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NOTICE

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Abstract. This paper presents and discusses the first Deep-Level transient spectroscopy (DLTS) data obtained from measurements carried out on both Schottky barriers and homojunction devices of GaInNAs. The effect of N and In doping on the electrical properties of the GaNInAs devices, which results in structural defects and interface states, has been investigated. Moreover, the location and densities of deep levels related to the presence of N, In, and N+In are identified and correlated with the device performance. The data confirmed that the presence of N alone creates a high density of shallow hole traps related to the N atom and structural defects in the device. Doping by In, if present alone, also creates low-density deep traps (related to the In atom and structural defects) and extremely deep interface states. On the other hand, the co-presence of In and N eliminates both the interface states and levels related to structural defects. However, the device still has a high density of the shallow and deep traps that are responsible for the photocurrent loss in the GaNInAs device, together with the possible short diffusion length.

INTRODUCTION

Geisz (1) has shown that GaInNAs can be grown lattice-matched to GaAs with a bandgap of 1.0 eV. Initial performance data of prototypes of the GaInNAs solar-cell lattice-matched to GaAs have confirmed its potential for ultrahigh-efficiency three- or four-junction devices. To obtain cells that are more efficient than existing devices, sufficient photocurrent from the 1.0 eV junction must be produced to match the photocurrents of the GaNInAs and GaAs junctions. However, a very low photocurrent and limited quantum efficiency were observed. Initially, this was attributed to short diffusion lengths (2).

The electrical performance of the semiconductor devices is limited by the defects and impurity centers that are present in the bulk, surface, and interface regions. Therefore, possible trap levels near the depletion region of the device can also be a primary potential contributor to the loss in photocurrent. Deep-level transient spectroscopy (DLTS) is one of the most useful techniques for characterizing the deep level in semiconductor devices. This paper presents and discusses the first DLTS data obtained from measurements carried out on both Schottky barriers and heterojunction devices of GaInNAs.

EXPRIMENTAL METHODS

Growth of GaNInAs

GaInNAs was grown by atmospheric and low-pressure metal-organic vapor-phase epitaxy using trimethylgallium (TMG), trimethylindium (TMI), arsine (AsH_3), and 1,1-demethylhydrazine (DMHy). Growth temperatures ranged from 550 °C to 650 °C. GaNAs, GaInAs, and GaInNAs Schottky barriers were prepared by using Au back and sputtered Au/Pd alloy as front contacts.

DLTS Measurements

DLTS measurements were carried out on these Schottky barriers, in addition to p-n junctions of the GaNInAs devices. Schematics of the structure of Schottky and mono-junction devices are shown by Figures 1a and 1b. The configuration of the DLTS

| Au grid |
| p-GaAs |
| p-GaInP |
| p-GaInNAs |
| n-GaInNAs |
| n- GaAs buffer |
| n- GaAs substrate |
| Au/Sn back contact |

p/n homojunction (PA277)
(a)

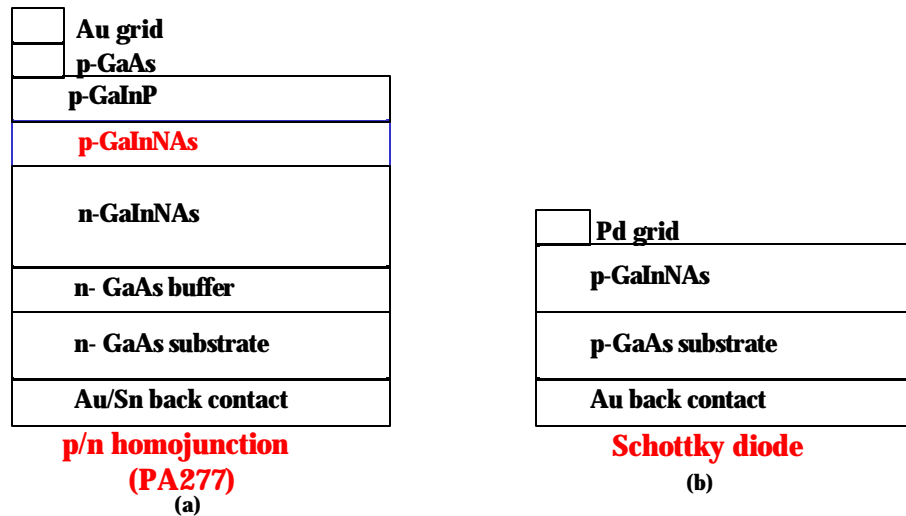| Pd grid |
| p-GaInNAs |
| p-GaAs substrate |
| Au back contact |

