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Two-dimensional electron gas in AlGaN/GaN heterostructures

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The formation of a two-dimensional electron gas (2DEG) system by an AlGaN/GaN heterostructure has been further confirmed by measuring its electrical properties. The effect of persistent photoconductivity (PPC) has been observed and its unique features have been utilized to study the properties of 2DEG formed by the AlGaN/GaN heterointerface. Sharp electronic transitions from the first to the second subbands in the 2DEG channel have been observed by monitoring the 2DEG carrier mobility as a function of carrier concentration through the use of PPC. These results are expected to have significant implications on field-effect transistor and high electron mobility transistor applications based on the GaN system. © *1997 American Vacuum Society.*
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I. INTRODUCTION

GaN wide band-gap semiconductors have been recognized as technologically very important materials.[1–7] They have recently attracted considerable interest due to their applications for optical devices, which are active in the blue and ultraviolet (UV) wavelength regions, and electronic devices capable of operation at high-power levels, high temperatures, and harsh environments. Devices based on low band-gap materials, such as Si and GaAs, operate only in the red and near infrared wavelength regions and show poor tolerance to operation at high-power levels or elevated temperatures or in chemically hostile environments due to the low band gap, the uncontrolled generation of intrinsic carriers, and their low resistance to caustic chemicals. Due to their large dielectric strengths, GaN based devices can operate at much higher voltages for any dimensional configuration. Furthermore, they are virtually immune from environmental attack. One of the strongest motivations of the current research in the GaN system is its potential for fabricating high-power green/blue/UV lasers and electronic devices. High electron mobility transistors and field-effect transistors, based on AlGaN/GaN heterostructures, hold promise for high-frequency microwave as well as for high-power and high-temperature electronic device applications and offer the advantage of high carrier mobilities due to the formation of two-dimensional electron gas (2DEG) by a heterojunction.[8,9] However, practical operation of these devices still requires detailed material and device characterization and optimization.

In this work, the properties of a two-dimensional electron gas formed by an AlGaN/GaN heterojunction interface have been probed by Hall measurements. We have observed sharp electronic transitions resulting from multiple subbands in the 2DEG channel by monitoring the 2DEG carrier mobility as a function of carrier concentration through the use of persistent photoconductivity (PPC). As a consequence of PPC, the device is sensitive to light and the sensitivity is associated with a persistent photoinduced increase in the 2DEG carrier mobility and density.

II. EXPERIMENT

As shown in Fig. 1, the device structure investigated in this work consisted of a 2 μm highly insulating GaN epilayer followed by a 25 nm thick unintentionally doped n-type GaN conducting channel, again followed by a 25 nm thick unintentionally doped n-type $\mathrm{Al_{0.1}Ga_{0.9}N}$ epilayer. The structure was deposited over a basal plane sapphire substrate with an AlN buffer layer using a low-pressure metalorganic chemical vapor deposition (MOCVD) system. The Ohmic contacts were formed by soldering In spots directly onto the sample. The sample size was about 1 cm×1 cm and the Ohmic contacts were about 1 mm in diameter. The typical room-temperature carrier concentrations (due to N vacancies) were, respectively, 1×10^{17} and $5\times10^{17}\ \mathrm{cm^{-3}}$ for n-GaN and n-$\mathrm{Al_{0.1}Ga_{0.9}N}$ epilayers grown under similar conditions.[8] The 2DEG electron density and mobility were determined by variable-temperature Hall measurements. Illumination of the sample was achieved using a mercury lamp ($h\nu>E_g$ of GaN) or a neon lamp ($h\nu<E_g$ of GaN). Details of PPC characterization procedures were similar to those described previously for a p-type GaN epilayer.[10]

III. RESULTS AND DISCUSSIONS

The 2DEG carrier mobilities at different temperatures have been measured in the dark and under illuminated conditions, and the results are shown in Fig. 2. During the course of this investigation, we have used a mercury lamp ($h\nu>E_g$ of GaN) and a neon lamp ($h\nu<E_g$ of GaN) as excitation sources and found that both light sources gave similar results. Since high-temperature properties are very important for device applications based on these materials, we have replotted the 2DEG mobilities at elevated temperatures in the inset of Fig. 2. Several interesting and important

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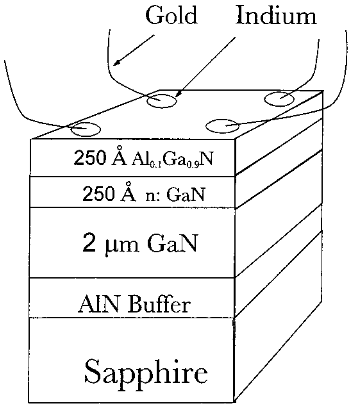

FIG. 1. Schematic diagram of the MOCVD grown AlGaN/GaN heterostructures used in this work.

