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Comparison of Dominant Electron Trap Levels in n-Type and p-Type GaAsN Using Deep-Level Transient Spectroscopy

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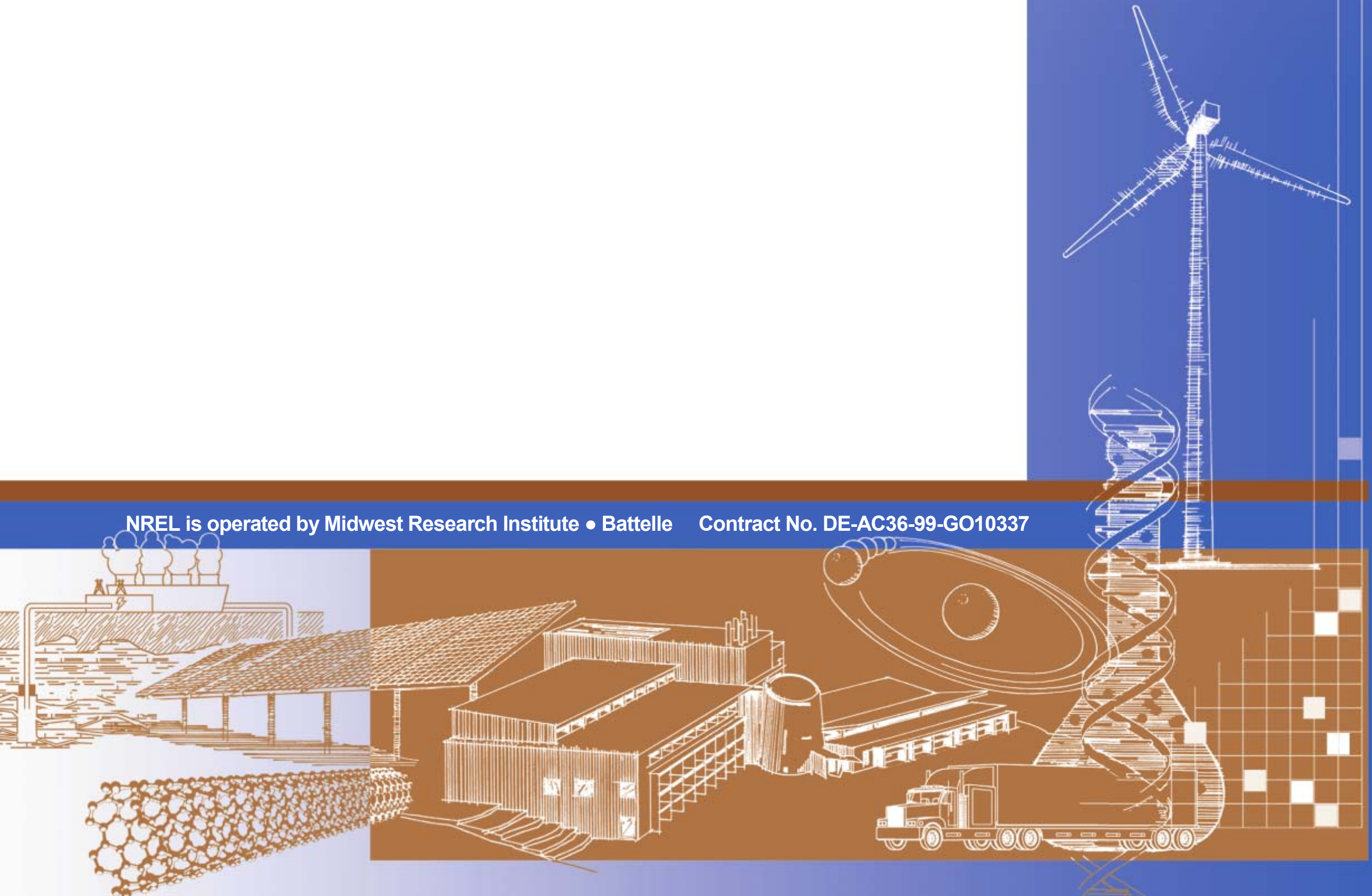
Conference Paper
NREL/CP-520-38916
November 2005

Presented at the 2005 DOE Solar Energy Technologies Program Review Meeting
November 7–10, 2005
Denver, Colorado



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Comparison of Dominant Electron Trap Levels in n-Type and p-Type GaAsN Using Deep-Level Transient Spectroscopy

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ABSTRACT

Higher-efficiency solar cells improve the likelihood that concentrator photovoltaic systems will become cost effective. A four-junction GaAs- and Ge-based solar cell incorporating a 1-eV bandgap material has an ideal AM0 efficiency of ~40% and could also be used in a terrestrial concentrator module. The dilute-N GaAsN alloy's bandgap can be reduced to near 1 eV when the nitrogen content is 2% - 3%. Indium can also be added to the alloy to improve lattice matching to GaAs and Ge. We have used deep-level transient spectroscopy (DLTS) to characterize traps in both p-type and n-type GaAsN. For each type of material, the dominant DLTS signal corresponds to an electron trap having an activation energy of about 0.35 eV for p-type GaAsN and about 0.45 eV for n-type GaAsN. In both types of materials, the trap concentrations, modified by λ-effect factors, increase with both increasing N content and increased doping.

