Negative capacitance in GaN/AlGaN heterojunction dual-band detectors


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A study of trap states in $n^{+}$-GaN/AlGaN heterostructures using electrical, thermal, and optical analyses is reported. Capacitance-voltage-frequency measurements showed negative capacitance and dispersion, indicating interface trap states. Infrared spectra identified three impurity related absorption centers attributed to shallow Si-donor (pinned to the AlGaN barrier), N-vacancy/C-donor, and deep Si-donor (pinned to the GaN emitter) impurities with corresponding activation energies of 30.8 ± 0.2, 125 ± 1, and 140 ± 2 meV, respectively. The shallow Si-donor impurity had a relaxation time of 155 ± 9 μs, while the C-donor/N-vacancy and deep Si-donor impurities appear to behave as a single trap state with a relaxation time of 1.77 ± 0.05 μs. Multiple analysis techniques allowed the determination of the activation energies of these impurity related centers and the study of the effects of trap states on the electrical behavior of the detector.


I. INTRODUCTION

Radiation-hard, solar blind, high-speed optoelectronic devices have been developed based on gallium nitride device structures.\(^1\) Previously developed GaAs/AlGaAs detectors provided efficient operation in a wide range of infrared (IR) wavelengths.\(^2\)–\(^4\) With the advent of GaN based materials, detectors have been developed,\(^5\) which operate simultaneously in both the IR and ultraviolet (UV) ranges.

Capacitance measurements allow the determination of charge distribution and the identification of the presence of interface states in semiconductors, as an applied bias contributes to carrier capture and emission at interface trap states. These traps will be charged and, thus, produce a dipole layer in the vicinity of the interface.\(^6\) Small modulations in ac bias will cause a change in the barrier height, and the position of the Fermi level will shift relative to its equilibrium position, thus, changing the characteristics of the detector.

Here, the effects of trap states on the capacitance-voltage (C-V) and capacitance-frequency (C-f) characteristics of $n^{+}$-GaN/Al$_{0.026}$Ga$_{0.974}$N detectors are reported. While the measurements reveal the location and mechanisms by which the defect states operate, other methods of analysis are needed to identify the sources of the trap states. IR spectroscopy revealed three impurity related absorption centers that were identified as N-vacancy, C-donor, and Si-donor. The components of the trapping mechanisms, which responded to thermally assisted tunneling, could be discerned from thermal activation energies obtained from an Arrhenius plot. Thus, using multiple methods for the analysis of trap states indicated changes in the electrical behavior due to the presence of trap states, along with the identification of the mechanisms by which the trap states operated.

II. EXPERIMENT

The $n^{+}$-GaN/Al$_{0.026}$Ga$_{0.974}$N structures (sample 1158) were grown by low pressure metal-organic chemical vapor deposition on c-plane sapphire substrates. The UV/IR dual-band detector structure, depicted in Fig. 1, consists of a $n^{+}$-GaN top-contact emitter layer, an Al$_{0.026}$Ga$_{0.974}$N barrier layer, and a $n^{+}$-GaN bottom-contact layer. The Al$_{0.026}$Ga$_{0.974}$N barrier layer had an Al fraction of 0.026, which introduces a work function of 88 meV. Both contact layers were $n^{+}$-doped with silicon to a doping concentration of 5 × 10$^{18}$ cm$^{-3}$. Due to the high doping concentration of all $n^{+}$-GaN contact layers, the contact layers can be treated as a semimetal since the doping concentration is greater than the

![FIG. 1. (Color online) (a) The structure of the detectors consists of an undoped Al$_{0.026}$Ga$_{0.974}$N layer located between a $n^{+}$-GaN top-contact (emitter) layer and a bottom-contact layer. Both $n^{+}$-GaN layers were $n^{+}$-doped with Si to a concentration of 5 × 10$^{18}$ cm$^{-3}$. When forward biased, the top-contact was positive and the bottom-contact was negative. The emitter layer was fully etched; the barrier and the bottom-contact layers were the same regardless of the etching process. (b) Top view of the structure showing the metal rectangular contact. The emitter region inside the rectangular contacts has been fully etched. IR detection takes place by free carrier absorption, while the UV response is due to the interband transitions.](https://example.com/fig1.png)
Mott transition in GaN (~8 × 10^{17} cm^{-3}). Thus, the n^+GaN/Al_{0.026}Ga_{0.974}N interface is analogous to a metal-semiconductor interface.

