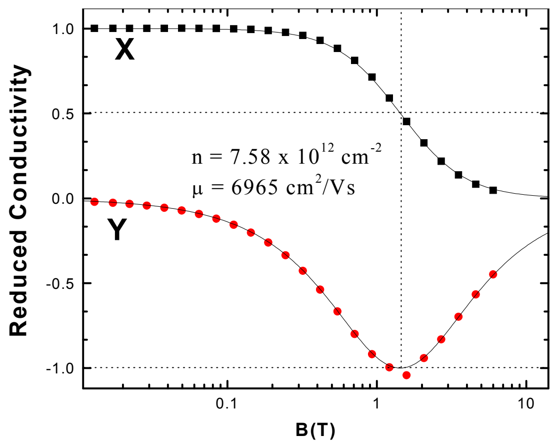

FIG. 3. A typical reduced conductivity as a function of the magnetic field at 1.2 K. The reduced conductivities X and Y are σ_{xx} and $2\sigma_{xy}$ divided by the zero field conductivity, respectively. The maximum field used is 6 T. The solid lines are the fit to the magnetic field data. Following the analysis of Kim *et al.* only a single carrier type is present with a mobility of $\mu = 6965$ cm^2/Vs and a carrier density of $n = 7.58 \times 10^{12}$ cm^{-2}. The dashed lines are provided for reference, only. This data is from sample C.

two-dimensional systems. It allows the extraction of several key transport parameters of the 2DEG. Assuming only one subband is occupied, and neglecting the contribution of higher harmonics, the oscillatory part, $\Delta\rho_{xx}$, of the magnetoresistivity is given by:[47]

$$\frac{\Delta\rho_{xx}}{2\rho_o} = 2\,\frac{\chi}{\sinh(\chi)}\,\exp\left(\frac{-\pi}{\omega_c\tau_q}\right)\cos\left(\frac{2\pi\varepsilon}{\hbar\omega_c}-\pi\right), \qquad (1)$$

where $\chi = \dfrac{2\pi^2 k_B T}{\hbar\omega_c}$, $\omega_c = \dfrac{eB}{m^*}$, τ_q is the quantum scattering time, $\varepsilon = \dfrac{\hbar^2\pi n}{m^*}$ is the Fermi energy, k_B is the Boltzman constant, $\hbar$ is the reduced Plank's constant, T is the temperature, B is the magnetic field, m* is the effective mass, and n is the electron density of the 2DEG. Since the oscillations are periodic in 1/B and since the frequency of the oscillations depends only on the carrier density of the 2DEG, one can determine the carrier density of the 2DEG by plotting the position of the extrema in 1/B as a function of Landau levels (integers). The quantum scattering time, τ_q, and the effective mass, m*, can be evaluated, respectively, from the magnetic field and the temperature dependence of the amplitude of the oscillations using equation 1.

Initial SdH measurements on the five samples investigated showed no oscillations in fields up to 8 T and in temperatures as low as 1.2 K. Before we cite the absence of SdH oscillations as evidence of the absence of a 2DEG in these structures, it is important to first recall that the temperature dependent Hall effect data (see Figure 2) supports the presence and not the absence of a 2DEG. Second, it is equally important to note that the first Shubnikov-de Haas oscillations reported in AlGaN/GaN on sapphire were not visible in fields below 8 T either.[48] Gaska *et al.*[49], reporting on Shubnikov-de Haas oscillations in AlGaN/GaN on SiC substrates, did not observe oscillations below 6T in samples with even higher mobilities than those of the samples studied here. Redwing *et al.*[36] reported the observation of Shubnikov-de Haas oscillations in AlGaN/GaN samples grown on SiC, but not in AlGaN/GaN samples grown on sapphire, even at temperatures as low as 0.5 K despite the fact the samples used in that study were of comparable Hall mobilities. Braña *et al.*[50], reporting on the scattering times of AlGaN/GaN on sapphire with reported mobilities higher than those of our samples, did not observe SdH oscillations below 8 T. However, they did observe oscillations in higher fields. Dimitrov *et al.*[51], reporting on the study of 2DEGs in Ga-faced and N-faced AlGaN/GaN heterostructures grown by plasma-induced molecular beam epitaxy (PIMBE) and metalorganic chemical vapor deposition on sapphire, did not observe SdH oscillations in the PIMBE grown samples below 8 T but did observe the oscillations in Ga-faced MOCVD sample below 8 T. Therefore, the absence of the oscillations in our samples below 8 T is not unique to AlGaN/GaN structures grown on silicon.

