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Electron Traps in p-Type GaAsN Characterized by Deep-Level Transient Spectroscopy

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ELECTRON TRAPS IN P-TYPE GaAsN CHARACTERIZED BY DEEP-LEVEL TRANSIENT SPECTROSCOPY

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ABSTRACT

We have used deep level transient spectroscopy to detect traps in p-type GaAsN grown by metal-organic chemical vapor deposition. Although minority-carrier electrons are not intentionally injected into the depletion region of the measured samples, electron traps are detected in both Schottky barrier and p-n junction devices. The electron-trap signal can exist using only reverse biases during measurement, and checks of series resistance and minority-carrier injection using an optical source also confirm the electron-trap signal. For dilute-nitrogen p-n junction samples, the electron trap gives the dominant signal peak. The peak's magnitude, which corresponds to trap density, correlates to amounts of nitrogen incorporated during growth and reduced open-circuit voltage during light-characterization. The p-type GaAsN layers have net acceptor carrier concentrations in the mid-10^{16} to low-10^{17} cm^{-3}, as determined by capacitance voltage profiling. The electron-trap concentration is dependent on the N content, but values, when traps are filled to saturation, range from 10^{15} to 10^{16} cm^{-3}. The electron signal peak shows a shoulder peak on some samples, giving another close energy level. The electron-trap activation energy is somewhat dependent on the trap filling time, but ranges from about 0.15 to 0.30 eV, and is usually near 0.2 eV for the largest peak when filled to saturation.

INTRODUCTION

The bandgap of the GaAsN alloy can be reduced to near 1 eV when the nitrogen content is about 2%. Indium can also be added to the alloy to improve lattice matching to GaAs and Ge [1,2]. Both of these properties are advantageous to developing a four-junction high-efficiency solar cell, consisting of GaInP, GaAs, InGaAsN, and Ge. Such a structure has an ideal AM0 efficiency over 40%, and could also be used in a terrestrial concentrator module [3]. However, poor minority-carrier properties have limited the usefulness of the GaAsN alloy in such a solar cell [4].

We have used deep level transient spectroscopy (DLTS) [5] to characterize traps in p-type GaAsN. We started with GaAs solar cells that showed no DLTS peaks. Nitrogen was then added to the active layers of these solar cells so that resulting DLTS data could be used to identify a detrimental defect level. While others have measured the GaAsN alloy by DLTS and report several levels of both hole and electron traps [6-10], we detect one dominant peak in Zn-doped material. The same defect signal also appears as the largest peak in unintentionally doped (uid) material. The appearance of this peak with added N correlates to a detrimental reduction in the solar cell's open-circuit voltage beyond that associated with decreased bandgap [11].

EXPERIMENT

The epitaxial layers studied here were grown by atmospheric-pressure metal-organic chemical vapor deposition using trimethylgallium or triethylgallium, arsine, and dimethylhydrazine on Zn-doped GaAs substrates. The growth temperature ranged from 570°C to 650°C to better control N content, which is estimated from x-ray diffraction measurement. A series of pn junction samples were grown with increasing amounts of N. Samples MF057, MF058, MF152, MF153, and MF166 have about 0.05%, 0.1%, 0.25%, 0.6%, and 1.2% N, respectively. The bandgaps range from 1.4 to 1.2 eV. The junction is formed using a highly doped n-type GaAs layer and 1-mm square contacts deposited on top. A Schottky contact sample was also made by sputtering gold dots of 0.75 and 1.0 mm diameter on an as-grown uid GaAsN layer. This sample has a N content similar to MF166 and a bandgap also near 1.2 eV. All samples had ohmic contacts on the back surface.

Most data were collected using an Accent Optical Technologies DLTS system. Optical DLTS data were collected using a Sula Technologies DLTS system. Samples measured on either system were only reverse-biased. Traps were filled when the sample was biased to less reverse bias or zero bias for a defined filling pulse time.

RESULTS AND DISCUSSION

The addition of a small amount of nitrogen led to a positive peak in the DLTS spectra that was not seen for GaAs with no N added. As shown in Fig. 1, a positive peak corresponding to minority-carrier electron trapping occurs near 125 K for a 23 s^{-1} rate window. Long filling pulses 10 s in duration were used to assure the signal had reached a saturation in magnitude. The peak heights, which are proportional to trap density, increase with increasing N content.

The inset of Fig. 1 shows nearly linear data points on an inverse capacitance squared versus voltage plot, and thus illustrates the uniform p-type doping density over the bias range used for the DLTS measurement (-1 V to 0 V). Linear fits of the data give net acceptor concentrations in the mid-10^{16} cm^{-3} for all samples.