Schottky diode
(b)

Figure 1 Schematic diagram of the structure of GaInNAs Schottky (b) and homojunction (a) devices.

system is depicted by the schematic diagram of Figure 2. The system consists of a sensitive capacitance measurement apparatus with adequate transient response, a pulse generator to provide rapid changes in the diode bias, a correlator, a variable-temperature crystal, and a data-acquisition computer. The DLTS measurement is based on the rate-window concept, where the measuring apparatus only responds when the transient is within this window (3). If the emission rate of an existing trap changes with the sample temperature, the instrument will show a response peak at the temperature at which the emission rate is within the window. The emission rate is given by

$$e = [(\sigma\ v\ N) / g] \exp[-\Delta E / kT] ,$$

where σ is carrier capture cross-section; v is mean thermal velocity of carriers in the band; g is the degeneracy of the trap level; and ΔE is the energy between the trap level and the carrier.
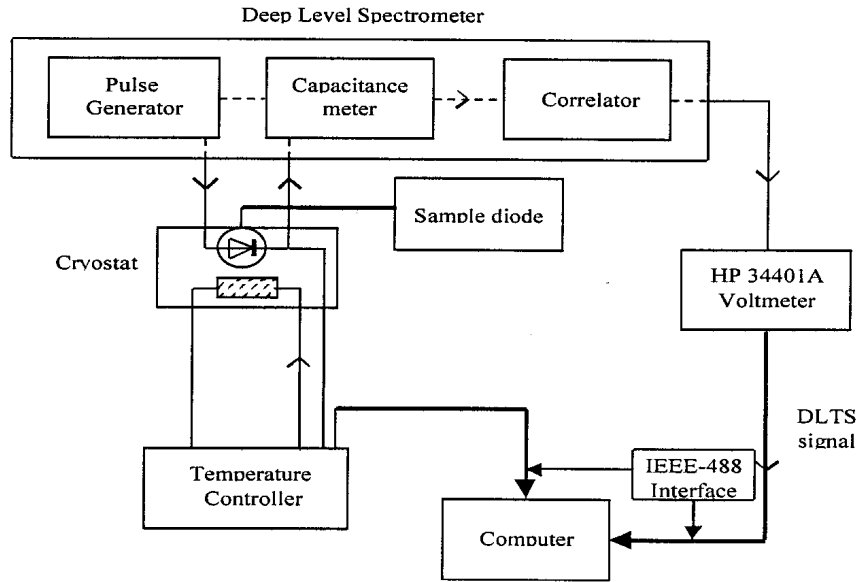
Deep Level Spectrometer

Figure 2 Schematic diagram of the DLTS apparatus.