The absence of SdH oscillations does not necessary imply that no 2DEG is present in these structures. So, why were the oscillations not observed? Several explanations could be considered. First, it is entirely possible that in fields higher than 8 T and/or in temperatures lower than 1.2 K, SdH oscillations could be revealed, but neither of these was explored as our system is not capable of delivering higher fields or lower temperatures. Second, the presence of a strong parallel conduction path would mask the oscillations. However, this possibility was ruled out two different ways: (a) Our variable field Hall effect measurements have confirmed the absence of any significant parallel conduction. (b) Since parallel conduction manifests itself as a monotonic increase in the magnetoresistance as a function of the magnetic field, its effects could be removed to recover the oscillations by simply taking the second derivative of the magnetoresistance as a function of B. This was performed and no oscillations were recovered. Third, if the mobility is not high enough, oscillations would not be expected in the field and temperature ranges used here. However, the samples on which SdH oscillations were performed all had Hall mobilities that were close to 7000 cm^2/Vs. Our previous work,[36] and that of others,[51] on AlGaN/GaN heterostructures on substrates other than Si with comparable, or even lower, mobilities did exhibit SdH oscillations. Therefore, the absence of the oscillations could not be explained by the mobility values measured here. Fourth, at a fixed temperature, the amplitude of the oscillations is completely determined by the quantum scattering time, τ_q. Therefore, if the scattering time is too small, it would lead to a broadening of the Landau levels. If this broadening is large enough, the spacing between Landau levels would be washed out and no oscillations could be observed. Since the spacing between Landau levels is directly proportional to the magnetic field, this fourth possible explanation could be tested by using higher field values. However, as discussed earlier, our system is not designed to deliver fields higher than 8 T. We believe, as we will show later, the quantum scattering time is too low to observe the oscillations in the field and temperature ranges used in this study.

The magnetoresistance of a 2DEG is influenced by two characteristic scattering times; the classical scattering time, τ_c, and the quantum scattering time, τ_q. The classical scattering time is determined from the expression $\mu = e\tau_c/m^*$, where μ is the Hall mobility determined from low field Hall effect measurements. The quantum scattering time is a measure of the collision broadening of the Landau levels and is determined from the amplitude of the SdH oscillations. At a fixed temperature equation 1 can be rewritten as:[52,53]

$$\ln\left(\frac{1}{4}\frac{\Delta R}{R_o}\frac{\sinh(\chi)}{\chi}\right) = C - \left(\frac{\pi m^*}{e\tau_q}\right)\frac{1}{B}, \qquad (2)$$

where C is a field- independent term, R_o is the zero field resistance and ΔR the amplitude of the oscillations. The quantum scattering time is determined from the slope of the line obtained by plotting the left hand term of this expression versus 1/B. Depending on the value of this scattering time, oscillations in the magnetoresistance may or may not be observed at a given field value. The two characteristic times, τ_c and τ_q, are not equal.[54,55] One, τ_c, is dominated by large angle scattering whereas the other, τ_q, is sensitive to all scattering angles with all scattering events contributing with equal weight to the broadening of the Landau levels. Therefore, if small angle scattering plays an important role in our samples, the onset of the oscillations would be pushed to higher fields. Since small angle scattering does not impact τ_c, one can test the role of these scattering mechanisms by evaluating the ratio of the two scattering times, τ_c/τ_q. In the presence of small angle scattering, this ratio becomes much larger than unity. This ratio, however, cannot be determined without the observation of the SdH oscillations. In our previous work on AlGaN/GaN structures grown on sapphire,[56] we found that illuminating the sample with a blue LED resulted in a persistent photocurrent (PPC). That PPC study showed the scattering times changing following exposure to blue light. We decided to investigate the PPC effect in the current AlGaN/GaN structures on Si. A blue (λ = 470 nm) LED was again used to illuminate the sample. A persistent photocurrent was observed and the carrier concentration increased as a result. However, no SdH oscillations were observed. This was tried on two samples and the results were similar. Extended exposure of the sample to light from the blue LED resulted in the saturation of the carrier density, but did not lead to the observation of the SdH oscillations. Variable magnetic field Hall effect measurements were carried out after illumination and again only a single carrier type was present. The blue LED was removed and replaced with a UV LED having a characteristic wavelength of, λ = 395 nm. The sample was exposed briefly to UV radiation at 80 K. Exposure to UV radiation resulted in a persistent photocurrent. The sample was then cooled down, with the LED off, and SdH measurements were performed in the dark at 1.2 K. The data revealed the presence of well-defined Shubnikov-de Haas oscillations. Additional samples were subsequently exposed to UV radiation and similar SdH oscillations became visible, confirming the presence of a 2DEG in these

