Persistent photoconductivity and defect levels in *n*-type AlGaN/GaN heterostructures

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Persistent photoconductivity effects have been characterized in *n*-type $Al_{0.15}Ga_{0.85}N$/GaN heterostructures using both monochromatic light and room light illumination. Time constants of $\sim 1\times10^4$ s have been observed, and measurements of photocurrent specta performed using various illumination geometries and techniques have shown that defect levels exist in both the $Al_{0.15}Ga_{0.85}N$ and GaN layers. Broad distributions of defect levels with excitation energies lower than the bandgap energies are found in both $Al_{0.15}Ga_{0.85}N$ and GaN, and evidence is observed that these levels contribute significantly to the aforementioned persistent photoconductivity effects. The photocurrent spectra also reveal the presence of a level with an excitation energy of 3.36 eV that contributes to the persistent photoconductivity in the heterostructure. *© 1998 American Institute of Physics.* [S0003-6951(98)03516-5]

III–V nitrides have been a subject of intense recent research for applications in visible and ultraviolet light-emitting devices and in high-power, high-temperature electronic devices. Despite remarkable advances in optoelectronic and electronic device performance, it is well recognized that numerous and varied structural and electronic defects exist in these materials;[1–3] an understanding of these defects and their potential influence on device properties is of increasing importance for optimization of device performance. A number of recent studies have demonstrated the existence of persistent photoconductivity (PPC) in *n*-GaN,[4] *p*-GaN,[5,6] and $Al_xGa_{1-x}N$/GaN heterostructures,[7] the presence of which suggests the possibility of device instabilities associated with charge trapping. Detailed characterization of PPC effects can provide information about defect levels in these materials and is especially useful for III–V nitrides because the activation energies of many levels in these materials can exceed the thermal excitation limit of measurements such as deep level transient spectroscopy.

In this letter, we present studies of PPC and measurements of photocurrent spectra in *n*-type $Al_{0.15}Ga_{0.85}N$/GaN heterostructures. Significant PPC effects with very long decay times are observed at room temperature. Several well defined features together with a broad envelope are observed in the photocurrent spectra, and have been assigned to defect levels in either $Al_{0.15}Ga_{0.85}N$ or GaN based on measurements performed using various illumination conditions and techniques. Correlations between the presence of these levels and the PPC effect have also been investigated.

Samples for these studies were grown by metalorganic chemical vapor deposition (MOCVD), and consisted of 3 μm nominally undoped GaN grown on a sapphire substrate, followed by a nominally undoped $Al_{0.15}Ga_{0.85}N$ layer either 300 or 500 Å in thickness. Thick layers of nominally undoped GaN and $Al_{0.15}Ga_{0.85}N$ grown under similar conditions were found to be highly resistive. The growth temperature was 1100 °C. A detailed description of the sample growth conditions and procedures can be found elsewhere.[8] Schottky diodes were fabricated by deposition of Ti/Al to form ohmic contacts, followed by deposition of Ni/Au to form Schottky contacts consisting of 320-μm-diam dots. Despite the low dopant concentrations in the epitaxial layers, capacitance–voltage profiling revealed the formation, due to the piezoelectric effect,[9,10] of a two-dimensional electron gas (2DEG) at the $Al_{0.15}Ga_{0.85}N$/GaN interface with a typical sheet carrier concentration of $\sim 3\times10^{12}\ \mathrm{cm}^{-2}$. Figure 1 shows the sample structure and illumination geometry used in this work. Photocurrent measurements were performed with a constant forward bias applied to the diode. The effects of sample illumination by either room light or monochromatic light from a halogen cycle lamp and monochromator were investigated.

