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Persistent photoconductivity in a two-dimensional electron gas system formed by an AlGaN/GaN heterostructure

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Persistent photoconductivity (PPC) effect associated with a two-dimensional electron gas (2DEG) in an AlGaN/GaN heterojunction device has been observed. As a consequence, the device was observed to be sensitive to light and the sensitivity was associated with a permanent photoinduced increase in the 2DEG carrier mobility and density. By formulating the PPC buildup and decay kinetics, we attributed the observed increase in the 2DEG carrier density and mobility to the photoionization of deep level impurities (DX like centers) in the AlGaN barrier material. In the PPC state, we were able to continuously vary the 2DEG carrier density in a single sample through photoexcitation and it has been found that the 2DEG carrier mobility increases almost linearly with the carrier density in the 2DEG channel. At 10 K, an electron mobility of 5800 $cm^2/V\cdot s$ has been obtained in a PPC state. Implications of these observations on the device applications based on AlGaN/GaN heterojunctions have also been discussed. © *1997 American Institute of Physics.* [S0021-8979(97)05615-6]

I. INTRODUCTION

GaN based devices offer great potential for applications such as high-power electronics, uv-blue lasers, and solar-blind detectors.[1] Researchers in this field have made extremely rapid progress toward materials growth as well as device fabrication. Room temperature blue lasers have been demonstrated recently for the GaN system.[2] High electron mobility transistors (HEMT) and field-effect transistors (FET), 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 a two-dimensional electron gas (2DEG) by a heterojunction.[3–5] However, practical operation of these devices still require detailed material and device characterization and optimization. In this article, we report the observation of persistent photoconductivity (PPC) effects associated with the 2DEG system in an AlGaN/GaN heterojunction. As a consequence, the device is sensitive to light and the sensitivity is associated with a persistent photoinduced increase in the 2DEG carrier mobility and density. As for the AlGaAs/GaAs modulation doped field-effect transistors, PPC by itself is not a problem for device operation, but its presence indicates the possibility of other device instabilities associated with cases such as charge trapping.[6,7] Additionally, the system of 2DEG in AlGaN/GaN heterojunctions is a novel structure and may offer unique physical properties due to the large band offset between AlGaN and GaN.

II. EXPERIMENT

The device structure investigated in this work consisted of a 2-μm-thick highly insulating GaN epilayer followed by a 25-nm-thick undoped n-type GaN conducting channel, again followed by a 25-nm-thick undoped n-type $Al_{0.1}Ga_{0.9}N$ epilayer. The structure was deposited over a basal plane sapphire substrate using a low pressure metal organic chemical vapor deposition (MOCVD) system. The typical room temperature electron concentrations (due to N vacancies) were, respectively, 1×10^{17} and 5×10^{17} cm^{-3} in n-type GaN and $Al_{0.1}Ga_{0.9}N$ epilayers grown under similar conditions. Previous experimental measurements have confirmed the formation of 2DEG at the $Al_xGa_{1-x}N$/GaN heterointerface.[3–5] The temperature dependencies of the electron density and mobility to be shown later in the present work again confirms the existence of a 2DEG in this structure. In our experiment, the 2DEG electron density and mobility were determined by the variable-temperature Hall-effect measurement technique. 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.[8]

III. RESULTS AND DISCUSSION

The 2DEG carrier density, n_s, has been measured in a dark state at different temperatures between 10 and 350 K, as shown in Fig. 1. We see that the carrier freeze-out behavior at low temperatures was absent. This is in sharp contrast to the typical behavior of a three-dimensional (3D) GaN system in which the 3D carrier density is thermally activated in the same temperature range, i.e., decreases exponentially with temperature.[9] This indicates that the dark equilibrium 2DEG density is truly controlled by the interface depletion effects in the AlGaN barrier, rather than by thermal ionization of impurities in the n-GaN layer, which further confirms the formation of a 2DEG at the AlGaN/GaN interface due to band bending. Similar features have been observed previ-