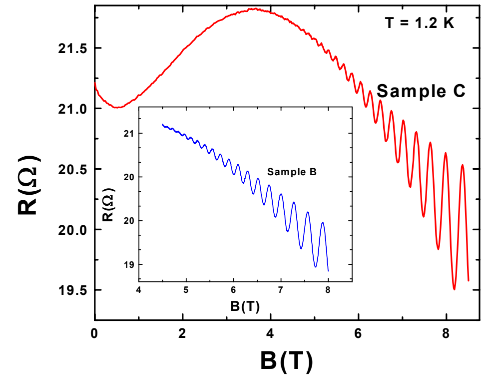

FIG. 4. Longitudinal resistance, R_{xx}, as a function of B at 1.2 K showing the presence of well defined Shubnikov-de Haas oscillations. (The SdH oscillations became visible only after the samples were exposed to UV radiation from a 395 nm LED.) Sample B had the structure shown in Figure 1(a) and sample C had the structure shown in Figure 1(b).

structures. Figure 4 shows a typical result for two different samples. Sample B is of the structure shown in Figure 1a and Sample C is of the structure shown in Figure 1b. At low fields, the magnetoresistance exhibits weak localization behavior that is commonly reported in AlGaN/GaN structures.[50,57] Further studies of the negative magnetoresistance at low fields are planned and the results will be reported elsewhere. Data on R_{xy} as a function of B were also gathered to investigate the presence of Hall plateaus, which is a signature unique to 2DEGs. However, as indicated in Figure 5, no such plateaus were observed. This is a common result in AlGaN/GaN studies.[50,58] In the case of our study, the absence of the plateaus can be explained by the data presented in the inset of Figure 5. Plotted in the inset is the second derivative of the R_{xy} as a function of B, for a magnetic field greater than 6 T. SdH oscillations are clearly present. The presence of these oscillations would mask any plateaus if present. The mixing of R_{xx} with R_{xy} due to poor Hall contact alignment in the van der Pauw samples is responsible for the oscillations in R_{xy}.

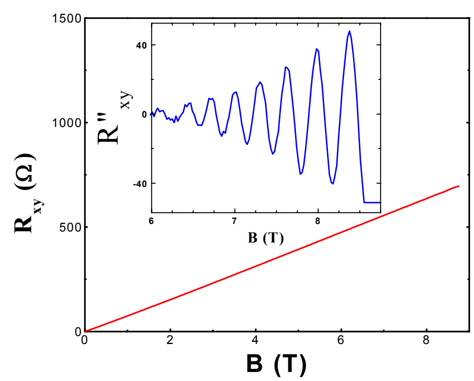

FIG. 5. The Hall resistance, R_{xy}, as a function of B at 1.2 K for sample C, indicating the absence of Hall plateaus. The inset shows the second derivative of R_{xy} as a function of B, reflecting the presence of the SdH oscillations which is an indication of R_{xx} mixing with R_{xy}.

