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# Defect Trapping in InGaAsN Measured by Deep-Level Transient Spectroscopy

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# Defect Trapping in InGaAsN Measured by Deep-Level Transient Spectroscopy

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## ABSTRACT

Deep-level defects in p-type InGaAsN films grown by metal-organic chemical vapor deposition and molecular-beam epitaxy are investigated by deep-level transient spectroscopy (DLTS). A series of as-grown samples having varying N and In composition showed a deep hole trap with an activation energy ranging from 0.6 to 0.8 eV and an electron trap with an activation energy ranging from 0.1 to 0.4 eV. The electron trap activation energy decreased with increasing N content. Optical DLTS measurements similarly revealed the shallow electron traps, but did not show the deeper hole-trap peaks. A deep electron trap was detected when using forward bias to inject electrons during pulse filling. Together, the deep electron trap and deep hole trap may form a recombination center. This also suggests that generated carriers could recombine quickly, and therefore, such a recombination center may have prevented a deep-trap signal during optical DLTS.

## 1. Introduction

Adding nitrogen to GaAs initially reduces the bandgap [1-3]. This alloy can be grown epitaxially on GaAs, and lattice-matching can be improved by also adding In [4]. With about 2% N and 6% In, a 1-eV bandgap material lattice-matched to GaAs can be attained [4,5]. 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 of 41% [6], but to date, poor minority-carrier properties have limited the material's usefulness in multijunction cells [5,7]. Deep-level transient spectroscopy (DLTS) is a powerful technique for characterizing material defects and impurities and can provide information to identify lifetime-killing defects that degrade device performance.

## 2. Experimental

A series of samples with varying N and In composition were grown by metal-organic chemical vapor deposited (MOCVD) and molecular-beam epitaxy (MBE) on conductive GaAs substrates. Details about the growth processes may be found elsewhere [5,8,9]. An ohmic contact was deposited on the back surface, and Schottky contacts formed by sputtered Au were deposited on the top surfaces. Estimates of N content were obtained by measuring bandgap and X-ray diffraction [5]. The samples were then characterized by measuring room-temperature carrier concentration using the capacitance-voltage (C-V) technique [10]. DLTS data were collected using a SULA Technologies [11] instrument that uses up to 12 rate windows of different time constants. Temperature was scanned at a rate of 10 K per minute, and data for each rate window were collected during both upward and downward temperature sweeps. These data were then averaged to account for any temperature lag between the thermocouple and the sample.

## 3. Results and Discussion

DLTS data were collected with an applied reverse bias of 1 V, a pulse amplitude of 1 V (to 0 V), and a pulse width of 10 ms. The data for the 0.2-ms rate window during the heating cycle are shown in Fig. 1. The $\Delta C$ values are the capacitance changes during the rate windows and are plotted as trap density [12].