Using dry etching techniques, the structures were processed to form square mesas with the areas inside the metal rectangular contact fully etched. However, the n^+GaN layer under the rectangular contact remained intact (0.2 μm thick), thus, a small n^-GaN/Al_{0.026}Ga_{0.974}N heterojunction would still be present at the top-contact/barrier interface. The UV/IR dual-band detector operates by collecting carriers from both intraband IR transitions in the n^+GaN emitter layer and interband UV transitions in the Al_{0.026}Ga_{0.974}N barrier layer, as discussed in detail elsewhere. Etching the top-contact emitter will drastically reduce the IR active region of the sample; however, the n^+GaN layer under the rectangular contact will remain intact between the metal contact and the Al_{0.026}Ga_{0.974}N barrier.

C-V and C-f measurements were carried out using a computer-controlled Hewlett-Packard 4284A LCR meter. C-V scans were taken from −2 to +2 V with a 50 mV step width and sine output amplitude set at 5 mV from 100 Hz to 1 MHz, while the C-f scans were taken between 1 kHz and 1 MHz. When forward biased, the top-contact was positive and the bottom-contact was negative. Under reverse bias, the top-contact was negative and the bottom-contact was positive. Different aspects of the electrical behavior can be studied using C-V and C-f characteristics. The applied voltage can either be held constant, and the ac frequency varied or the frequency can be held constant and the applied voltage varied. In the C-V profiles (see Fig. 2), negative capacitance was observed at frequencies of 10–500 kHz, which falls in the range of ~6–600 kHz where negative capacitance occurred in the C-f profiles.

III. RESULTS AND DISCUSSION

When described in terms of charge accumulation at an interface, the capacitance is defined in terms of electrostatics,

\[ C_0 = \frac{\varepsilon_0 \varepsilon A}{L}, \]

where \( \varepsilon \) is the relative dielectric permittivity, \( \varepsilon_0 \) is the dielectric permittivity in a vacuum, \( A \) is the mesa area, and \( L \) is the thickness of the barrier layer. However, this description can only result in positive capacitance, as the total electric current is due solely to the displacement current and there is no contribution from a conduction current. Only in specific cases (high frequency or low temperature) can the capacitance be described by the electrostatic approximation, referred to as the geometric capacitance \( C_0 \). The geometric capacitance for a 600 × 600 μm² mesa area is ~2.9 pF.

In order to describe the negative capacitance in terms of transient currents, capacitance must be defined in terms of the imaginary part of the total admittance \( Y(\omega) \),

\[ C(\omega) = \frac{1}{\omega} \text{Im}[Y(\omega)] = \frac{1}{\Delta V} \int_0^\infty \delta J(t) \cos(\omega t) \, dt. \]  

When the transient current \( J(t) \), transient relaxation current \( \delta J(t) \), and geometric capacitance \( C_0 \) are included, the capacitance is described by

\[ C(\omega) = C_0 + \frac{1}{\omega \Delta V} \int_0^\infty \frac{-d\delta J(t)}{dt} \sin(\omega t) \, dt. \]

In Eq. (3), the sign of the second term is dependent on both the frequency and the behavior of the transient relaxation current in the time domain, specifically, the time derivative. In response to a small voltage step \( \Delta V \), if \( \delta J(t) \) exhibits a positive-valued behavior (as reported in cases of impact ionization of impurities and other interface effects) and the magnitude is greater than \( C_0 \), then the integral in Eq. (3) will become negative, resulting in a negative capacitance. Frequency-dependent capacitance dispersion (FDCD) was observed in the C-V profiles, as shown in Fig. 2(a), and has been attributed to the presence of frequency-dependent trap states. Such phenomena have been observed in the 10 kHz–1 MHz regions of other GaN/AlGaN heterojunctions such as Schottky diodes and heterojunction field effect transistors. In addition to FDCD, negative capacitance was observed in the C-V profiles of the n^-GaN/Al_{0.026}Ga_{0.974}N samples for frequency values of 10, 100, and 500 kHz. Negative capacitance has been observed in various other detector structures. The phenomenon has been attributed to carrier generation and recombination at interface states, most likely due to the presence of occupied trap states at the emitter-intrinsic layer interface. Due to the symmetry in the C-V profiles for both forward and reverse biasing, it is assumed that the processes responsible for negative capacitance and FDCD are present at both heterointerfaces.