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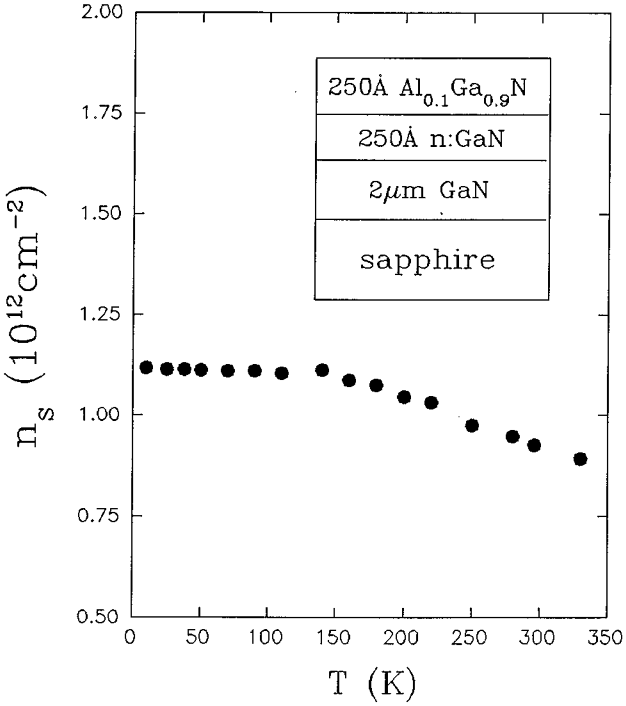

FIG. 1. 2DEG carrier density, n_s, in an $Al_{0.1}Ga_{0.9}N/GaN$ heterostructure vs temperature, T, measured in a dark state. The inset shows the device structure used for this study and it consists of a 2-μm-thick highly insulating GaN epilayer followed by a 25-nm-thick undoped n-type GaN conducting channel, again followed by a 25-nm-thick undoped n-type $Al_{0.1}Ga_{0.9}N$ epilayer.

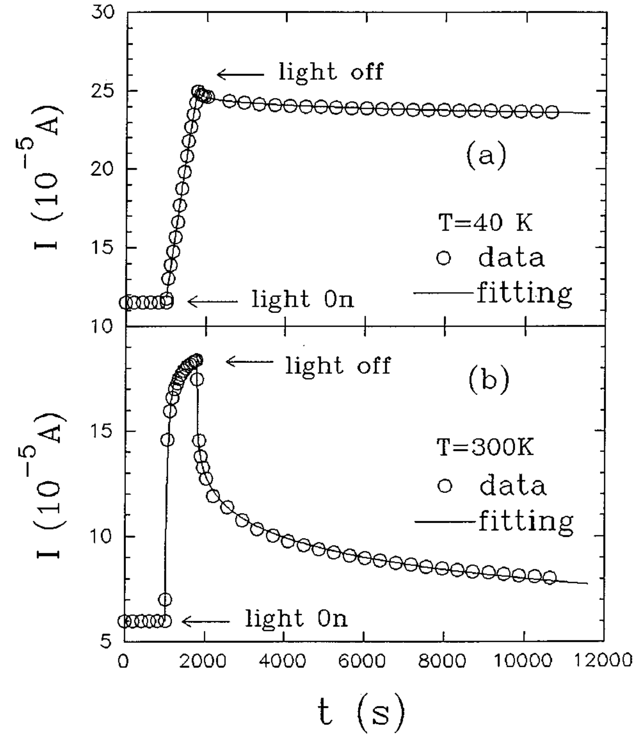

FIG. 2. Buildup and decay kinetics of PPC associated with the 2DEG system in $Al_{0.1}Ga_{0.9}N/GaN$ heterostructure measured at two representative temperatures, (a) $T = 40$ K and (b) $T = 300$ K. The solid curves are the least squares fit of experimental data with $I_{PPC}(t) = I_d + (I_{max} - I_d)(I - e^{-\alpha t})$ for the buildup part and with $I_{PPC} = I_d + (I_0 - I_d)\exp[-(t/\tau)^\beta]$ for the decay part.

ously for 2DEG systems in AlGaAs/GaAs[10] and AlGaN/GaN heterojunctions.[11] In fact, at temperatures $150\text{ K} < T < 350\text{ K}$, the carrier density decreases with an increase of temperature. This is due to the fact that more carriers start to occupy the second subband at higher temperatures. It is well known that the lowest energy states in the upper subband in the 2DEG channel are localized due to interface roughness and therefore cannot contribute to the Hall effect measurement.[12–14] However, as more carriers start to occupy the extended states of the upper subband when the temperature further increases, an increase in carrier density with temperature is expected.

The conductivity in the 2DEG channel at the AlGaN/GaN interface is extremely sensitive to light. More strikingly, as shown in Fig. 2, photoinduced increase in the conductivity persists for a long period of time after the removal of light, an effect which is referred to as persistent photoconductivity (PPC). Such an effect has been observed in AlGaAs/GaAs heterostructures only at low temperatures.[10,12] As for the AlGaAs/GaAs system,[6,12] there are three possible 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 layer with a subsequent charge separation by the electric field from the macroscopic barrier due to band bending. In order to identify the main mechanism for PPC, 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. Under the excitation condition of $h\nu < E_g$ of GaN, the energy of the excitation photons is not large enough to generate electron-hole pairs in the GaN layer. For the case of $h\nu > E_g$ of GaN, in addition to the photoexcitation of deep level impurities, band-to-band excitation also generates electron-hole pairs in the GaN layer. In our experiment, we found that both light sources gave similar results and we therefore believe that mechanism (iii) is less likely. In order to discriminate between mechanisms (i) and (ii), 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 seems to suggest that mechanism (ii) can be precluded for our device structure. These results suggest that the carrier density in the 2DEG channel is primarily contributed by the transfer of photoexcited electrons from the deep level impurities (or DX centers) in the AlGaN barrier layer.