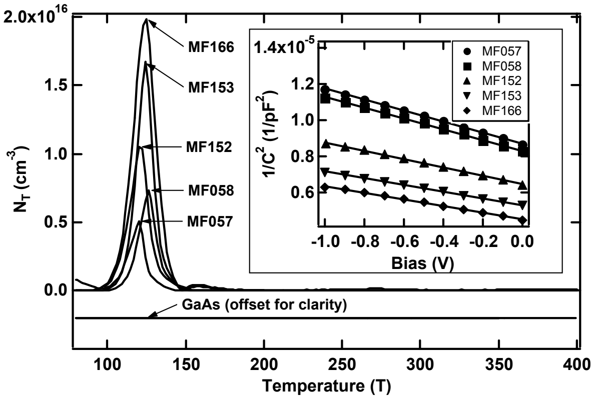

Fig. 1. DLTS spectra using a 23 s^{-1} rate window and long signal-saturating filling pulses (10 s) for GaAsN pn junction samples with increasing amounts of N. The positive peak corresponds to an electron trap. Capacitance-voltage data plotted in the inset graph show uniform net acceptor concentrations of $3.5x10^{16}$, $3.6x10^{16}$, $4.6x10^{16}$, $5.7x10^{16}$, and $5.8x10^{16}$ cm^{-3} for MF057, MF058, MF152, MF153, and MF166, respectively.

The DLTS data represented by Fig. 1 are plotted in an Arrhenius plot in Fig. 2. Fits of the data for each sample give an electron trap activation energy of about 0.2 eV, and intercept values give corresponding capture cross sections. The electron trap concentration values at saturation also increase with increasing N content. We estimate these densities using a standard DLTS algorithm for material having uniform trap distribution.

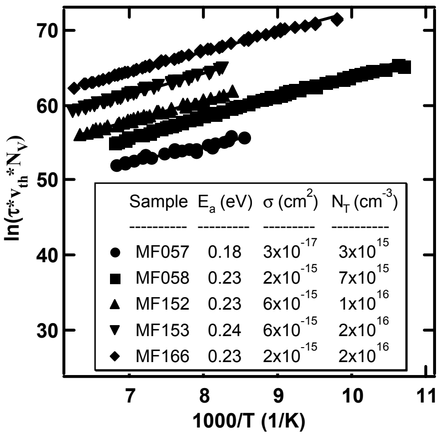

Fig. 2. Arrhenius plot created from DLTS data of Fig. 1. The curves are vertically offset by +3 for clarity.

The Schottky-barrier p-type GaAsN sample was similarly measured and characterized by DLTS. Filling pulse widths ranging from 10 µs to 10 s were used to fill the traps during the 0 V bias. As shown in Fig. 3, there is a negative peak near 290 K, which corresponds to a majority carrier (hole trap) with an activation energy of about 0.7 eV. However, for this work, we will focus on the positive electron-trap peaks at low temperature that are similar to those seen in the pn junction samples. Although minority-carrier traps are not expected to be detected when applying only reverse bias, and perhaps even less expected with a Schottky barrier, we nonetheless observed similar electron trap peaks: one that has a larger amplitude at about 110 to 120 K and one that is a shoulder at about 150 K. When plotting the data on an Arrhenius plot, the larger peak at saturation results in an electron trap with an activation energy of 0.19 eV, whereas the shoulder peak corresponds to 0.22 eV. The peak temperature values of the positive peaks are seen to shift to slightly lower temperatures as the filling pulse width is increased. The corresponding activation energies then decrease as shown in the inset of Fig. 3, suggesting a possible band of electron traps [12]. The filled trap concentrations, which are proportional to the signal amplitudes, are also plotted in the inset of Fig. 3.

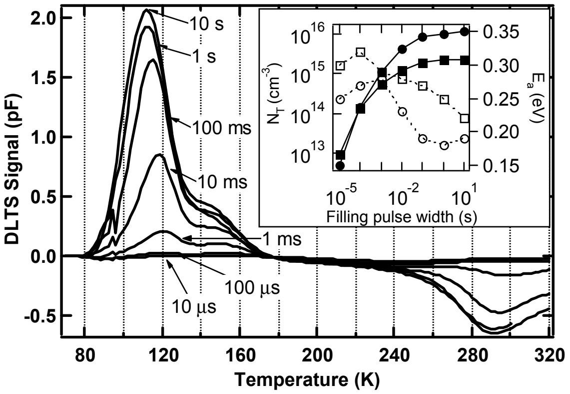

Fig. 3. DLTS spectra using a 23 s^{-1} rate window and various filling pulse widths for a Schottky p-type GaAsN sample. The inset shows calculated trap densities and activation energies for the positive peaks as a function of filling pulse: circles for large peak and squares for shoulder peak; filled symbols for trap density on left scale and open symbols for activation energy on right scale.