The band diagram, including the location of the defect states under zero bias (in addition to the detection mechanism), is shown in Fig. 3(a). In the figure, the n^-GaN top-contact is to the left of the intrinsic Al_{0.026}Ga_{0.974}N barrier layer and the n^-GaN bottom-contact is to the right; the diagram is intended to show the area between metal contacts. When a bias is applied across the device, as shown in Fig. 3(b), electrons with sufficient energy will either surmount the barrier or fill up any available trap states at the emitter-barrier interface. However, under certain frequency and bias conditions, electrons that possess sufficient energy will be able to dislocate any electrons already present in trap states below the Fermi level in a process similar to impact ioniza-
tion or the Auger effect. These ionized trap states then act as electron recombination centers. In a $n^+$-doped semiconductor, the relaxation times of electron recombination centers below the Fermi level are faster than those of the trap states above the Fermi level due to the excess of available electrons. When the electron occupancy of states below the Fermi level exceeds the occupancy of electrons above the Fermi level, the interface charge density variation is reversed and the capacitance becomes negative.

The negative capacitance observed in the $C$-$f$ profiles, as seen in Fig. 2(b), allowed for the extrapolation of trap state relaxation times. The transitions from positive to negative capacitance occurred around 6 kHz, while the transition from negative to positive capacitance was at $\sim 600$ kHz. These two frequencies correlate with $f^{-1}$ relaxation times of $155 \pm 9$ and $1.77 \pm 0.05$ $\mu$s, respectively. The faster relaxation time can be attributed to trap states below the Fermi level, possibly C-donor/N-vacancy and deep Si-donor defect states (pinned to the $n^+$-GaN emitter layer), and the slower relaxation time to trap states above the Fermi level is probably due to shallow Si-donor states in the $n^+$-GaN barrier layer. At frequencies less than 6 kHz, both generation and recombination processes occur; however, the dominant trap states (shallow Si-donor) are located above the Fermi level and, consequently, the capacitance is positive. At $\sim 6$ kHz the trap states associated with a long relaxation time (slow trap states) are saturated and the electron recombination centers exhibiting short relaxation times (fast trap states) become dominant, thus, producing a negative capacitance. The fast trap states remain active until $\sim 600$ kHz, above which these trap states also become saturated. Once both generation and recombination processes have become inactive, due to high frequency, the capacitance returned to a positive value and approached the geometrical capacitance of the sample.

In order to model the $C$-$f$ curves, the contributions from both majority and minority carriers are incorporated by including both positive and negative exponential components into the transient response current. The corresponding capacitance calculated from Eq. (3) is then

$$C(\omega) = C_0 + \frac{a_1 \tau_1}{1 + (\omega \tau_1)^2} - \frac{a_2 \tau_2}{1 + (\omega \tau_2)^2},$$

where $a_1$ and $a_2$ are constants and $\tau_1$ and $\tau_2$ are the relaxation times of the majority and minority carriers, respectively. Relaxation times $\tau_1 = 140 \pm 20$ $\mu$s and $\tau_2 = 1.74 \pm 0.10$ $\mu$s were found using Eq. (4) and were in agreement with the $f^{-1}$ relaxation times from the $C$-$f$ profiles. However, the amplitude of the $C$-$f$ profiles could not be fitted using a Debye relaxation model, indicating that non-Debye processes are active in the sample. In the high-frequency limit ($\omega \to \infty$), the capacitance will approach the geometric capacitance of the sample due to finite inertia of the carrier transport processes when both the faster and slower traps can no longer respond.

The broad peak response peak observed in the IR spectra (see Fig. 4) between 8 and 14 $\mu$m is due to free carrier absorption. However, absorption peaks related to impurity transitions are observed superimposed on the free carrier response between 11 and 13.6 $\mu$m. Based on previous reports, the three impurity related absorption peaks were attributed to shallow Si-donor impurities in the Al$_{0.026}$Ga$_{0.974}$N barrier layer with a $1s$-$2p$ transitional energy of 23.1 $\pm 0.1$ meV, which corresponds to an activation energy of 30.8 $\pm 0.2$ meV. C-donor and/or N-vacancy impurities were attributed to the transitional energy of approximately 93.4 $\pm 0.5$ meV, which correspond to an activation energy of 125 $\pm 1$ meV. The third peak with a transitional energy of 105 $\pm 1.5$ meV and activation energy of 140 $\pm 2$ meV is attributed to Si-donor impurities at the heterointerface, which are pinned to the impurity band in the $n^+$-GaN emitter layer. The conduction band offset of the $n^+$-GaN/AlGaN heterointerface was calculated to be 137 $\pm 7$ meV, which is consistent with the activation energy of 140 $\pm 2$ meV.

