

DEFECT-RELATED TRAPPING AND RECOMBINATION IN METAMORPHIC GaAs_{0.72}P_{0.28} GROWN ON GaAs

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ABSTRACT

Since the bandgap of metamorphic GaAsP can be tuned through a range of energies in a high-radiance region of the solar spectrum, this alloy may be useful in multi-junction solar cells. For this application, achieving high conversion efficiency will require a good understanding of the defects that accompany lattice-mismatch in this system. We use photoluminescence and deep-level transient spectroscopy (DLTS) on GaAs_{0.72}P_{0.28} to identify defect-related energy levels and assess their impact on photovoltaic device performance. Low temperature photoluminescence spectra reveal a broad defect-related band approximately 0.10 eV below the band-to-band emission. At 165 K and above, thermal activation out of the defect-related band appears to enhance the band-to-band radiative mechanism. DLTS measurements on p-type GaAs_{0.72}P_{0.28} suggest the presence of a hole trap with a comparable depth (~0.09 eV) and thermal escape temperature, but the collective results are difficult to interpret. An alternative approach assuming a reciprocal rather than logarithmic dependence on time is compelling, but the proposed hopping-transport model will require further testing.

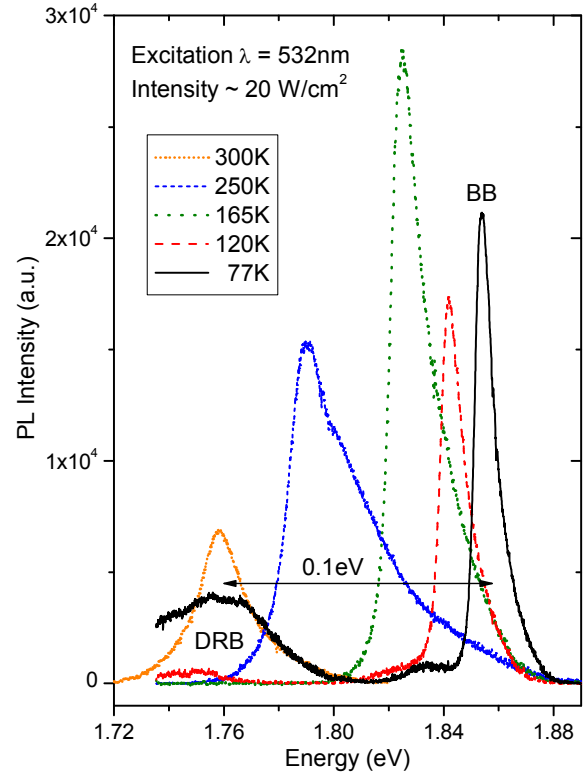


Fig. 2: Photoluminescence spectra for the DH shown in Fig. 1(a). Note the broad defect-related band (DRB) approximately 0.1eV below the 77K and 120K band-to-band (BB) emission.

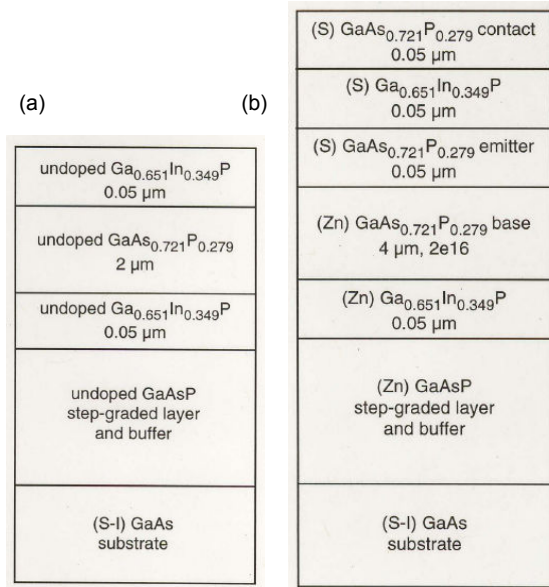


Fig. 1: MOVPE DH (a) and diode (b) structures (not to scale).