To determine any possible correlation between the composition of the GaNInAs films and the location of the detected traps and their density, DLTS measurements were carried out on Schottky devices made of GaNAs, GaInAs, and GaNInAs films. In this way, traps related to each of the two dopants were identified. The results of these measurements are illustrated, in the form of DLTS spectra and the associated Arrhenius dependencies, in Figs 3, 4, and 5. Figure 3 shows that two hole traps, HN1 and HN2, are detected in nitrogen-doped p-GaAs films. HN1 is located at 0.13 eV. The energy level of HN2 ranges between 0.16 and 0.22 eV. The exact location of NH2 changes with the concentration of N. It is also possible that the density and energy level of HN2 is affected by the presence of C impurities, which could form C-N complex states. In some of the GaNAs devices, an additional hole trap was detected at 0.47 eV. The density of this trap (1.4×10^{15} cm^{-3}) is comparable to that of the trap HN2 and is
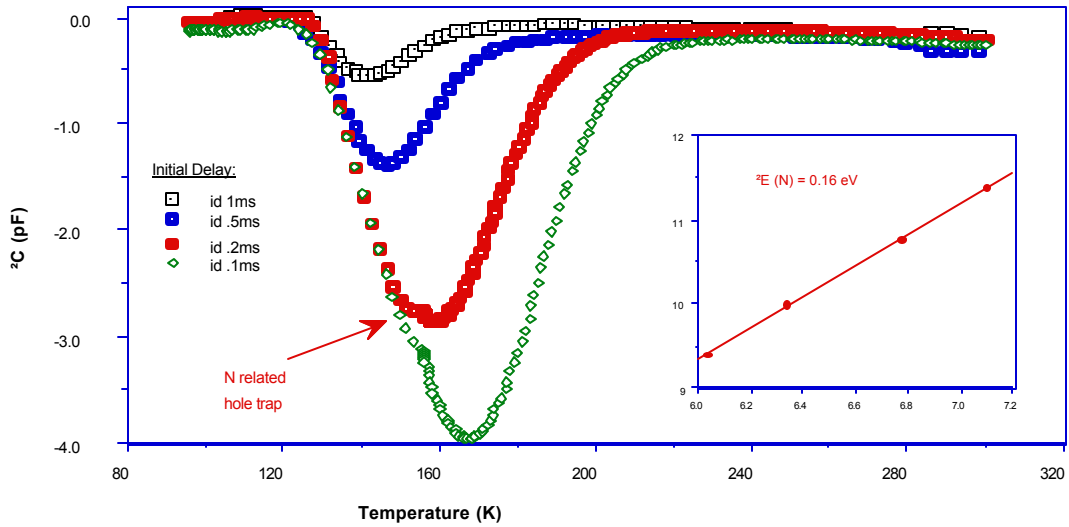
Figure 3 DLTS spectra and Arrhenius plot of GaInAs Schottky diode.

