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ABSTRACT

Dilute nitride alloys provide a powerful tool for engineering the band gap and lattice constant of III-V alloys. However, nitrogen degrades the performance of GaAs solar cells. This project seeks to understand and demonstrate the limits of performance of GaInNAs alloys by (a) correlating deep-level transient spectroscopy (DLTS) data with device performance and (b) using molecular beam epitaxy (MBE) to reduce background impurity concentrations.

1. Objectives

The Solar Program seeks to develop technologies that can provide cost-effective electricity generation. One strategy to reduce cost is to use concentrating optics to focus the sunlight on small, high-efficiency solar cells. Multijunction solar cells have achieved the highest efficiency (39%) of any technology and have the theoretical potential to achieve efficiencies equivalent to or exceeding all other approaches. Dilute nitride materials have demonstrated a range of band gaps, providing a possible pathway to higher-efficiency multijunction cells. The objective of this project is to explore the potential and limitations of the dilute nitride alloys for solar cells, especially $Ga_{1-3x}In_{3x}N_xAs_{1-x}$ with a band gap of 0.9-1.3 eV.

2. Technical Approach

2.1 Correlation of Device Performance with DLTS

DLTS measurements of GaInNAs alloys show numerous features, implying that these alloys contain many defects. Here, we reduce the complexity of the DLTS spectra and correlate the data with device performance to determine which of the DLTS features may be of importance.

2.2 Achievement of High-Photocurrent GaInNAs Cell

The minority-carrier diffusion lengths of p-type 1-eV GaInNAs are too short to measure, and, thus, cannot be optimized directly. Instead, GaInNAs solar cells are dominated by field-aided collection that is correlated with low background carrier concentration. GaInNAs grown using a p-i-n structure with wide depletion widths (usually) shows high photocurrents. We pursue MBE as a pathway to lower the background carrier concentrations and increase the photocurrent.

3. Results and Accomplishments

3.1 Correlation of DLTS Data and Device Performance

Although undoped dilute nitride solar cells usually outperform doped cells due to enhanced field-aided collection, the interpretation of DLTS spectra of p-i-n cells is complicated. We observed that the DLTS spectra were greatly simplified by the use of doped active layers. Indeed, growth conditions were used that resulted in only one dominant feature in the DLTS spectra. GaAs-GaNAs junctions were studied to ensure that defects were observed on only one side of the junction.[1-5]

The dark currents of GaAs/GaNAs n-p diodes (with p-type GaNAs active layers) correlated with the observation of an electron trap (Fig. 1). This correlation does not prove a causal relationship, but the decrease of the open-circuit voltage is semi–quantitatively explained by a reduction in the electron quasi-Fermi level by the electron trap (Fig. 2).[1]

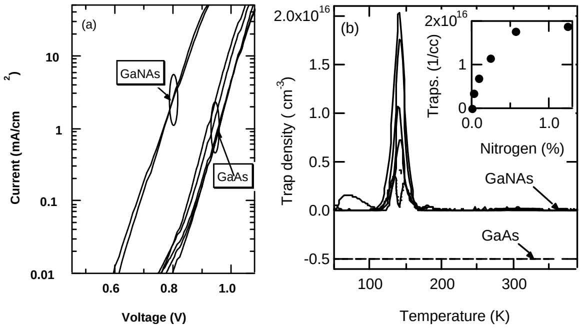

Fig. 1. (a) Dark I-V curves comparing GaN_xAs_{1-x} ($x < 0.1\%$) and GaAs diodes. (b) DLTS data for GaN_xAs_{1-x} samples with $x < 1.2\%$. The GaAs scans (dashed lines) are offset for clarity; the height of the peak for the GaN_xAs_{1-x} samples (indicating trap concentration) increased with x (see inset).[1]

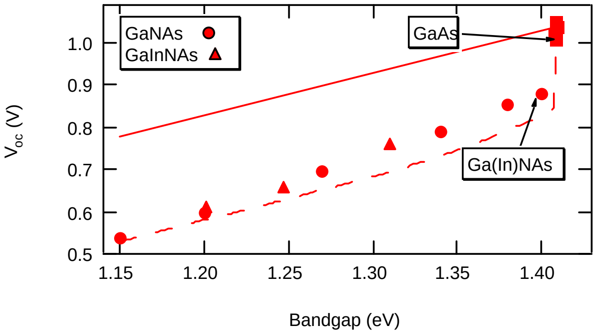

Fig. 2. Open-circuit voltage as a function of band gap for GaAs (squares) and Ga(In)NAs solar cells. The solid line shows the unity slope expected for the open-circuit voltage if it followed the band gap; the dashed line shows the semi-quantitative model.[1]

The study of n-type GaAs/GaNAs diodes showed a similar electron trap.[3,4] The concentration of electron traps was observed to increase with doping for both the p-type and n-type GaNAs. Much work remains to prove the importance of the observed electron trap, identify its origin, and determine the extent to which its effects can be reduced.