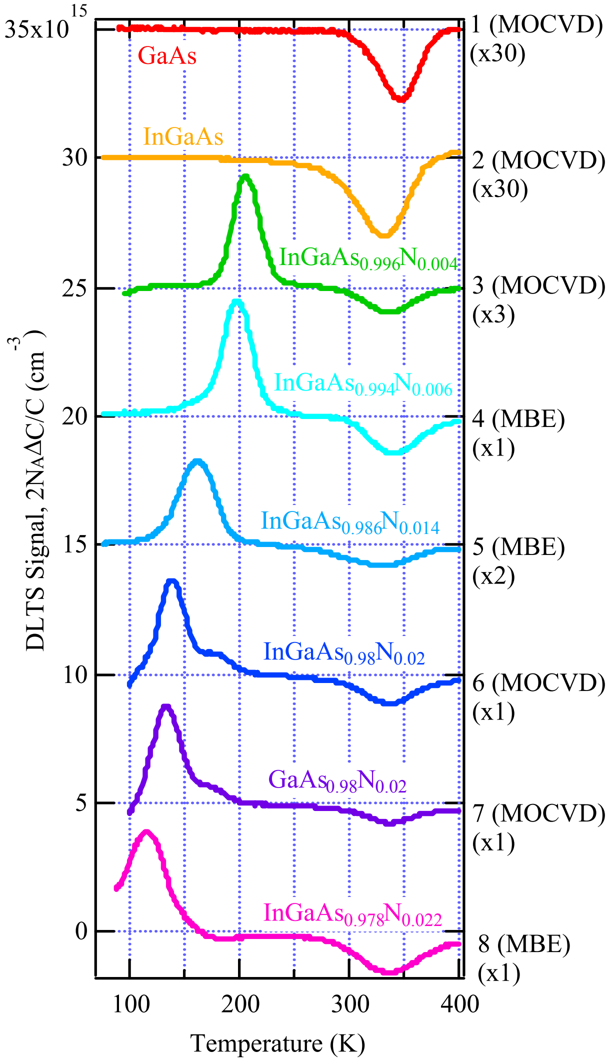

Figure 1. Trap concentration from DLTS measurement using 0.2-ms rate window. For clarity, each trace is offset by $5 \times 10^{15}$ and multiplied by the factor shown on the right axis.

The maximum temperature points are then plotted on an Arrhenius plot with the corresponding rate-window time constants. These data are shown in Fig. 2. Open symbols correspond to majority-carrier hole traps (negative peaks), whereas filled symbols correspond to electron traps (positive peaks). The data points are fit by linear equations, giving slope and intercept values. The activation energies, $E_a$, are determined from the Arrhenius plots' slope [10] and are also shown in Fig. 2.

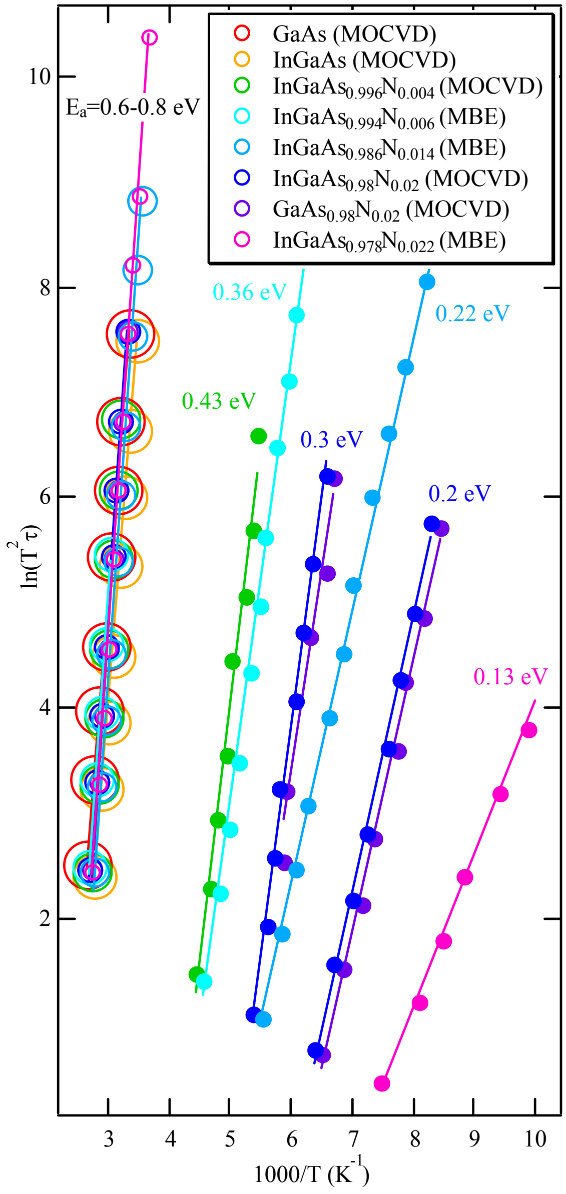

Figure 2. Arrhenius plot of DLTS data collected on samples using 1-V reverse bias, 1-V pulse amplitude, and 10-ms pulse width. Open symbols show hole traps.