So why did UV exposure induce the presence of the SdH oscillations? We believe, as discussed earlier, small angle scattering is responsible for the absence of the oscillations before illuminating the samples with UV light. Following exposure of the samples to UV light, persistent photocurrent

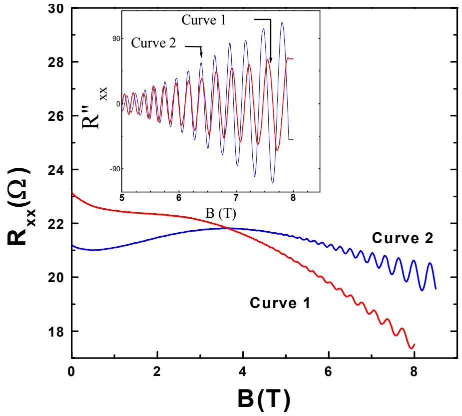

FIG. 6. Longitudinal resistance, R_{xx}, as a function of B for sample C at T = 1.2 K. The data for both curves were collected in the dark and after the sample was exposed to UV radiation. The exposure time for Curve 1 was shorter than that for Curve 2. Presented in the inset are the corresponding second derivatives of R_{xx} as a function of B showing the amplitudes of the oscillations for Curve 2 to be larger.

was induced and a significant increase in the carrier concentration was observed. This increase in the carrier density resulted in increased screening of the 2DEG. The increased screening leads to a rise in the quantum scattering time, τ_q. A larger τ_q would allow the presence of the oscillations at lower magnetic fields. The data collected in this study supports this argument. Consider what was observed, for instance, in one of the samples, sample A, which had the same structure as sample B (shown in Figure 1a). Before illuminating this sample, the carrier density was measured to be 6.83 x 10^{12} cm^{-2} at 4.2 K. Following exposure with light from a blue (λ = 470 nm) LED, the carrier density increased to 8.72x10^{12} cm^{-2}. Despite the 27% increased in the carrier concentration, no oscillations were observed. This same sample was later exposed to light from a UV LED (λ = 395 nm). At 1.2 K the carrier density further increased to 9.08 x 10^{12} cm^{-2}. The collected SdH data following this exposure revealed the presence of SdH oscillations below 8 T. Although these oscillations were not well defined, nevertheless they were present. Data was also collected for a longer exposure to UV. The carrier density increased even further to 9.61 x10^{12} cm^{-2} (a 40% increased compared to the before illumination value) at 4.2K. The SdH oscillations were observed and were better defined; an indication of an increase in τ_q with the carrier density.

Similar behavior was observed in additional samples. For instance, Figure 6 shows two sets of data taken on sample C. They were both taken in the dark, but after the sample was exposed to UV illumination. The exposure time for Curve 1 is less than that for Curve 2. It is clear from Figure 6 that the amplitude of the oscillations at a fixed field is larger for the curve with the higher carrier density (Curve 2) than for the curve with the lower carrier density (Curve 1). The inset of Figure 6 is a plot of the second derivative of R_{xx} as a function of B. The data indicates that the amplitude of the oscillations is larger for Curve 2, for all given field values. This is what one would expect if the quantum scattering time is longer for the data in Curve 2. Indeed, the quantum scattering times calculated from the data of the two

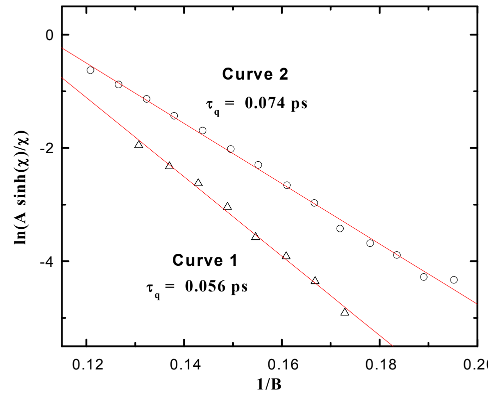

FIG.7. Dingle plots at T = 1.2 K for sample C. The lines indicate the best fit to the data. The data was collected from Curves 1 and 2 shown in Figure 6. Curve 1 corresponds to τ_q of 0.056 ps and Curve 2 is characterized by a τ_q value of 0.074 ps; a 32% percent difference.

curves support our conclusion. Using the Dingle plot shown in Figure 7, and assuming an effective mass value of $0.22m_o$, from equation 2 we determined the value of τ_q for Curve 1 to be 0.056 ps and that of Curve 2 to be 0.074 ps; a ~32% difference.