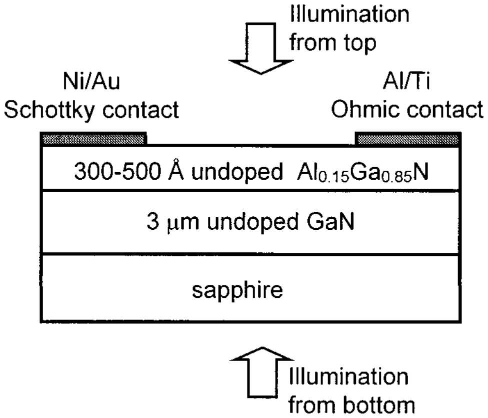

FIG. 1. Schematic diagram of a nominally undoped $Al_{0.15}Ga_{0.85}N$/GaN Schottky diode structure and of the illumination geometry used in this work.

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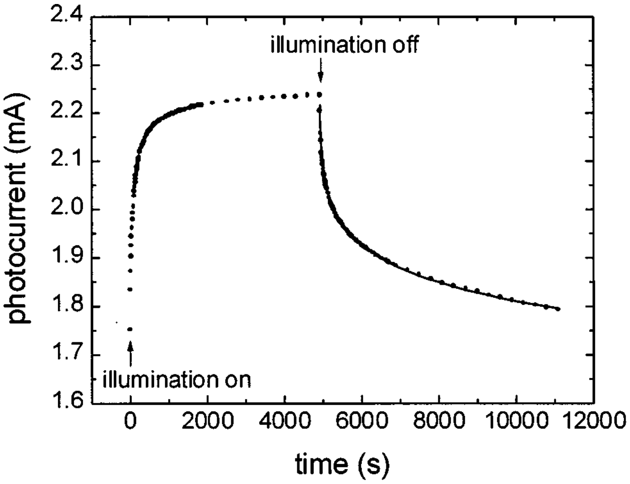

FIG. 2. Transient response in diode current when the illumination source is introduced and removed. The circles are experimental measurements, and the solid line a stretched-exponential fit to the data.

Figure 2 shows the current as a function of time and illumination in a 500 Å $Al_{0.15}Ga_{0.85}N/GaN$ Schottky diode with monochromatic illumination at a photon energy of 3.37 eV. A persistent photoconductivity effect is clearly observed, and similar transient behavior is seen when room light or other monochromatic light with photon energy ranging from 2 to 3 eV is used as the illumination source. The decay in photocurrent after turning off the illumination is well described by a stretched-exponential function

$$I(t)=I_0+B_0\exp[-(t/\tau)^{\beta}]\quad(0<\beta<1),$$

where t is the time, τ is the characteristic time constant for decay of the photocurrent, β is the decay exponent, I_0 is the initial dark current, and B_0 is a constant. A least-squares fit to the experimental data yields a time constant $\tau\sim1.0\times10^4$ s, roughly an order of magnitude longer than previously reported values for n-type or p-type GaN, and a decay exponent $\beta\sim0.2$, which is comparable to previously reported values.[11,12] A sum of exponentials with up to three components has also been used to fit the experimental data of Fig. 2, but was not able to provide an accurate fit over the entire range of time shown in the figure.

To investigate the energy distribution of trap levels, photocurrent spectra were measured for excitation energies ranging from 2.2 to 4 eV. In order to reduce the effect of PPC lag on spectrum features, the incident light wavelength was scanned at a speed of ~0.2 Å/s. Scans in which the wavelength was decreased with time showed similar features to those in which the wavelength was increased. Figure 3(a) shows photocurrent spectra for 500 Å $Al_{0.15}Ga_{0.85}N/GaN$ Schottky diode for a range of forward-bias voltages, with illumination provided from the top. In these spectra, peaks at ~3.7, 3.42, and 3.36 eV can be seen, together with a broad tail extending from the GaN band edge to ~2.2 eV. The 3.7 eV peak is near the band edge of $Al_{0.15}Ga_{0.85}N$ (3.8 eV), and the 3.42 eV peak corresponds to the band edge of GaN.[13] The origin of 3.36 eV peak is not clear thus far. The existence of the broad tail suggests a broad distribution of defect levels within the band gap. Normalization of the measured photocurrent spectrum by the incident photon density did not significantly alter these observations.