1. Objectives

The Solar Program seeks to develop higher-efficiency III-V solar cells for concentrator photovoltaic (CPV) systems, therefore improving the likelihood that CPV systems will become cost effective.

2. Technical Approach

Deep-level transient spectroscopy (DLTS) is a powerful technique that can identify and characterize defect levels that may be limiting performance in solar cell materials.

3. Results and Accomplishments

The epitaxial layers studied here were grown by atmospheric-pressure metal-organic chemical vapor deposition on p- and n-type conductive GaAs substrates. One series of samples was grown with increasing amounts of N for both p-type and n-type GaAsN. Another series of samples held N content constant while varying Zn-doping for p-type GaAsN and Se-doping for n-type GaAsN. The bandgaps range from 1.4 to about 1.2 eV.

Capacitance-voltage (CV) and DLTS data were collected using an Accent Optical Technologies Fourier transform DLTS system. This system uses a 1 MHz modulating signal. Samples were measured between 0 V and 1 V reverse bias. The leads connected to the sample contacts are reversed to apply opposite polarity bias to n-type samples. Traps were filled when the sample, which was held at a reverse bias of 1 V, was biased to 0 V for a filling pulse width of 1 s, which ensured signal saturation.

The addition of small amounts of nitrogen led to peaks in the DLTS spectra for both p-type and n-type GaAsN. As shown in the upper graph of Fig. 1, a positive peak corresponding to minority-carrier electron trapping occurs near 125 K using a 23 s^{-1} rate window for the p-type GaAsN samples. The lower graph of Fig. 1 shows a negative peak, corresponding to a majority-carrier electron trap, occurring between 150 K and 170 K for the n-type GaAsN samples.

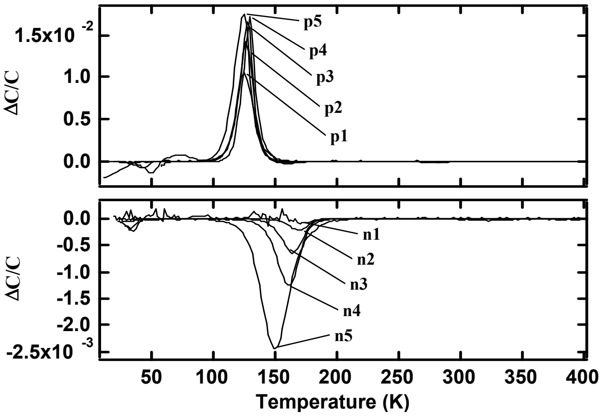

Fig. 1. DLTS data for p-type GaAsN (upper graph) and n-type GaAsN (lower graph).

The N-varying samples are labeled p1 through p5 for the p-type samples and n1 through n5 for the n-type samples. Samples p1 through p5 contain 0.05%, 0.1%, 0.25%, 0.6%, and 1.2% N, respectively. Samples n1 through n5 contain 0.011%, 0.033%, 0.11%, 0.23% and 0.45% N, respectively.

Although not typically expected unless optical injection or forward bias is applied, minority-carrier electron traps are observed for the p-type GaAsN. Electrons from the n-type side can fill empty traps by surmounting the potential energy due to the band bending in the depletion region. Without forward bias, this process takes time, especially at the low temperatures of the DLTS peak trap emission. According to a thermionic emission estimate, the time to fill these traps at low temperature agrees with the experimental value approaching seconds to trap-filled saturation.

The trap density, N_T, is proportional to the DLTS peak magnitude. The λ-effect factor accounts for some traps within the depletion region always being full and some never being filled. We use depletion widths and carrier concentrations from CV data measured at the temperature where the DLTS peak occurs, and the trap activation energy, E_a, attained from the DLTS data, to calculate the adjusted trap densities. For the n-type samples, N_T increases by a factor of ~4. The p-type samples' trap densities are also adjusted to account for the carrier concentration measured at low temperature and the volume where electrons are actually trapped by modeling each sample at DLTS-peak temperatures using simulation software. A factor of ~50 accounts for the narrow trap-filling region about 10 nm from the junction. Here, the electric field is near its maximum value, ~$2x10^5$ V/cm. Field-enhanced emission, such as Poole-Frenkel emission, may effectively lower the measured E_a by ~0.1 eV. The n-type samples are more heavily doped, and modeling shows trap emission also occurs within similar field strength. The adjusted E_a and N_T values are plotted in Fig. 2. E_a values are near 0.4 eV; N_T increases with increasing N content for both types of materials.