To further support our analysis, we evaluated the ratio of the classical scattering time to the quantum scattering time, τ_c/τ_q. This ratio is expected to be much larger than unity when small angle scattering is significant. This ratio was determined to be ~16 for curve 1 and ~13 for Curve 2. Note that both ratios are much larger than unity supporting our claim that small angle scattering is an important scattering mechanism in these structures. It is interesting to note that the ratio is smaller for the higher carrier density curve. This is to be expected if small angle scattering becomes screened and the wave function is now pushed closer to the interface where interface roughness will start to play an important scattering mechanism.[59] While the difference between the values of τ_q for curves 1 and 2 is about 32%, the corresponding difference between the τ_c values is only 3%; an indication that small angle scattering is a dominant scattering mechanism. This conclusion is also supported by the data presented by other groups on AlGaN/GaN heterostructures grown on substrates other than Si. For instance, Dimitrov *et al.*[51] reported a τ_q value of 0.16 ps for a sample where the SdH oscillations were well defined in fields as low as 5 T. However, they reported a τ_q value (0.07 ps) that is less than half as long for a sample where the onset of the SdH oscillations was at 9 T, despite the fact the Hall mobilities in these samples were very similar; 4500 cm^2/Vs and 4100 cm^2/Vs, respectively. Furthermore, they reported an even shorter τ_q value, 0.05 ps for a sample where the onset of the oscillations is above 10 T. Shah et al.[60] also reported an increase of τ_q with the carrier density; an indication of increased screening.

What then is the source of the small angle scattering centers? The reported behavior is common to both AlGaN/GaN structures studied. One structure was intentionally doped while the other was not. One structure had an AlGaN spacer while the other did not and the Al mole fraction was not the same. We speculate this small angle scattering is either due to remote ionized impurities in the AlGaN layer or to ionized surface states. Surface states are believed to play an important role in AlGaN/GaN heterostructures. However our data can not distinguish between the two possible sources. We leave this issue an open question for now. In order to elucidate this behavior, a systematic study of the magnetoresistance as a function of the wavelength of the light source is planned.

IV. CONCLUSION

We have investigated AlGaN/GaN structures on silicon using transport measurements. The results of our variable temperature Hall effect measurements indicated a 2DEG in all samples. Room temperature Hall mobilities higher than 1500 cm^2/Vs and carrier densities in the order of $1x10^{13}$ cm^{-2} were observed. For comparable carrier densities and Al mole fraction, the recorded mobilities in these samples are consistent with the mobility values recorded in AlGaN/GaN structures grown on either sapphire or silicon carbide substrates. Low temperature, variable magnetic field measurements indicated that a single carrier type dominates conduction and that parallel conduction is not significant. Shubnikov-de Haas oscillations were observed, confirming the presence of a 2DEG in these structures. However, these oscillations became visible in the fields and temperatures available in our system only after the sample was exposed to UV photons. This behavior is not unique to AlGaN/GaN on silicon. The absence of SdH oscillations in fields up to 8 T and in temperatures as low as 1.2 K was observed and reported in AlGaN/GaN structures on both sapphire and silicon carbide. Furthermore, SdH oscillations were elicited in an AlGaN/GaN structure on silicon carbide following exposure to radiation from a UV LED. We propose that small angle scattering is responsible for the absence of the oscillations in the AlGaN/GaN structures on Si before exposure to UV illumination. This conclusion was supported by our calculated τ_c/τ_q ratio values, which were much larger than 1, and by comparison to other published results on AlGaN/GaN heterostructures grown on substrates other than Si. Based on the results of our measurements, the quality of these AlGaN/GaN structures on Si is comparable to the good quality structures grown on other substrates with similar carrier densities and Al mole fractions. Eliminating the source of the small angle scattering, which is believed to be the source suppressing the SdH oscillations, would enhance the quality of these structures even further.

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