However, a more powerful method for identifying the PPC mechanism is to formulate its buildup and decay kinetics. We have formulated the buildup and decay kinetics of PPC observed in our AlGaN/GaN heterojunction and found that the PPC buildup and decay kinetics are identical to those of (DX) centers in AlGaAs. The buildup of PPC caused by DX centers in AlGaAs has been experimentally observed and theoretically formulated to follow[15]

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

where α is a constant, I_d is the initial dark conductivity, and

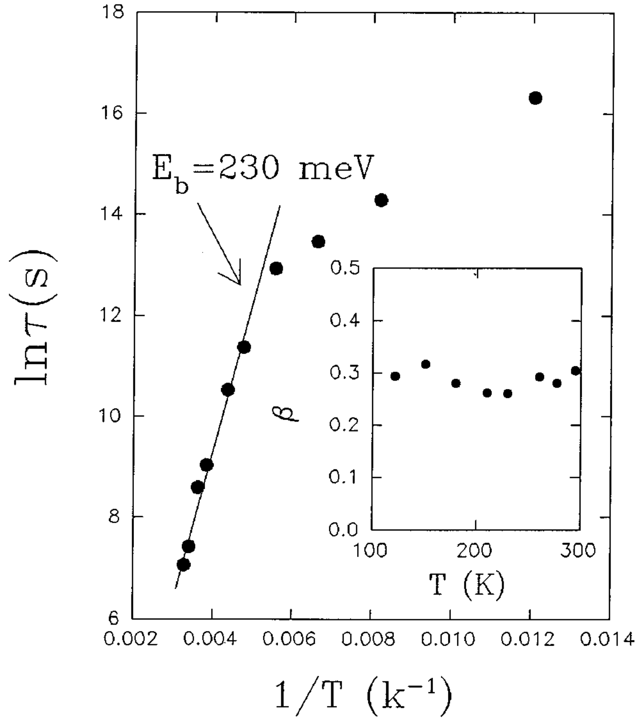

FIG. 3. The Arrhenius plot of the PPC decay time constant τ ($\ln \tau$ vs $1/T$), which gives an energy barrier of about 230 meV for the capture of electrons in the 2DEG channel by deep level impurities in the AlGaN material. The inset shows the decay exponent, β, as a function of temperature.

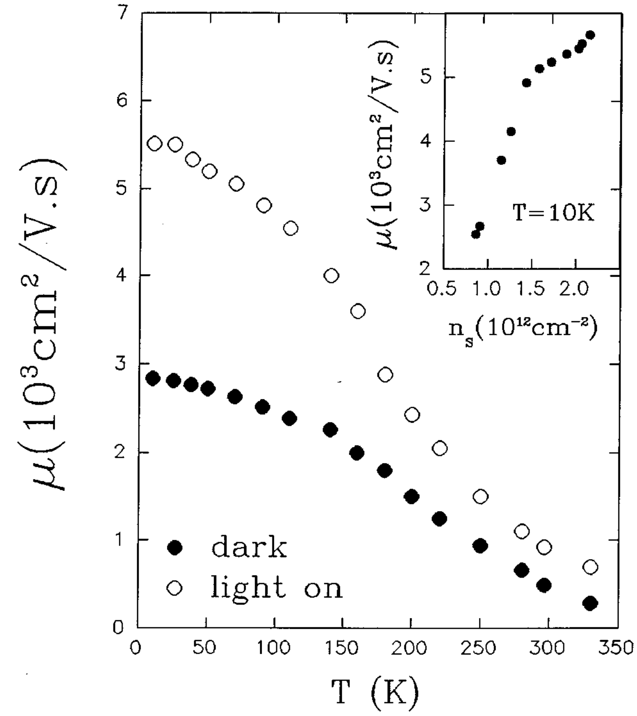

FIG. 4. 2DEG mobility, μ, as a function of temperature, T, measured in a dark state (solid dots) and in a PPC state (open circle). The inset shows the 2DEG mobility, μ, as a function of carrier density, n_s, at 10 K, where the variation of the electron density is achieved by the use of PPC.