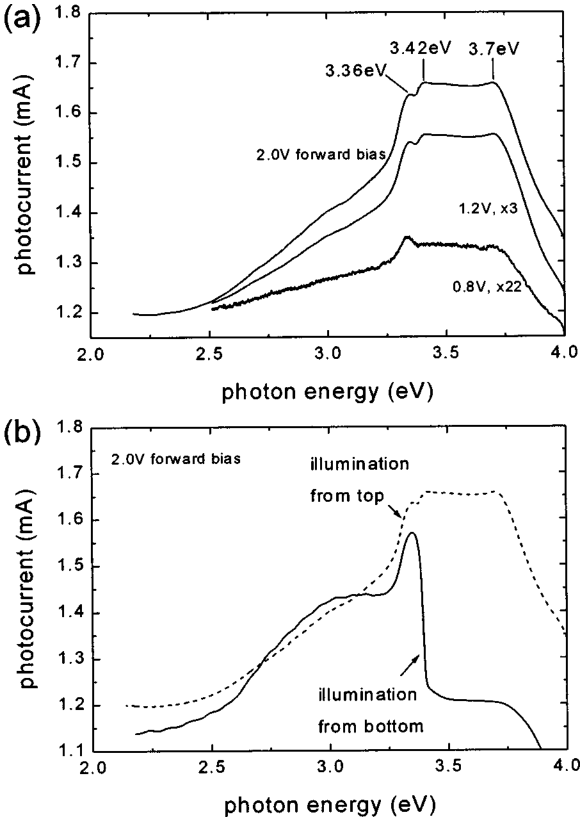

FIG. 3. (a) Photocurrent spectra measured at various bias voltages for a 500 Å $Al_{0.15}Ga_{0.85}N/GaN$ Schottky diode, for illumination provided from the top of the sample. (b) Photocurrent spectra from the same structure, obtained at 2.0 V bias with illumination from the top (dashed line) and bottom (solid line) of the sample.

Because photoexcited carriers from both GaN and $Al_{0.15}Ga_{0.85}N$ can cause an increase in photocurrent, measurements performed using illumination from the top of the sample do not allow levels in the GaN layer to be distinguished from those in the $Al_{0.15}Ga_{0.85}N$ layer. Comparison of photocurrent spectra measured with illumination from the top and from the bottom of the sample have provided insight into the physical location of various transitions within the Schottky diode structure. Figure 3(b) shows photocurrent spectra for the same diode as in Fig. 3(a), but with illumination from the bottom. In this geometry, significant attenuation due to absorption within the thick GaN layer is expected. Only photons which are not significantly absorbed in GaN, but can be absorbed to produce excess free carriers either in $Al_{0.15}Ga_{0.85}N$ or near the $Al_{0.15}Ga_{0.85}N/GaN$ interface, will cause an increase in photocurrent. As seen in Fig. 3(b), illumination from the bottom causes the features above the band edge of GaN to become much weaker, with the 3.36 eV peak and the broad tail arising from defect levels becoming the dominant features. The magnitude of the 3.36 eV peak changes only slightly in the different illumination geometries, which suggests that radiation at this energy is not significantly absorbed in GaN and that the concentration of the associated defect level in the thick GaN layer is low. In both illumination geometries, the broad distribution of defect levels is observed, but the distribution varies with the illumination geometries. There exists a plateau below the GaN band edge in the bottom-illumination spectra, while the photocurrent decreases monotonically with decreasing energy