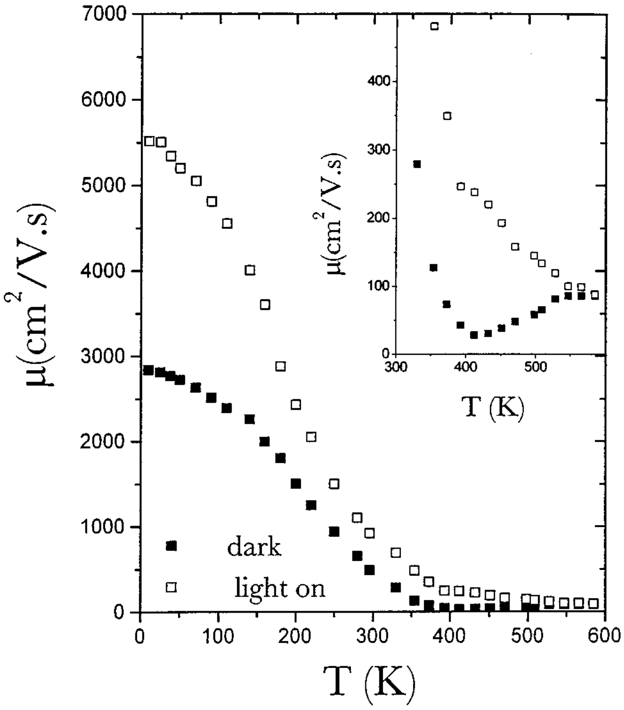

FIG. 2. 2DEG mobility, μ, as a function of temperature, T, measured in the dark (solid squares) and under illumination (open squares) conditions. For a better illustration, the 2DEG mobilities obtained at the elevated temperatures are shown in the inset.

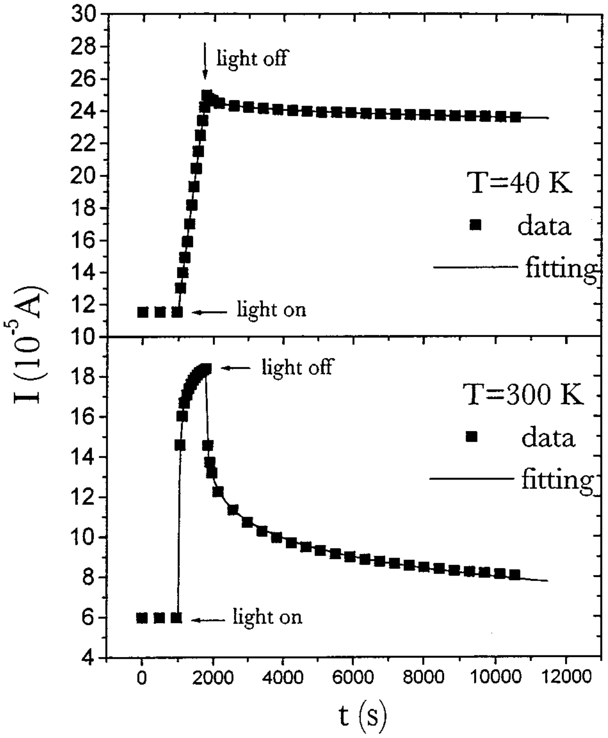

FIG. 3. PPC behavior in an AlGaN/GaN heterostructure at different temperatures, where solid curves are the least-squares fit of the data using the formula $I_{\mathrm{PPC}}(t)=I_d+(I_{\max}-I_d)(1-e^{-\alpha t})$ for the buildup and $I_{\mathrm{PPC}}(t)=I_d+(I_0-I_d)\exp[-(t/\tau)^{\beta}]$ for the decay.