Electrical-pulse DLTS data show that each sample contains a hole trap with the peak occurring near 350 K, as seen in Fig. 1. These activation energies range from 0.6 to 0.8 eV. N-containing samples also show a positive, electron-trap signal at low temperature. The corresponding activation energies (0.43 to 0.13 eV) become smaller with increasing N content, which suggests that the level may be fixed relative to the valence band [9].

Optical DLTS (ODLTS) data were also collected using a pulsed xenon flashlamp, in substitution of electrical pulses, to fill trap levels. The samples were similarly reverse-biased at 1 V. The solid lines of Fig. 3 show ODLTS signals for the 0.2-ms rate window. The corresponding electrical-pulse DLTS spectrum are shown using dotted lines.

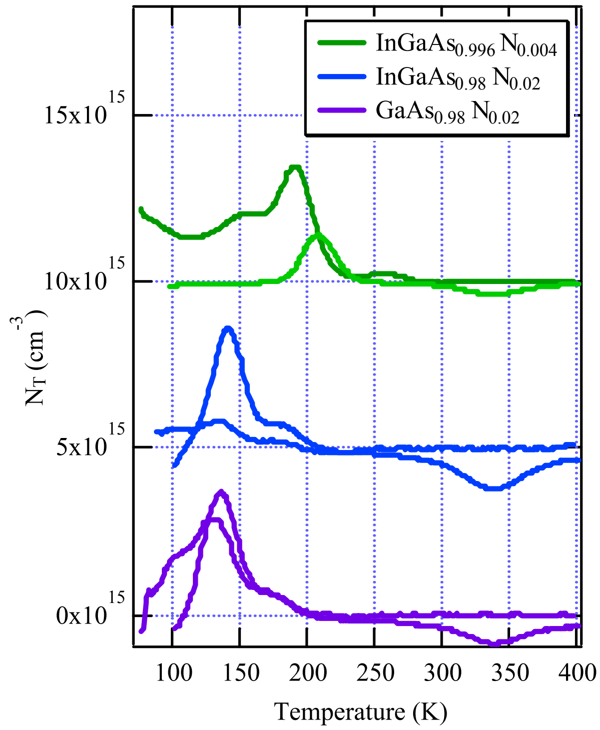

Figure 3. Trap concentration from ODLTS measurement using 0.2-ms rate window (solid lines). Electrical-pulse signal is shown for comparison (dotted lined). For clarity, traces for each sample are offset by $5x10^{15}$.

The initial intention of ODLTS measurements was to verify the positive electron trap signal at low temperatures. When measuring DLTS and pulsing just in reverse bias, only majority-carrier signals are expected in the DLTS spectrum. DLTS sign reversal due to high series resistance [13] was considered. However, impedance measurements verified that the parallel capacitance and resistance equivalent circuit assumed by the DLTS meter did not lead to a sign reversal. Using optical pulses to generate excess electrons and holes allows us to measure both trapped electrons and holes. The ODLTS data plotted in Fig. 3 verify the electron trap signal.

The positive DLTS peak corresponds to roughly $10^{15}$ $cm^{-3}$ trapped electrons. Without optical generation or forward-bias injection, these electrons may originate from thermal generation. Dark current-voltage (I-V) data were collected as a function of temperature [14]. The reverse saturation current at a reverse bias of 1 V (the same reverse bias for DLTS measurement) is plotted in Fig. 4. The data are graphed as an Arrhenius plot, and linear fits of ln(I) versus

1/T give activation energies of 0.3, 0.07, and 0.03 eV. The small activation energy at low temperature allows for sufficient dark-generation current to fill ~$10^{15}$ $cm^{-3}$ electron traps.