INTRODUCTION

When light is absorbed in a solar cell, the difference between the photon energy and the bandgap energy is forfeited in the form of heat. This loss can be minimized by integrating several junctions with bandgaps spanning the solar spectrum in a single device, so that individual photons are absorbed in layers with more closely matched gaps. Multi-junction (tandem) solar cells based on this arrangement have achieved the highest conversion efficiencies to date, exceeding 40% under concentrated illumination. [1] And tandem devices based on metamorphic (lattice-mismatched) schemes have now surpassed lattice-matched designs in peak performance. [1] Mismatched structures are likely to contain a higher

density of defects, which produce new energy levels in the forbidden gap of the semiconductor. These localized defect states can act as carrier traps or recombination centers, impairing the performance of photovoltaic devices. But unlike lattice-matched configurations, the bandgaps in metamorphic systems can be optimized for maximum efficiency.

While metamorphic GaAsP has been employed in a variety of applications over the years, with recent renewed interest in growth on silicon for inexpensive two-junction cells, [2] it is not utilized in any current three-junction designs. As we continue to seek higher efficiencies with ever more complex monolithic designs, incorporation of this aluminum-free ternary alloy will surely be considered. For example, GaAsP is an excellent candidate for reaching one of the target bandgaps in an idealized four-junction solar cell with the top junction fixed at 1.85eV (GaInP lattice-matched to GaAs). [3]

EXPERIMENT AND RESULTS

In this report, we focus on GaAs_{0.72}P_{0.28}, which has a lattice-mismatch of approximately 1% relative to the GaAs substrate. Schematics of our metal-organic vapor phase epitaxy (MOVPE) test structures, showing the GaAsP step-graded buffer and GaInP confinement layers, are presented in Fig. 1. Temperature-dependent

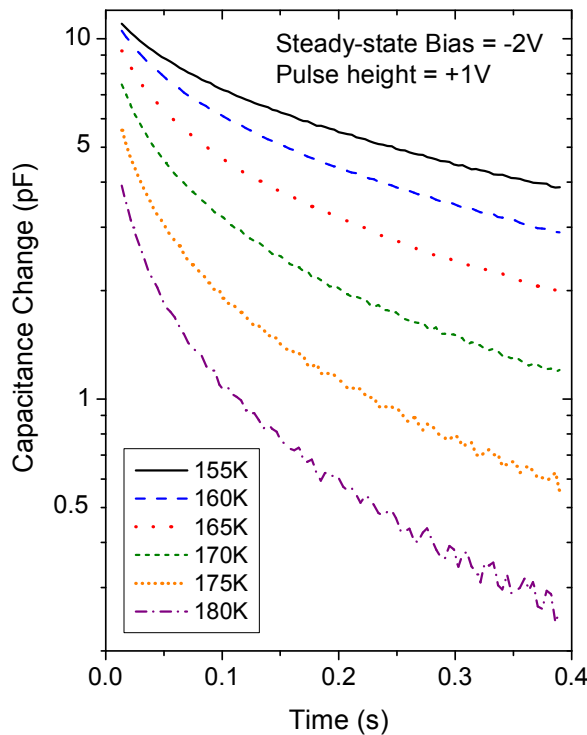


Fig. 3: GaAsP n+/p transient capacitance plotted on a logarithmic scale. Measurement temperatures are given in the legend.