To confirm that the negative capacitance displayed by the $n^+$-GaN/Al$_{0.026}$Ga$_{0.974}$N sample was due to the presence of C-donor/N-vacancy and deep Si-donor defect states below...
the Fermi level, and not the shallow Si-donor states in the Al0.026Ga0.974N barrier layer, a similar n+ GaN/Al0.026Ga0.974N structure (sample 1547) was used to obtain thermal activation energies. The n+ GaN/Al0.026Ga0.974N structure had the same Si doping concentration (5 × 10^{18} \text{ cm}^{-3}) and shallow Si-donor activation energy (from IR spectra) as the n+ GaN/Al0.026Ga0.974N structure, but did not exhibit negative capacitance as the position of the C-donor and N-vacancy defect states were above the Fermi level due to an increased Al fraction. For comparison, a C-f profile from the n+ GaN/Al0.026Ga0.974N sample is provided in the inset of Fig. 2(b). Thus, an Arrhenius plot could be constructed using C-f relaxation times at temperatures ranging from 50 to 166 K and a thermal activation energy of 15 ± 1 meV was obtained for the n+ GaN/Al0.026Ga0.974N structure. Other groups reported\textsuperscript{16} similar thermal activation energies of 12–17 meV for shallow Si-donor impurities in GaN structures.

The energy difference of approximately 16 ± 1 meV between the activation energy estimated by IR spectroscopy and the thermal activation energy obtained from the Arrhenius plot indicates that the shallow Si-donors contribute to carrier transport through both thermionic emission and thermally assisted tunneling due to barrier thinning. The discrepancy between these two activation energy values is due to the fact that an Arrhenius plot provided the thermal activation energy required for the particle to reach an excited bound-state energy level where thermally assisted tunneling could take place through the potential barrier. In the case of thermally assisted tunneling, the activation energies obtained by an Arrhenius plot will therefore be lower than the activation energies obtained by IR spectroscopy, as observed here.

Combining the present experimental data, summarized in Table I, a comprehensive model including impurity trap states for n+ GaN/Al0.026Ga0.974N heterostructure can be constructed. The fast trap states are tentatively assigned to C-donor/N-vacancy and deep Si-donor defect states at the heterointerface positioned below the Fermi level, while the slow trap states appear to be correlated with shallow Si-donor impurities in the barrier layer positioned above the Fermi level. C-donor and N-vacancy related impurities are known to be incorporated into the material from the utilized organic precursors, such as the trimethylgallium (TMGa) or trimethylaluminum (TMAI) used as the Ga and Al precursors, respectively, and defects in the crystalline structure. Si-donor related impurities are due to dopant migration from the top- (or bottom-) contact layers. The concentration of Si-donor traps have been found to correlate with Si-dopant incorporation during the growth process.\textsuperscript{16}

### IV. CONCLUSION

In summary, using C-V and C-f characterizations, negative capacitance and FDCD of n+ GaN/Al0.026Ga0.974N heterostructures were analyzed. Using both IR spectroscopy and thermal activation energies, the fast trap states are attributed to deep Si-donor and C-donor/N-vacancy defect states that are approximately 140 ± 2 and 125 ± 1 meV, respectively; and the slow trap states are shallow Si-donor states located in the Al0.026Ga0.974N barrier layer at the heterointerface with an activation energy of 30.8 ± 0.2 meV and a thermal activation energy of 15 ± 1 meV. Calculated (140 ± 20 and 1.74 ± 0.10 μs) and λ\textsuperscript{f} (155 ± 9 and 1.77 ± 0.05 μs) relaxation times were consistent to within the degree of uncertainty, with the \( \lambda \) relaxation times having a smaller uncertainty owing to the electron recombination center’s non-Debye relaxation mechanism. Although multiple methods of determining activation energies allow for the identification of impurity traps, the additional use of C-V and C-f measurements provides information about the effects these trap states have on the electronic and optical properties of n+ GaN/Al\textsubscript{1-x}Ga\textsubscript{x}N detectors.

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