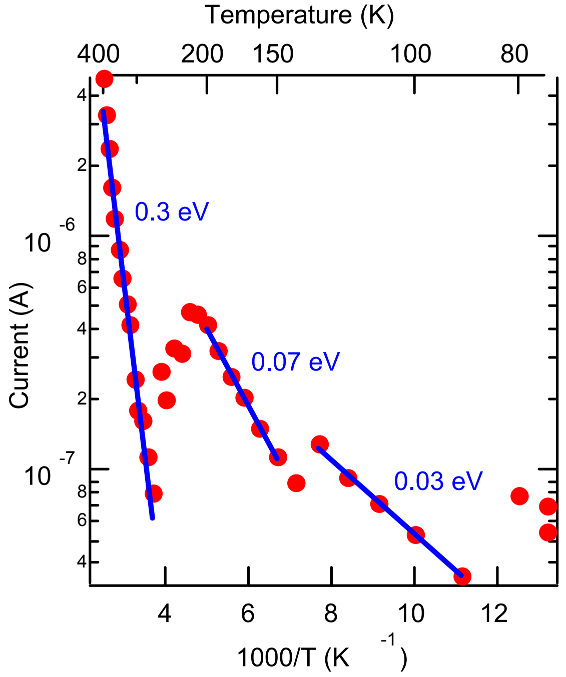

Figure 4. Temperature-dependent reverse saturation current measured by dark I-V at 1V reverse bias. Linear fits with corresponding activations energies are shown.

Although ODLTS data was used to verify the shallow electron trap, it also led to initial speculation that the deep hole trap is also a recombination center. Figure 3 shows that reverse-bias-pulsing DLTS gives a deep hole trap signal. However, when equal numbers of excess electrons and holes are generated optically at the higher temperatures, there is no deep hole trap signal. This suggests that the excess electrons and holes recombine before trapping can be detected by DLTS.

A recombination center should show evidence of trapping both electrons and holes. In reverse-bias-pulsing DLTS, majority-carrier holes outnumber the electrons and give the negative peaks as seen in Figs. 1 and 3. Pulsing to forward bias during the filling pulse can lead to injected electrons. Then, further increasing of the forward bias can lead to excess electrons eventually outnumbering the holes. The DLTS signals for increasing amounts of forward bias are shown in Fig. 5. The positive electron trap signal overwhelms the hole trap signal at the highest forward-bias pulses. Thus, there is evidence for a deep electron trap (~0.7 eV), in addition to the deep hole trap. Together, these deep traps may form a recombination center and be detrimental to solar cell performance.

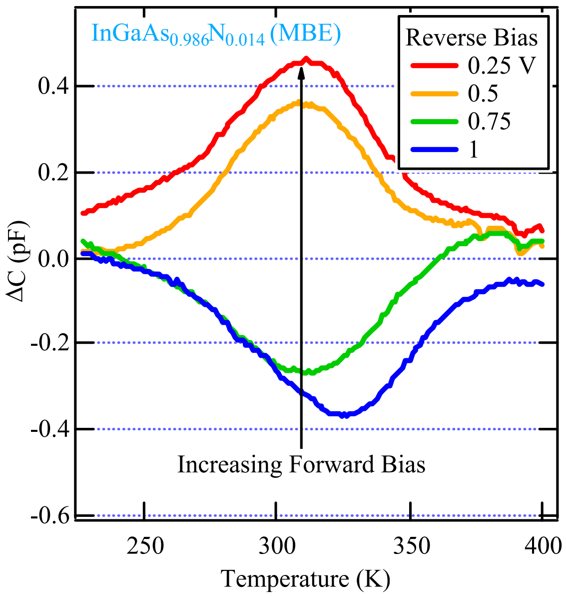

Figure 5. The DLTS signal is shown to change from a negative (hole trap) peak to a positive (electron trap) peak with increasing electron injection corresponding to increasing forward bias.

## 4. Summary

We have performed DLTS measurements on MOCVD- and MBE-grown InGaAsN samples with varying amounts of In and N. A shallow electron trap was detected, and its activation energy varied with N content. Large reverse bias currents suggest that this trap is filled in reverse bias by thermal generation.

A deep hole trap was detected in reverse bias. As the filling pulse increased into forward bias, a deep electron trap emerged. The deep electron trap and deep hole trap may act together to form a recombination center. Lack of a deep level signal from ODLTS may also be evidence of such a recombination center.

## 5. Acknowledgements

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