This Schottky sample was measured again using reverse-bias conditions of -1, -2, -3, and -4 V. The pulse filling bias is 1 V higher than the reverse-bias value for a duration of 10 s. The DLTS results are plotted in Fig. 4. The left inset shows the majority hole-concentration of $2x10^{17}$ cm^{-3} as measured by capacitance-voltage. The right inset shows the electron trap signal from optical DLTS when using a flash lamp for trap filling. Additionally, we verified that the positive signal was not due to high series resistance [13,14] by adding a known series resistance that did invert the signal. The DLTS data are plotted in an Arrhenius plot shown in Fig. 5.

Although the signal is smaller at the larger reverse biases, a positive peak is observed for all four bias conditions. However, the signal magnitude does not decrease proportionally to the reduction of the space charge region width. Instead, the peak magnitude is reduced much more quickly. A modeling program was used to investigate this signal reduction and address the source of electrons to fill the traps.

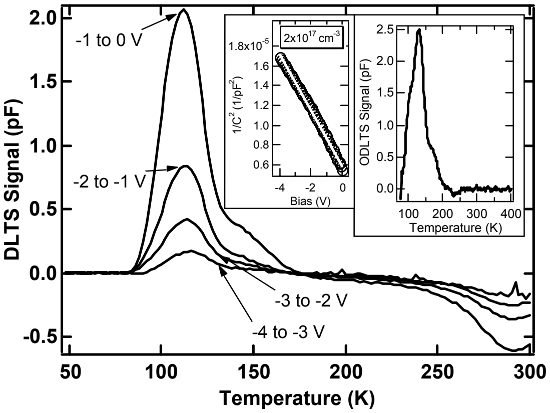

Fig. 4. DLTS spectra using a 23 s^{-1} rate window, 10 s signal-saturating filling pulses, and varying bias conditions for a Schottky barrier GaAsN sample. The left inset shows the majority hole concentration from capacitance-voltage. The right inset shows optical DLTS results for a similar rate window.

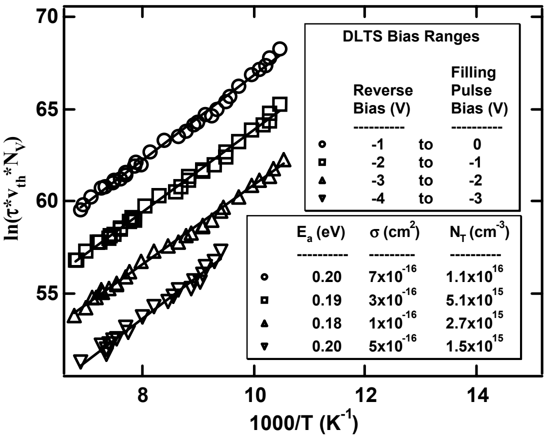

Fig. 5. Arrhenius plot created from DLTS data of Fig. 4. The curves are vertically offset by +3 for clarity.

We used the SimWindows [15] modeling program to solve for the spatially dependent Fermi level position in a zero-biased and reverse-biased Schottky barrier device. We calculated a Schottky barrier height of about 0.9 eV based on experimental measurements of bandgap (1.2 eV), built-in potential barrier (0.8 eV), and carrier concentration ($2x10^{17}$ cm^{-3}). The numerical solutions for 0 V and -1 V applied bias give the relative positions of the conduction and valence band edges and the Fermi level or quasi-Fermi levels, as shown in Fig. 6. An estimated electron trap level is shown 0.2 eV below the conduction band as a visual aid.

The relative position of the Fermi level, E_F, or electron quasi-Fermi level, E_{Fn}, with respect to the conduction band gives the probability that states in this region are occupied by electrons. The electron concentration is spatially integrated and reaches its maximum value within the first few nanometers near the interface. This gives a value of the total number of electrons per unit area. The difference of these electron densities calculated at two different biases corresponds to the DLTS signal of electron traps that can become occupied and then thermally emit when using those same biases as the reverse bias and filling pulse bias of a DLTS measurement. Without knowledge of the total number of electron states, we normalize these differences to give a relative amount of trapped electrons for various pulse conditions. The line plotted in Fig. 7 shows these normalized changes in electron density between biases having steps of 0.2 V. For example, the largest value corresponds to a reverse bias of -0.2 V and a filling pulse to 0 V and is normalized to 1.0. DLTS data for the sample are taken using the same steps of 0.2 V. The filling pulse width is increased until the peak amplitude saturates. These data are shown in the inset of Fig. 7. The normalized saturation values are plotted in Fig. 7 for each bias condition using the filled circles and lie very near to the modeled values (line).