I_{max} is the saturation level. While the decay of PPC associated with DX centers in AlGaAs follows a stretched-exponential function,[15]

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

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 2 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 with Eq. (2) for the PPC decay. It has been demonstrated that PPC,[16] caused by spatial separation of photogenerated electrons and holes by the electric field from the macroscopic barrier due to band bending, decays logarithmically in time. Thus our results shown in Fig. 2 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 barrier material. The PPC decay times constants, τ, are very long, especially at low temperatures. At temperatures $T>200$ K, τ is thermally activated as shown in Fig. 3, from which we obtain an energy barrier for the capture of electrons in the 2DEG channel by the deep level impurities in AlGaN of about 230 meV for the heterojunction investigated here. It is this large energy barrier that prevents the decay of photoexcited electrons. The fitted values of the PPC decay exponent, β, are around 0.3 for all temperatures.

We have also measured the corresponding 2DEG carrier mobilities in a dark state and also in a PPC state at different temperatures and the results are shown in Fig. 4. The typical temperature dependence of the 3D electron mobility of a semiconductor is absent in the 2DEG system here. In the 3D GaN epilayers, the scattering is dominated by ionized impurities at low temperatures and by phonons at higher temperatures. Hence the 3D 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.[5,9] On the contrary, the electron mobility in the 2DEG channel increases monotonically with a decrease of temperature and is systematically higher than those in the GaN epilayers deposited under similar conditions. In AlGaN/GaN heterostructures, the energy difference between the bottom of the conduction band of AlGaN and GaN allows the electrons from the donors (N vacancies) in the AlGaN to fall into the GaN, creating a 2DEG. Thus the electrons in the 2DEG channel are spatially separated from the positive ions in the AlGaN, leading to a higher mobility for the 2DEG system than the epilayers. More importantly, the mobility in the 2DEG system shown in Fig. 4 enhances significantly for all temperatures after photoexcitation in the PPC state. We attribute the 2DEG mobility increase to the increased electron density in the 2DEG channel, n_s, after illumination in the PPC state.

To support this interpretation, it is necessary to investigate the dependence of the electron mobility on the carrier density at fixed temperatures in the 2DEG channel. By utilizing the key features in the PPC state, i.e., the very long lifetimes of photoexcited charge carriers and the continuous variation of carrier density in the 2DEG channel in a single sample, we have measured the 2DEG electron mobility, μ, as a function of the carrier density, n_s. The inset of Fig. 4 illustrates the result for a representative temperature at 10 K, which indeed shows that μ increases linearly with n_s when passing from the dark to the saturated PPC state. Similar trends have been observed for all temperatures up to 400 K. A mobility value as high as 5800 $cm^2/V \cdot s$ at 10 K can be obtained in a PPC state. Notice that the highest 3D electron mobility reported for GaN epilayers to date is about 3000 $cm^2/V \cdot s$ at about 80 K.[9] The mobility enhancement due to photoexcitation at a fixed temperature can be attributed to the increased electron mean energy with an increasing carrier density in the 2DEG channel which leads to an improved screening and hence a reduced scattering between the 2DEG electrons with the ionized donor impurities. Similar behaviors have been observed previously for the 2DEG system in AlGaAs/GaAs[17] and AlInAs/GaInAs heterostructures at low temperatures.[18] Recently, an improved electrical performance of AlGaN/GaN modulation-doped field-effect transistors due to optical excitation has been observed,[4] which may be related to the photoinduced increase in carrier density and mobility in the 2DEG channel seen here.

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.[7] Thus we expect PPC seen here to have similar effects on the AlGaN/GaN heterojunction device characteristics as well. Systematic investigations on the dependence of the PPC properties on different growth conditions of AlGaN are needed and under way to elucidate the nature of the deep level defects which are responsible for PPC. Additionally, different approaches for device designs will also be employed to optimize the device performance. These in turn will eliminate or minimize effects of defect related instabilities in AlGaN/GaN heterojunction devices.

IV. SUMMARY

In summary, the formation of a 2DEG at an AlGaN/GaN heterojunction has been confirmed and its associated PPC effect has been observed. It is observed that the PPC effect causes persistent photoinduced increase in the 2DEG carrier density and mobility in the AlGaN/GaN heterojunction used here. By formulating the PPC buildup and decay kinetics, we have attributed PPC to the photoionization of deep level impurities (DX like centers) in the AlGaN barrier material. An energy barrier of about 230 meV for the capture of electrons in the 2DEG channel by these deep level impurities has been obtained. In the PPC state, the 2DEG carrier mobility increases almost linearly with photoexcited carrier density. At 10 K, an electron mobility of 5800 $cm^2/V \cdot s$ has been obtained in a PPC state. Implications of these observations on the device applications based AlGaN/GaN heterojunctions have also been discussed.

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