features can be observed. (i) The typical temperature dependence of the three-dimensional electron mobility of a semiconductor is absent here, which further confirms the formation of a 2DEG in the AlGaN/GaN heterostructure. For example, in GaN epilayers, the scattering is dominated by ionized impurities at low temperatures and by phonons at higher temperatures. Hence, the electron mobility in GaN epilayers increases as temperature decreases from room temperature and reaches a maximum value between 50 and 150 K, and it then decreases as temperature further decreases due to ionized impurity scattering.[8,11] To the contrary, the electron mobility in the 2DEG channel increases monotonically with a decrease of temperature. This is a direct consequence of the ionized impurity concentration in the 2D system being almost constant due to the interface depletion effects. Hence, the monotonical decrease of the carrier mobility with temperature just reflects the fact that the electron–phonon scattering rate increases with an increase of temperature. (ii) The 2DEG mobility is enhanced significantly for all temperatures after photoexcitation. We attribute this increase to the increased electron density in the 2DEG channel, n_s, while the system is in the persistent photoconductivity state. This will be discussed further later. (iii) The 2DEG mobility in the dark state reaches a minimum value of about 25 $\mathrm{cm}^2/\mathrm{V\,s}$ at 410 K. However, the 2DEG mobility is almost one order of magnitude higher at the same temperature under illumination. Thus, it is expected that the heterojunction device performance will improve under light illumination. This is important for device applications based on GaN. (iv) The 2DEG mobilities in the dark and under illumination approach the same values at temperatures above 580 K. This is the consequence of the absence of the PPC effect at these temperatures, so the light illumination can no longer alter the carrier concentration in the 2DEG channel at high temperatures.

The conductivity in the 2DEG channel at the AlGaN/GaN interface is extremely sensitive to light. More strikingly, as shown in Fig. 3, the photoinduced increase in the conductivity persists for a long period of time after the removal of light, an effect which is referred to as PPC. Such an effect has been observed in AlGaAs/GaAs heterostructures only at low temperatures ($T < 150$ K).[12] As for the AlGaAs/GaAs system,[12,13] we can identify three main mechanisms for the persistent increase in the conductivity in the 2DEG channel after illumination (or PPC) in AlGaN/GaN heterostructures: (i) photoionization of deep-level donors in the AlGaN barrier; (ii) photoionization of deep-level donors in the GaN layer; and (iii) the generation of electron–hole pairs in the GaN epilayer with subsequent charge separation at the interface, which requires the excitation photon energy to be larger than the energy gap of GaN. Experimentally, we found that the neon lamp ($h\nu < E_g$ of GaN) produces the PPC effect in the AlGaN/GaN heterostructure as well, and thus, the mechanism (iii) is less likely. Furthermore, we have also performed comparison measurements on GaN epilayers grown under similar conditions and found that the PPC effect is absent in the GaN epilayers, which precludes mechanism (ii). These results then suggest that the electron density in the 2DEG channel is contributed to primarily by the transfer of photoexcited electrons from the deep-level impurities (or DX centers) in the AlGaN epilayer.

The buildup of PPC caused by DX centers in AlGaAs has been experimentally observed and theoretically formulated to follow:[14]

$$I_{\mathrm{PPC}}(t) = I_d + (I_{\max} - I_d)(1 - e^{-\alpha t}), \tag{1}$$

where α is a constant, I_d is the initial dark conductivity, and $I_{\max}$ is the saturation level. While the decay of PPC associated with DX centers in AlGaAs follows a stretched-exponential function,[14]

$$I_{\mathrm{PPC}} = I_d + (I_0 - I_d)\exp[-(t/\tau)^{\beta}], \quad \beta < 1, \tag{2}$$

where I_0 is defined as the conductivity buildup level at the moment of light excitation being terminated, τ is the PPC decay time constant, and β is the decay exponent. Figure 3 shows the buildup and decay kinetics of PPC in our AlGaN/GaN heterostructure measured for two representative temperatures, (a) $T = 40$ K and (b) $T = 300$ K. The solid curves are the least-squares fit of data with Eq. (1) for the PPC buildup and Eq. (2) for the PPC decay. It has been demonstrated that PPC,[15] when caused by the spatial separation of photogenerated electrons and holes by an electric field at a macroscopic barrier, decays logarithmically in time. Thus, our results shown in Fig. 3 also suggest that the carrier density in the 2DEG channel is most likely due to the transfer of photoexcited electrons from the deep-level impurities in the AlGaN material. The PPC decay time constants, τ, are very long, especially at low temperatures. The fitted parameters for the PPC buildup and decay were $\alpha = 9.1 \times 10^{-4}$ s^{-1}, $\tau = 5.3 \times 10^{6}$ s, and $\beta = 0.35$ at $T = 40$ K and $\alpha = 5.7 \times 10^{-3}$ s^{-1}, $\tau = 1.3 \times 10^{3}$ s, and $\beta = 0.31$ at $T = 300$ K.