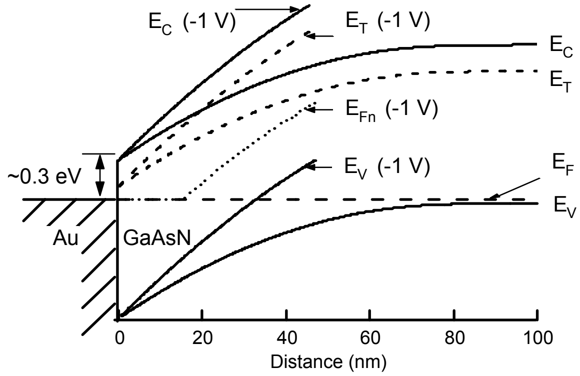

Fig. 6. Modeled band diagram and electron concen-tration for zero-bias and 1 V reverse bias.

The model's close fit suggests that the traps near the interface are filled and emptied during the changing bias conditions. The results are similar for the n^+p junction samples, as well. To fill the traps, electrons must surmount the conduction-band offset at the metal interface (for the Schottky barrier) and the conduction-band bending due to the built-in field and any applied reverse bias in order to penetrate a few nanometers into the GaAsN layer and become trapped. This energy is estibated to be about 0.3 eV, as shown in Fig. 6. An estimate of trap filling time can be calculated using thermionic emission [16]. Current over a potential barrier is given by

$$J = AT^2 \exp\left(-\frac{q\Phi_B}{k_B T}\right), \qquad (1)$$

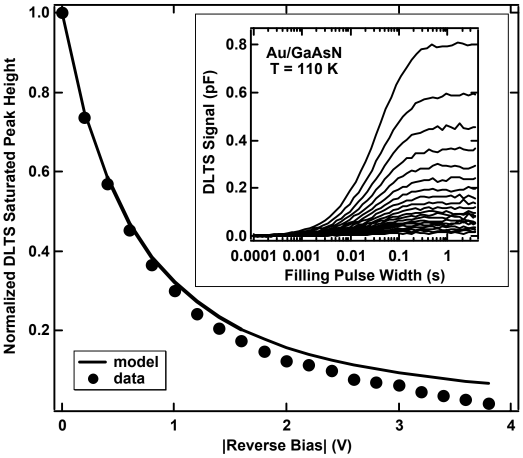

Fig. 7. Measured DLTS signal magnitude versus the modeled electron concentration. The inset shows trap filling data for the Schottky barrier GaAsN sample. The smallest signal represents biasing of -4 V to -3.8 V.

where A is the Richardson constant of 120 A/cm^2/K^2, q is electron charge, Φ_B is the potential barrier, and k_B is Boltzmann's constant. The amount of trapped charge necessary to give the corresponding DLTS signal can be estimated from the measured values before and just after the filling pulse when the applied voltage is the same and $Q_1/C_1=Q_2/C_2$. Using a doping value of 2x10^{17} cm^{-3}, depletion width of 150 nm, and capacitance changing from C_1=340 pF to C_2=342 pF, the trapped charge (Q_2-Q_1) is 2x10^{10} electrons/cm^2 or 3x10^{-9} C/cm^2. Before saturation, the traps continue to fill for roughly 0.1 s, and the resulting thermionic current is 3x10^{-8} A/cm^2. Using T=110 K, the potential barrier the electrons can surmount is ~0.3 eV, as speculated above and sketched on Fig. 6. Also, if the electrons are trapped in just a few nanometers near the interface instead of distributed across the changing depletion width, the resulting electron trap densities may actually be over 10 to 100 times larger than those calculated from standard DLTS analysis.

The agreement of the DLTS data to the model for the various bias conditions suggests that electron traps at or near the interface are filled and emptied during measurement. The n$^+$p junction samples have provided a different interface, yet the electron trap was still present. Recently, we have also measured p$^+$n junction samples and have detected a negative peak, which corresponds to a majority-carrier electron trap. Preliminary analysis of this electron trap gives an activation energy in the 0.3 to 0.4 eV range, and may be the same or similar defect. Detection of this level as a majority trap in n-type material also suggests it exists in the bulk GaAsN material.

SUMMARY

In summary, an electron trap having an activation energy near 0.2 eV was observed in p-type GaAsN using both n$^+$p junction and Schottky-barrier samples. The same minority-carrier electron trap peak was confirmed using optical carrier generation. The minority-carrier electron DLTS peaks were observed using only reverse-bias conditions. Modeling showed that reduced reverse bias allowed increased electron-trap occupation within a few nanometers of the metal or n$^+$p interface. An estimate of thermionic emission provided adequate current to fill these electron traps from the metal or n-type side of the junction.

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