attributed to structural defects in the film. On the other hand, Figure 4 shows that In-doped p-GaAs films are dominated by two levels. The first is a deep hole trap (HIn) at 0.36 eV. The second is an extremely deep level at energy levels ranging between 0.91and 0.94 eV (IIn). The observed change in the intensity of the IIn peak with bias voltage suggested that this level is due to deep interface states. The density of states of the IIn level ranges from 10^{12} to 10^{13} cm^{-3} which is very low compared to the doping density and carrier concentration. We also found that the energy level of IIn shifts to lower energy as the In concentration increases. The hole trap at 0.47 eV due to structural defects is also detected in the GaInAs devices. Two additional traps were observed at the 0.53 and 0.62 eV energy levels. The 0.53 eV trap, which is also observed in the GaNAs devices with high N concentration (> 5%), is attributed to structural defects (5). The density of this trap level is two orders of magnitude higher in the GaNAs than in the GaInAs devices. The 0.62 eV hole trap was observed only in the GaInAs devices and is attributed to Fe impurities (4). Composition analysis carried out using secondary-ion mass spectroscopy confirmed the presence of Fe impurities. As demonstrated by Figure 5, the presence of HN1, HN2, and HIn is confirmed in Schottky diodes made of GaNInAs. But only HN2 and HIn were detected in p-n mono-junction GaNInAs devices (Figure 6). It is worth noting that the hole trap
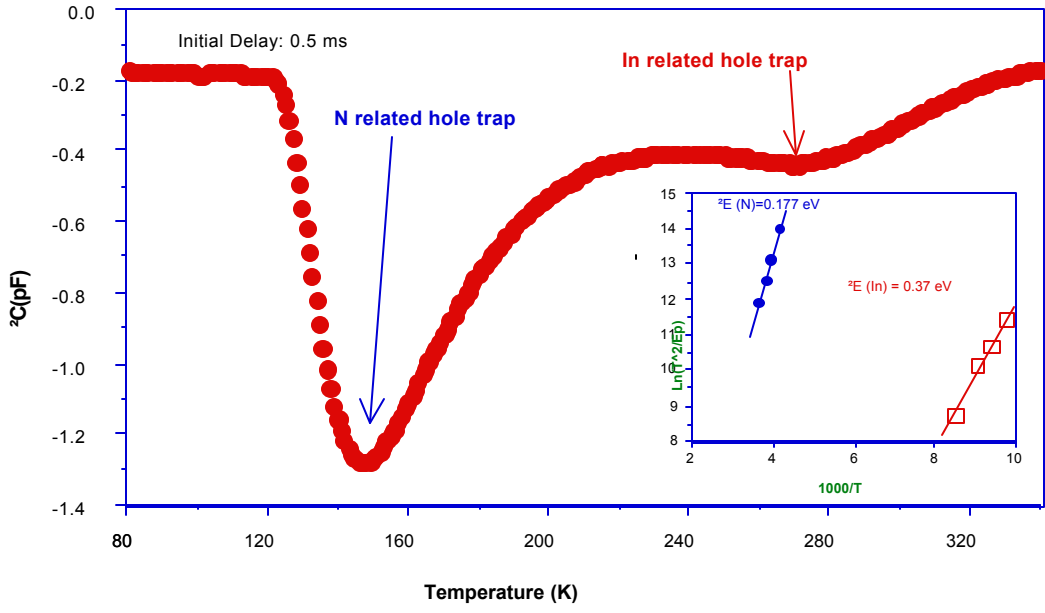
Figure 4 DLTS spectra and Arrhenius plot of GaInAs Schottky diode.
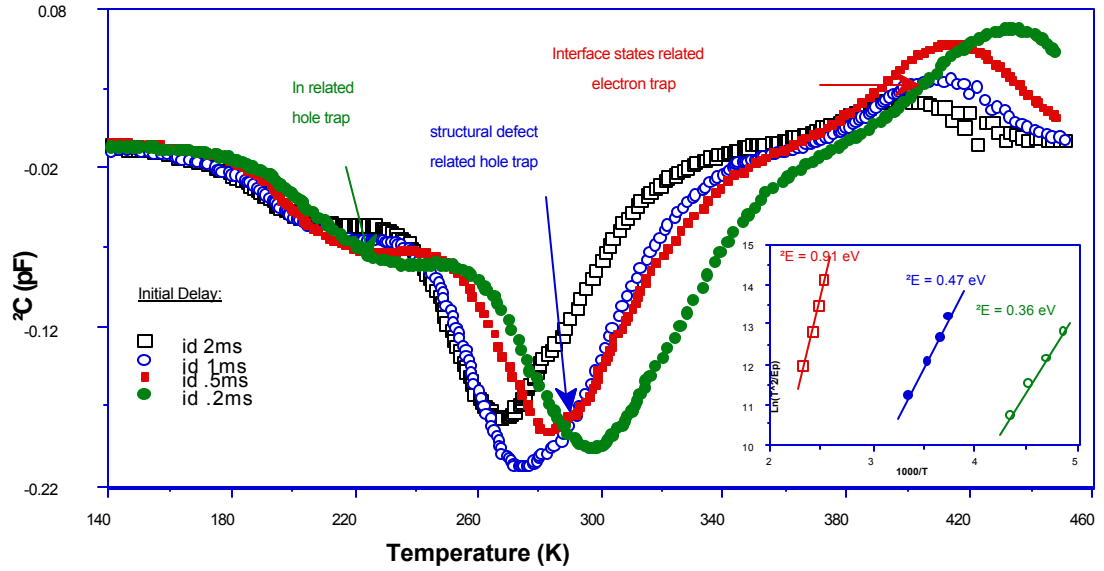

