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**ANALYSIS AND CONTROL OF CARRIER  
TRANSPORT IN UNIPOLAR BARRIER MID-  
INFRARED (IR) DETECTORS**

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**Final Report**

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## 1. Summary

Molecular Beam Epitaxy (MBE) growth quality is shown to have significant effects on the carrier transport, e.g., dark current of unipolar barrier infrared detectors constructed of InAs-based materials. MBE growth temperature effects the quality of InAs materials, as assessed by measured defects concentration, surface roughness, and photoluminescence (PL). InAs material quality correlates with dark current of InAs nBn detectors.

## 2. Introduction

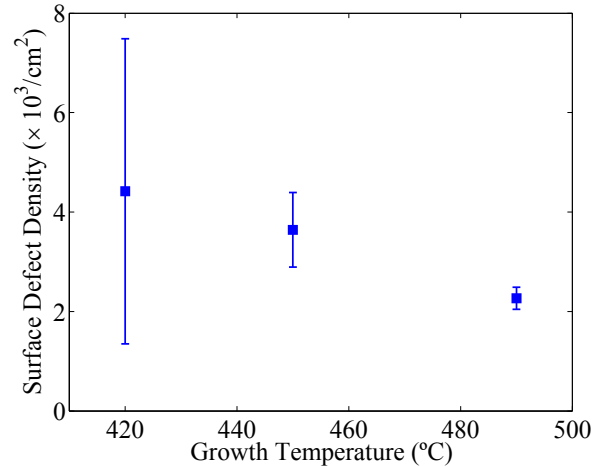
MBE-grown InAs/GaSb/AlSb materials are components of high performance mid-wave nBn mid-wave Infrared (IR) detectors. Material quality and surfaces can have deleterious effects on carrier transport. A study was carried out to investigate these effects

## 3. Methods, Assumptions and Discussions

### 3.1 Effects of InAs MBE Growth Temperature on Defect Concentration

The most important MBE growth parameter is growth temperature. Conventionally, InAs is usually grown in at temperatures near 400°C. This study investigated whether grown near 500°C would produce acceptable quality material. The motivation for increasing the InAs growth temperature is to make it compatible with the growth temperature needed for the growth of the AlAsSb barrier material of an nBn detector.

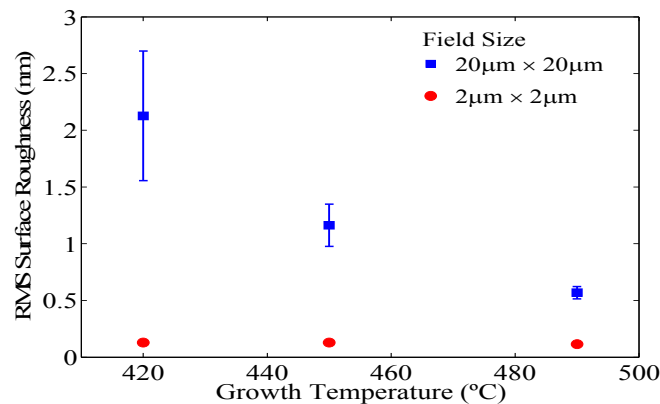
Three growth temperatures were studied, 420°, 450°, and 490°C. Investigations of the single InAs epitaxial layers through differential interference contrast microscopy (DIC), atomic force microscopy (AFM), steady-state PL, and time-resolved photoluminescence (TRPL) spectra all indicate monotonic improvement in material quality with growth temperature spanning the range of 420°C-490°C. An example of the improvement in material quality with growth temperature is the defect density trend shown in figure 1. Both the average defect density and the uniformity of the defect density were found to improve with growth temperature.



**Figure 1. Large-scale surface defect density on  $2\mu\text{m}$  thick InAs epitaxial layers as a function of MBE growth temperature. Error bars represent 95% confidence intervals about the mean values.**

### 3.2 Effects of InAs MBE Growth Temperature on Surface Roughness

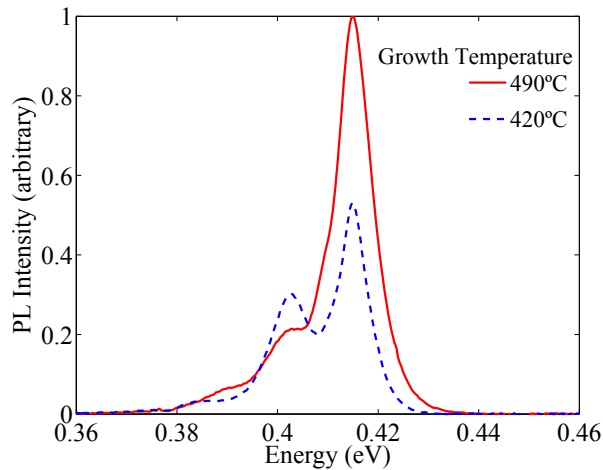
Samples were also investigated by AFM in order to examine surface roughness in the regions that appeared mirror smooth under DIC microscopy.  $2\mu\text{m}\times 2\mu\text{m}$  scans showed favorable step growth characteristics and root-mean-square (RMS) surface roughness values approximately equal to 0.13nm, independent of growth temperature. AFM scans of larger  $20\mu\text{m}\times 20\mu\text{m}$  fields revealed a trend resembling that of the large-scale surface defects: RMS surface roughness across this larger field size decreased with increasing growth temperature, as did the variation between measurements performed at several locations over the sample surface. RMS roughness at this scale decreased from a mean value of 2.1nm on the InAs layer grown at  $420^\circ\text{C}$  to 0.57nm on the layer grown at  $490^\circ\text{C}$ . The results of these RMS roughness measurements over both  $2\mu\text{m}\times 2\mu\text{m}$  and  $20\mu\text{m}\times 20\mu\text{m}$  fields are plotted in figure 2.