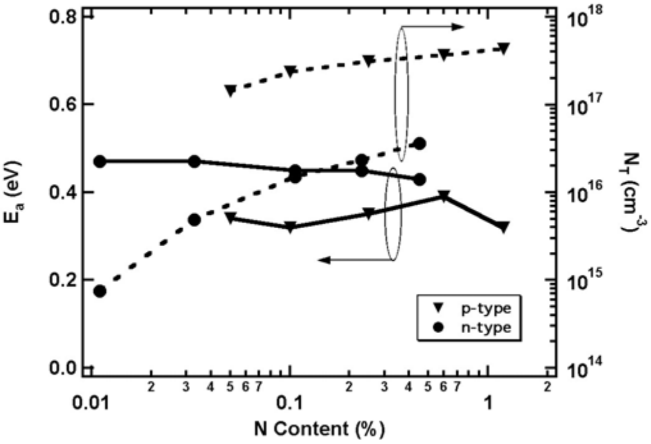

Fig. 2. E_a (solid lines) and N_T (dashed lines) for mid-10^{16} cm^{-3} p-type and mid-10^{17} cm^{-3} n-type GaAsN.

A second series of GaAsN samples for each doping type was also grown and had roughly constant N, ~0.25%, while varying the p-type and n-type doping levels. The adjusted parameters are plotted in Fig. 3.

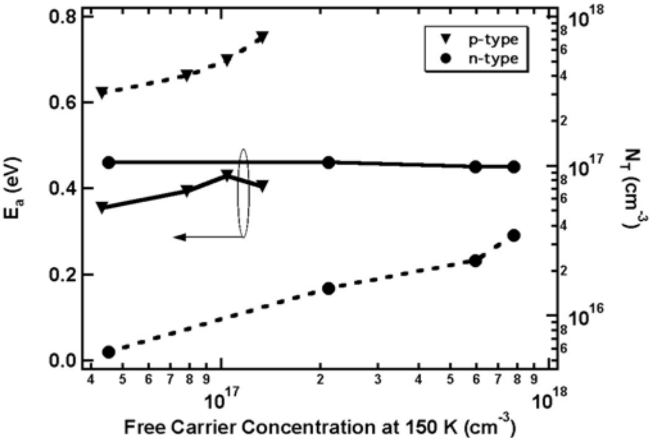

Fig. 3. E_a (solid lines) and N_T (dashed lines) for ~0.25% N, varying-doped p-type and n-type GaAsN.

4. Conclusions

An electron trap dominates the DLTS spectra for both p-type and n-type GaAsN samples. The details of the DLTS analysis include low-temperature CV measurement and software modeling that show that the trap emission occurs in regions of high electric field, and that Poole-Frenkel enhanced emission effectively increases E_a by about 0.1 eV. Calculation of the λ-effect factors showed that these should not be neglected: the majority-carrier trap concentrations were increased by about a factor of four, whereas, the minority-carrier traps (that are usually not reported for p-n junctions in reverse bias) showed very large correction factors approaching 50. In both types of materials, the trap concentrations, modified by λ-effect factors, increase with both increasing N content and increased doping.

ACKNOWLEDGEMENTS

This work was performed under DOE contract DE-AC36-99-GO10337.

MAJOR FY 2005 PUBLICATIONS

S. Kurtz, S. W. Johnston, J. F. Geisz, D. J. Friedman, and A. J. Ptak, "Effect of Nitrogen Concentration on the Performance of $Ga_{1-x}In_xN_yAs_{1-y}$ Solar Cells," *Thirty-First IEEE PVSC*, 595 (2005).

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
November 2005

2. REPORT TYPE
Conference Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Comparison of Dominant Electron Trap Levels in n-Type and p-Type GaAsN Using Deep-Level Transient Spectroscopy

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
S.W. Johnston and S.R. Kurtz

5d. PROJECT NUMBER
NREL/CP-520-38916

5e. TASK NUMBER
PVA6.3101

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-520-38916

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

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15. SUBJECT TERMS
Photovoltaics; solar; GaAsN; transient spectroscopy; PV; NREL

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPONE NUMBER** (*Include area code)*