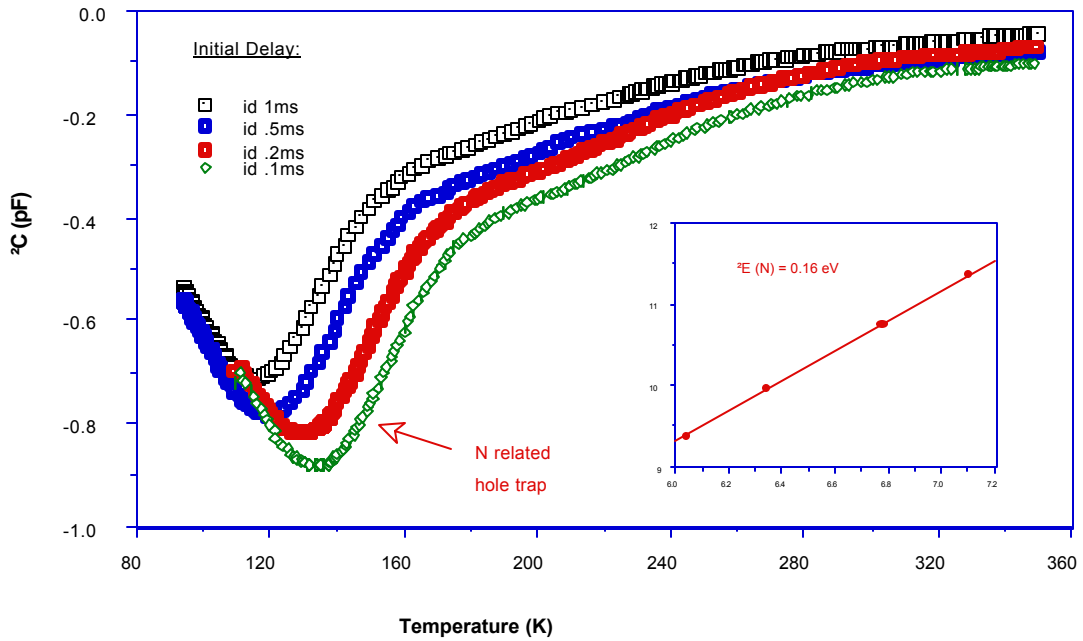Figure 5 DLTS spectra and Arrhenius of GaInNAs schottky diode.

Fig. 6 DLTS spectra and Arrhenius plot of GaInNAs p-n homojunction device.

resulting from structural defects was not observed in any of the GaInNAs devices. A summary of all deep levels detected in samples of different composition are shown in Table, I together with the assignment of their origin.

Table I. Summary of DLTS Levels in GaInNAs films as a Function of Composition

Energy Level Composition	Nitrogen-Related Levels		In-Related Levels		Additional Levels
	NH1 (0.13 eV)	HN2 (eV)	HIn (0.36 eV)	IIn (eV)	
GaN$_{2\%}$As		0.22			Hole trap at 0.47 eV (*)
GaN$_{2\%}$As	x	0.18			–
GaN$_{3\%}$As		0.17			–
GaIn$_{3\%}$As					0.47(*), 0.53(*), 0.62(+)
GaIn$_{3\%}$As			x	0.94	–
GaIn$_{8\%}$			x	0.91	0.47 (*)
GaIn$_{11\%}$N$_{2.9\%}$As		0.21	x		–
GaIn$_{8\%}$N$_{1.2\%}$As		0.18	x		–
GaAs					

(*) Structural defect   (+) Hole trap due to Fe impurity

CONCLUSION

In summary, we have investigated the effect of N and In doping on the electrical properties of the GaNInAs devices resulting from structural defects and interface states. Moreover, the location and densities of deep levels related to the presence of N, In, and N+In are identified and correlated with the device performance. From the above data, it is clear that the presence of N alone creates a high density of shallow hole traps related to the N atom and structural defects in the device. Doping by In, if present alone, also creates low-density deep traps (related to the In atom and structural defects) and extremely deep interface states. On the other hand, the co-presence of In and N eliminates both the interface states and levels related to structural defects (due to reduced lattice-mismatch of GaNInAs with GaAs). However, the device still has a high density of the NH2 shallow traps and the HI deep traps, which are primary contributors to the photocurrent loss in the GaNInAs device, together with the possible short diffusion length (2).

ACKNOWLEDGMENTS

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