**Figure 2. (Color online) RMS surface roughness obtained from AFM scans of InAs single epitaxial layers over  $20\mu\text{m}\times 20\mu\text{m}$  fields (blue squares) and  $2\mu\text{m}\times 2\mu\text{m}$  fields (red circles). Error bars represent 95% confidence intervals about the mean values.**

### 3.3 Effects of InAs MBE Growth Temperature on Optical Quality

Optical characteristics of the InAs layers were investigated by analyzing PL spectra. Both steady-state and time-resolved photoluminescence measurements were performed. Steady-state PL spectra obtained at a temperature of 15K are shown in figure 3 for the InAs layers grown at 420°C and 490°C. Both PL spectra show strong features centered at energies of 415 meV, corresponding to the excitonic bandgap, and 402 meV, likely corresponding to a donor-acceptor-pair (DAP) band. The observation of multiple spectral features in low-temperature PL spectra is generally indicative of high material quality, as defect-related states in lower-quality material will tend to broaden and/or obscure peaks. Several comparisons can be made between the two spectra to suggest that higher material quality has been obtained at higher growth temperature: the intensity of the excitonic bandgap peak, the ratio of intensities between the bandgap and DAP peaks, and the integrated spectral intensity are all greater for the sample grown at 490°C than for the sample grown at 420°C.



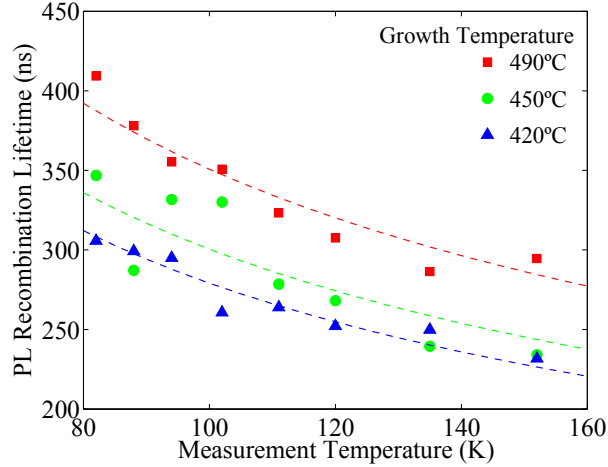
**Figure 3. (Color online) Steady-state photoluminescence spectra of 2 $\mu$ m thick InAs epitaxial layers grown at 420°C (dashed blue line) and 490°C (solid red line), measured at 15K.**

## 4. Results and Discussion

Time-resolved photoluminescence (TRPL) spectra were also collected and analyzed. Under conditions of low-level optical injection, the time dependence of the TRPL signal intensity was described well by a shifted and scaled single exponential decay model of the form (intensity of photoluminescence)  $IPL(t) = A \exp[-(t-t_0)/\tau]$ , where  $A$  and  $t_0$  are fit parameters and  $\tau$  is the PL recombination lifetime. The lifetime parameter  $\tau$  generally represents minority carrier recombination through SRH, radiative, and Auger processes; however under low injection the dependence of radiative and Auger recombination rates on optically generated excess carrier density leads to a reduction of those mechanisms. The minority carrier recombination lifetime determined here is therefore expected to be predominantly a SRH recombination lifetime.

Recombination lifetimes obtained from TRPL spectra recorded at various temperatures are shown in figure 4. At measurement temperatures  $\leq 150$ K, the

recombination lifetimes vary approximately as  $T^{-1/2}$ , as shown by the dashed fit lines. This is the expected temperature dependence for minority carrier recombination lifetimes limited by SRH processes. As SRH recombination proceeds through defect-related trap states, the generally longer recombination lifetimes observed from higher growth temperatures provides further evidence that this material is of higher crystalline quality.