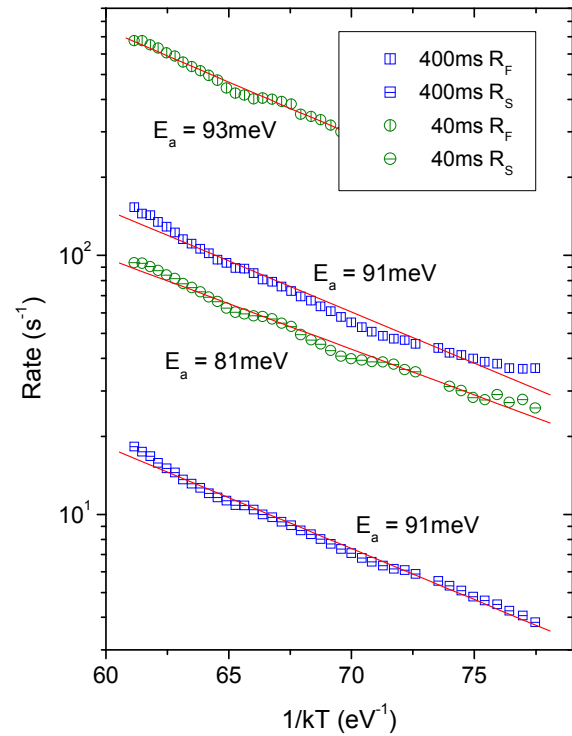


Fig. 4: Arrhenius plot of the fast and slow escape rates R_F and R_S deduced from double exponential fits to the capacitance transients shown in Fig. 3. Observation windows are specified in the legend.

photoluminescence spectra were obtained on the double heterostructure (DH) illustrated in (a), while DLTS measurements were performed on the N⁺/P diode (b). The 77 K photoluminescence spectrum (see Fig. 2) reveals a broad defect-related band (DRB) approximately 0.1 eV below the band-to-band (BB) emission. The DRB emission quenches with increasing temperature, as evident in the 120 K spectrum. Since the BB intensity drops along with the DRB at 120 K, we infer that nonradiative recombination through the DRB is augmented with temperature. At 165 K, where thermal activation out of the DRB becomes more probable, the BB emission recovers. Above 165 K, the BB intensity decreases monotonically, presumably due to the conventional decrease in the radiative recombination rate with temperature. [4] Similar thermal behavior is observed for excitation intensities ranging from ~ 10 to over 10^3 W/cm².

DLTS employs transient capacitance measurements on diodes during and after the application of a bias pulse to monitor the capture and emission of free carriers into and out of defect-related traps. During the pulse, electrons and/or holes are transported into the depletion region of the device, where they may be captured into lower energy states. After the pulse, when charge carriers should leave the depletion region,

the departure of trapped electrons and holes is delayed. By conducting the experiment over a range of temperatures, thermally activated processes can be identified and quantitatively described.

Ordinary DLTS employs a set of fixed rate windows to look for time scales that record significant variation in the capacitance. A fast capacitance meter measures the difference in capacitance ΔC at two delay times separated by the rate window. During a temperature scan, peaks in ΔC vs. T will be observed when the rate window is comparable to the escape time. Assuming Boltzmann-like thermal activation, an Arrhenius plot of window rate vs. $1/kT$ peak indicates the depth of the trap. In contrast, we use a digital storage oscilloscope in communication with a computer to record the full capacitance transient $C(t)$ at each temperature.

We usually use simple computational algorithms to conduct the equivalent of conventional analysis – fitting each transient to an exponential decay function and generating an Arrhenius plot of the results. However, in the p-type GaAsP under investigation here we observe severe non-exponential behavior in C vs. t as shown in Fig. 3. Double exponentials give good fits, but an Arrhenius plot of the results is non-physical (see Fig. 4). The deduced rates depend strongly on the observation time windows and the fast and slow rates, which would ordinarily be assigned to a shallow and a deeper level,