3.2 High Photocurrent GaInNAs Solar Cells

The photocurrent of dilute-nitride solar cells correlates with the depletion width. Unfortunately, GaInNAs alloys grown by metal-organic chemical vapor deposition have high background carrier concentrations (and, hence, low depletion widths). In FY2004, we used MBE growth to demonstrate that wide depletion widths resulted in much higher photocurrents for dilute nitrides (Fig. 3),[7,8] as expected from our analysis of the field-region collection.[6]

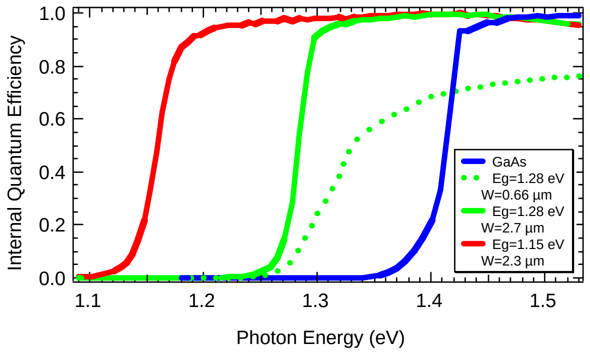

Fig. 3. Internal quantum efficiencies for MBE-grown GaNAs samples with different band gaps and depletion widths.[8]

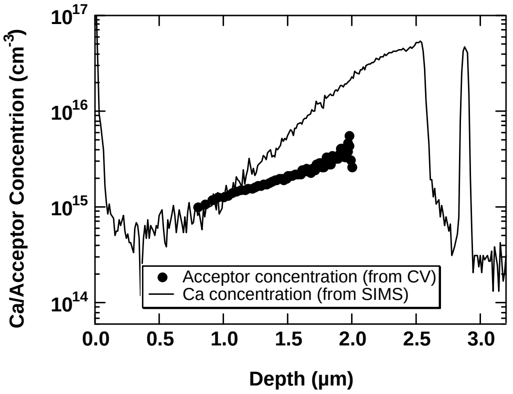

Fig. 4. Comparison of calcium concentration with net acceptor concentration for GaInNAs sample.[9]

It appears that the lower carbon and hydrogen concentrations associated with MBE growth allow the wide depletion widths to be obtained. However, the removal of carbon and hydrogen, though a necessary condition, is not sufficient to achieve the wide depletion widths. Other unintentional dopants and charged defects have the potential to reduce the depletion width. This year we discovered that calcium can be introduced into GaInNAs from surface contamination of the GaAs wafer.[9] An example of the correlation between unintentional calcium incorporation and observed background acceptor concentration is shown in Fig. 4.

Further system modifications are needed to sufficiently control the growth process in order to consistently achieve wide depletion widths. Although we have not yet achieved the widest depletion widths for 1 eV alloys, we have reason to believe that high photocurrents are achievable.

Unfortunately, the cells that show high photocurrents do not show GaAs-like photovoltages. This may imply that the electron traps discussed earlier are not the only defect affecting the photovoltage in GaInNAs. If low carrier concentrations do indeed reduce the density of electron traps (without a corresponding increase in photovoltage), there must be more problems left to be uncovered. Thus, we conclude that high photocurrents are likely to be achieved, but it is unlikely that high photovoltages will ever be realized.

4. Conclusions

We observe electron traps in GaNAs alloys and correlate them with device performance. MBE growth serves to reduce the background doping to provide improved photocurrents as long as all contaminants, including calcium, are controlled.

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REFERENCES AND MAJOR FY 2005 PUBLICATIONS

[1] S. Kurtz, S. Johnston, and H. M. Branz, "Capacitance-spectroscopy identification of a key defect in N-degraded GaInNAs solar cells" Appl Phys Lett **86**, 113506 (2005).

[2] S. W. Johnston, S. R. Kurtz, D. J. Friedman, et al.," Observed trapping of minority-carrier electrons in p-type GaAsN during deep-level transient spectroscopy measurement" Appl Phys Lett **86**, 072109 (2005).

[3] S. Kurtz, S. W. Johnston, J. F. Geisz, et al., "Effect of nitrogen concentration on the performance of Ga$_x$In$_{1-x}$N$_y$As$_{1-y}$ solar cells" in *Proceedings of the 31st IEEE PVSC* (IEEE, Orlando, Florida, 2005), p. 595.

[4] S. Johnston, S. Kurtz, D. J. Friedman, et al., "Electron traps in p-type GaAsN characterized by deep-level transient spectroscopy" in *Proceedings of the 31st IEEE PVSC* (IEEE, Orlando, Florida, 2005), p. 599.

[5] S. Prasad, A. Khan, S. W. Johnston, et al., "Evolution of defect complexes in InGaAsN" in *Proceedings of the 31st IEEE PVSC* (IEEE, Orlando, Florida, 2005), p. 731.

[6] D. J. Friedman, A. J. Ptak, S. R. Kurtz, et al., "Analysis of depletion-region collection in GaInNAs solar cells" in *Proceedings of the 31st IEEE PVSCe* (IEEE, Orlando, Florida, 2005), p. 691.

[7] A. J. Ptak, D. J. Friedman, S. Kurtz, et al., J. Appl. Phys. in press.

[8] A. J. Ptak, D. J. Friedman, S. Kurtz, et al., "Enhanced-depletion-width GaInNAs solar cells grown by molecular-beam epitaxy" in *Proceedings of the 31st IEEE PVSC* (IEEE, Orlando, Florida, 2005), p. 603.

[9] A. J. Ptak, D. J. Friedman, S. Kurtz, et al., "Role of calcium impurities in enhanced-depletion-width GaInNAs solar cells grown by molecular-beam epitaxy" J Vac Sci Technol B, submitted 9/05 (2005).

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