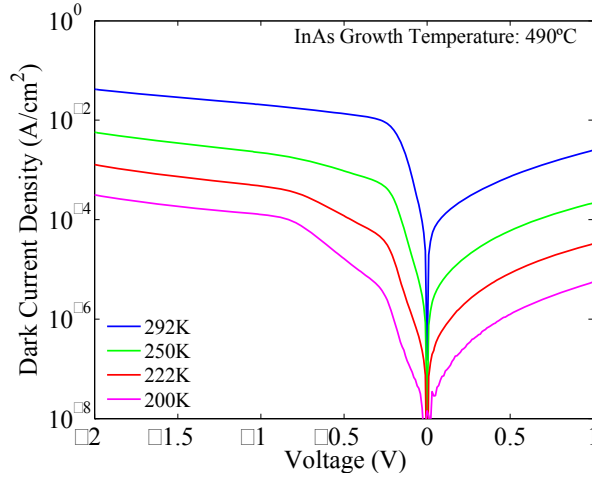
**Figure 4. (Color online) Minority carrier recombination lifetimes determined by fitting a single exponential decay model to low-level injection TRPL spectra obtained from InAs epitaxial layers grown at 420°C (blue triangles), 450°C (green circles), and 490°C (red squares). Dashed lines fit proportional to  $T^{-1/2}$ .**

#### Effects of InAs MBE Growth Temperature on Device Dark Current

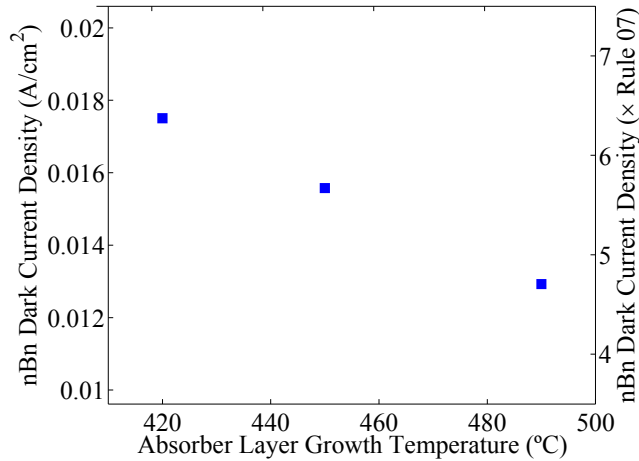
InAs-based nBn detectors have also been grown by MBE and characterized on the basis of dark current density. nBn detectors were produced with InAs layers grown at the same three substrate temperatures investigated for InAs growth in the previous section. The epitaxial structure of the nBn devices consisted of an InAs absorber layer identical to the single InAs epitaxial layers described above, that is, 2.0 $\mu\text{m}$  thick and unintentionally doped n-type, with an electron concentration of approximately  $1 \times 10^{16} \text{ cm}^{-3}$ . The absorber layer was followed by 0.1 $\mu\text{m}$  of lattice-matched AlAs<sub>0.16</sub>Sb<sub>0.84</sub> which was lightly Te-doped to maintain an n-type carrier concentration of  $\sim 1 \times 10^{16} \text{ cm}^{-3}$ . The AlAsSb barrier layer was grown at a substrate temperature of 500°C in all cases. Finally, an additional 0.2 $\mu\text{m}$  thick InAs contact layer was grown on top of the barrier layer, under the same conditions as the absorber.

Dark current density was measured as a function of applied voltage at several different temperatures for each of the three nBn detectors. Current-Voltage-Temperature (JVT) characteristics for the three devices were qualitatively similar, resembling the set of measurements obtained from the nBn with InAs layers grown at 490°C, shown in figure 5. All three devices developed diffusion-limited behavior under moderate reverse voltage, and the reverse saturation dark current densities exhibited full-bandgap thermal activation energy. Room-temperature (292K) reverse saturation dark current densities are plotted for the three nBn devices in figure 6 on an absolute scale and also as multiples of Rule 07. nBn dark current density displayed the same trend of improvement with InAs layer

growth temperature as did the physical and optical comparisons of the single InAs epitaxial layers.



**Figure 5. Dark current density measured as a function of applied voltage and sample temperature for an nBn device with InAs layers grown at 490°C.**



**Figure 6. nBn reverse saturation dark current density measured at room temperature (292K).**

## 5. Conclusions

InAs epitaxial layers and InAs-based nBn detectors have been grown by MBE in order to assess variations in InAs bulk material and interface quality, and in nBn dark current performance, with InAs growth temperature. Investigations of the single InAs epitaxial layers through differential interference contrast microscopy, atomic force microscopy, steady-state photoluminescence, and time-resolved photoluminescence spectra all indicate monotonic improvement in material quality with growth temperature spanning the range of 420°C-490°C. Likewise, nBn dark current density decreased monotonically with increasing InAs growth temperature over the same temperature range, and nBn detectors with dark current density within a factor of 5 of Rule 07 are reported.

## List of Acronyms

AFM	Atomic Force Microscopy
DAP	Donor-acceptor-pair
DIC	Differential Interference Contrast Microscopy
IPL	Intensity of Photoluminescence
IR	Infrared
JVT	Current-Voltage-Temperature
MBE	Molecular Beam Epitaxy
PL	Photoluminescence
RMS	Root-mean-square
SRH	Shockley-Read-Hall
TRPL	Time-resolved Photoluminescence

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