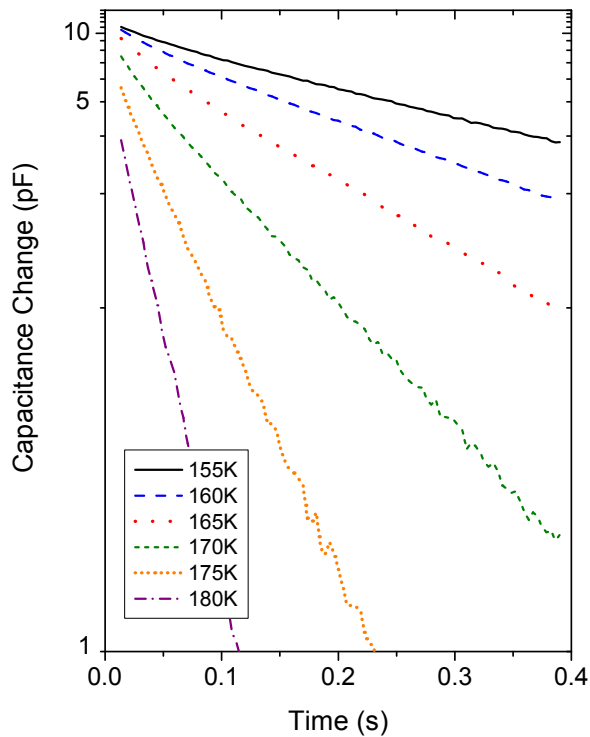


Fig. 5: Capacitance transients from Fig. 3 plotted on a reciprocal scale.

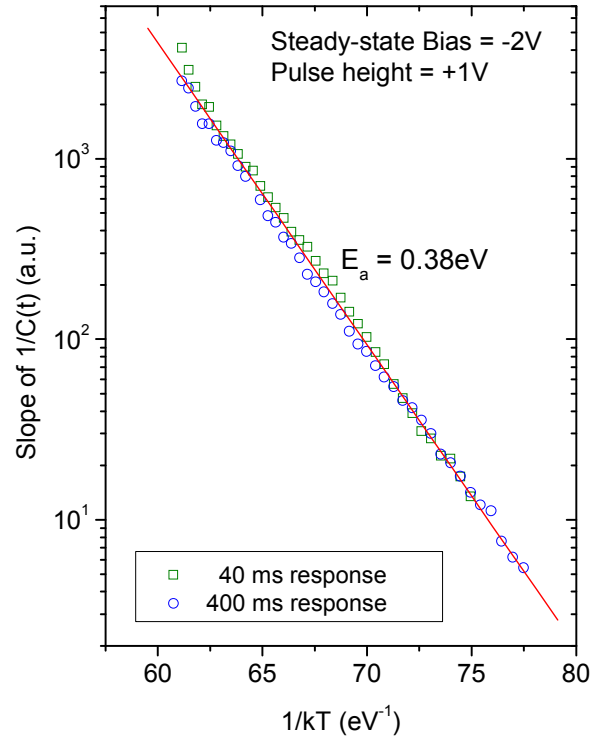


Fig. 6: Arrhenius plot of the slope of the reciprocal capacitance transients in Fig. 5 for the observation windows indicated in the legend.

have nearly identical activation energies of approximately 0.09 eV. Considering the breadth of the 0.1 eV deep DRB seen in photoluminescence, this inconsistency is not so surprising. If the non-exponential behavior is due to a broad defect-related band, we may need to use Laplace transform analysis [5] to accommodate the continuous distribution of levels contributing to the DLTS signal.

Alternatively, perhaps the functional form of the transients themselves should be reconsidered. We have discovered that a reciprocal dependence on time (as might occur for a hopping transport mechanism) [6] appears more suitable (see Figs. 5 and 6). In light of the awkward exponential analysis, the linearity and independence of observation time observed in these plots are compelling. We are currently testing this hypothesis by varying the magnitude of the bias pulse to investigate how the DLTS signal depends on transport distance.

Looking forward to new photovoltaic applications of this alloy, we believe that the defect-related levels studied here could have a measurable impact on device performance. Even though trapped carriers are readily activated out of the traps at 300 K, significant trap occupation will likely persist at room temperature. And the photoluminescence measurements indicate that energy loss via nonradiative recombination though the DRB can be substantial above 77 K.

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