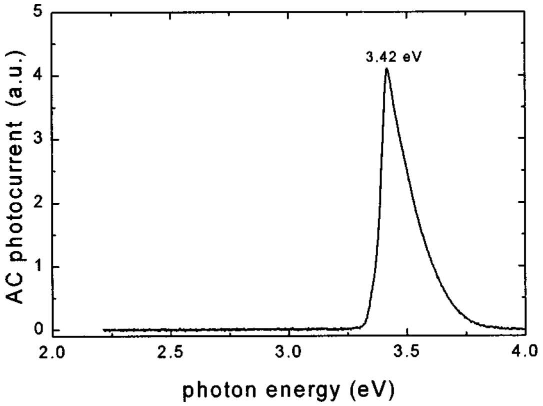

FIG. 4. AC photocurrent spectrum measured using a lock-in amplifier with illumination from the top of the sample chopped at a frequency of 338 Hz.

from the GaN band edge in the top-illumination spectra. Similar distributions of defect levels have also been observed by Qiu *et al.* in GaN epilayers.[14]

To investigate the correlation between the features observed in the photocurrent spectra and the observed PPC effects, AC photocurrent spectra were measured using a lock-in amplifier with excitation light chopped at a frequency $f = 338$ Hz. In such a measurement, persistent photocurrents with time constants much longer than $1/f$ will not be present in the signal from lock-in amplifier. The AC photocurrent spectrum measured with illumination from top of the sample is shown in Fig. 4. A single peak at 3.42 eV is seen corresponding to the GaN interband transition. The broad tail is not observed, demonstrating that excitation from the associated defect levels contributed primarily to the PPC effect. The signal between 3.7 eV and the GaN band edge, including a 3.7 eV peak, is much smaller than in the DC photocurrent spectrum shown in Fig. 3(a). This suggests that the photocurrent excited by radiation in this energy range is caused not by interband transitions in GaN, which would produce an AC photocurrent signal, but instead by excitation of defect levels in the $Al_{0.15}Ga_{0.85}N$ layer.

This aspect of the AC photocurrent spectra also provides clues about the origins of the broad tails observed below the GaN band-edge energy in the DC spectra. Like the defect levels observed below the GaN band-edge, defect levels in the $Al_{0.15}Ga_{0.85}N$ layer are likely to produce primarily persistent photocurrent. Given the range of energy spanned by the tail observed in the DC photocurrent spectra, it is not unreasonable to expect that a broad distribution of defect levels in $Al_{0.15}Ga_{0.85}N$ may extend to energies below the GaN band edge. The tail observed in the DC photocurrent spectra at energies below the GaN band edge may therefore comprise defect levels in both the GaN and the $Al_{0.15}Ga_{0.85}N$ layers. This may partially explain the observed differences in this energy range, described above and shown in Fig. 3(b), between DC photocurrent spectra for the different illumination geometries. The decrease in AC photocurrent observed in Fig. 4 at energies above the GaN band edge may be caused partly by the absorption of the incident light within the $Al_{0.15}Ga_{0.85}N$ layer. Finally, we observe in Fig. 4 that the 3.36 eV peak is not present in the AC photocurrent spectrum, suggesting that the excitation of carriers from this level contributes primarily to the persistent photocurrent.

In conclusion, we have performed detailed studies of persistent photoconductivity in *n*-type $Al_{0.15}Ga_{0.85}N/GaN$ heterostructures. PPC effects arising from defect levels in both the $Al_{0.15}Ga_{0.85}N$ and GaN layers were observed, with a typical time constant of $\sim 1 \times 10^4$ s. Measurements of photocurrent spectra performed using different illumination geometries and illumination techniques allowed us to distinguish between spectral features arising from deep levels in the GaN layer and those originating in $Al_{0.15}Ga_{0.85}N$. A level with excitation energy of 3.36 eV was observed in the structure, with detailed analysis indicating that its concentration is low in GaN and that excitation of carriers from this level contributes primarily to the persistent photoconductivity. Broad distributions of defect levels with excitation energies lower than the band-gap energies were detected in both the GaN and $Al_{0.15}Ga_{0.85}N$ layers, and excitation of these levels was confirmed to give rise to PPC effects in the Schottky diode.

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