By utilizing the key features in the PPC state, i.e., the very long lifetimes of photoexcited charge carriers and the continuous variation of the carrier density in the 2DEG channel in a single sample, we have measured the 2DEG electron mobility, μ, as a function of the electron sheet density, n_s. Figure 4 illustrates the result for a representative temperature at 10 K, which shows that μ increases almost linearly with n_s when passing from the dark to the saturated PPC state. A mobility value as high as 5800 cm^2/V s at 10 K in the PPC state is among the highest values reported for GaN. Similar trends have been observed for all temperatures up to 400 K. The mobility enhancement due to photoexcitation at a fixed temperature can be attributed to the increased electron mean energy with increasing carrier density in the 2DEG channel, which results in a less efficient interaction of the 2DEG electrons with the ionized donor impurities as well as an improved screening. Similar behaviors have been observed previously in AlGaAs/GaAs (Ref. 16) and AlInAs/GaInAs (Ref. 17) heterostructures at low temperatures. More interestingly, one should also notice that the mobility as a function of carrier density, plotted in Fig. 4, shows a sharp change in slope, as indicated by the arrow in Fig. 4. This is a clear indication of an electronic transition from the first subband to the second subband in the 2DEG channel. The carrier density at which the slope suddenly changes represents the onset density for the transition from the first to the second subband at 10 K. The total density of states of the first subband at $T = 0$ can be calculated and is about 10^{12} cm^{-2}. This value is consistent with our interpretation of the electronic transition, i.e., it is sufficiently small to allow the population of the upper subband in the PPC state.

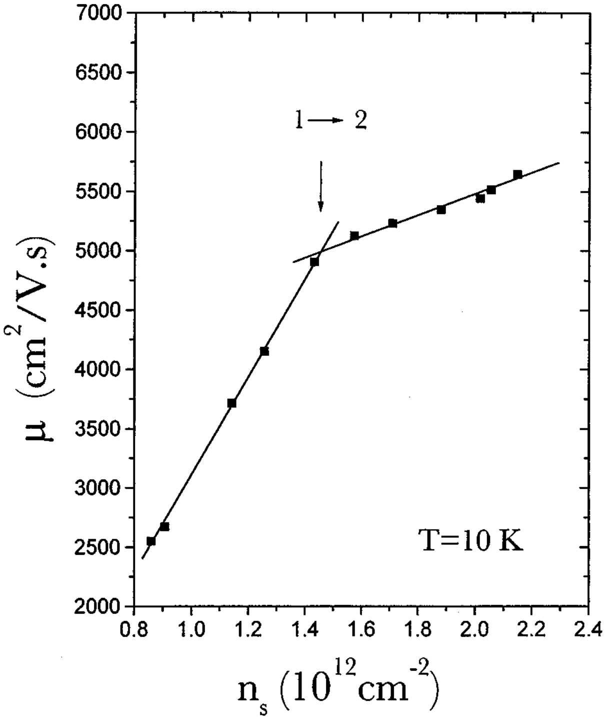

FIG. 4. The 2DEG electron mobility, μ, as a function of electron sheet density, n_s, measured at $T = 10$ K. The arrow indicates the onset electron sheet density at which the electron transport in the second subband becomes dominating.

The effects of PPC or DX centers on AlGaAs/GaAs heterojunction device characteristics have been well documented, namely sensitivity to light, a shift of the threshold voltage, and collapse of the drain $I-V$ characteristics.[18] Thus, we expect the PPC seen here to have similar effects on the AlGaN/GaN heterojunction device characteristics as well. Recently, an improved electrical performance of AlGaN/GaN modulation-doped field-effect transistors due to optical excitation has been observed,[9] which may be related to the photoinduced increase in carrier density and mobility in the 2DEG channel seen here.

In summary, electrical properties of AlGaN/GaN heterostructures have been probed by Hall measurements. The effect of PPC has been observed and its unique features have been utilized to study the properties of 2DEG formed by AlGaN/GaN heterojunctions. Sharp electronic transitions from the first to the second subband in the 2DEG channel have been observed by monitoring the 2DEG electron mobility as a function of electron sheet density through the use of persistent photoconductivity.

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