# High N-concentration GaInNAsSb materials for III–V solar cells with bandgaps below 0.8 eV

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***Abstract* — We report on the development of GaInNAsSb materials lattice-matched to GaAs with a bandgap of 0.8 eV or below. A set of GaInNAsSb p-i-n structures with nominal N compositions between 5% and 8% were grown by plasma-assisted molecular beam epitaxy (PAMBE). The x-ray characterization for these samples revealed good crystalline quality even at N concentration of 8%. The sample with 6% N exhibits good external and internal quantum efficiencies. With further improvements, these materials could realistically be employed in multijunction solar cells with 5 or 6 junctions, attaining efficiencies in the range of 50%.**

***Keywords—dilute nitrides; molecular beam epitaxy; multijunction solar cells; lattice-matching;***

MBE-grown lattice-matched dilute nitrides with ~1 eV bandgaps have been successfully employed as bottom junction in high-efficiency multijunction solar cells.[1] Further developments of multijunction solar cells with up to 6 junctions and conversion efficiencies of over 50% calls for integration of lattice-matched materials with bandgaps ($E_g$) below 0.8 eV. To this end bulk dilute nitrides with below 0.8 eV bandgaps have been relatively unexplored, and the quality and performance of these materials has remained modest.[2] In this study we report on the epitaxy and material properties of GaInNAsSb/GaAs lattice-matched heterostructures with up to 8% N compositions targeting bandgap energies below 0.8 eV.

Three GaInNAsSb p-i-n structures with 1 µm i-layer thicknesses were grown on 3" n-GaAs substrates thickness using a Veeco GEN20 MBE system. The system is equipped with SUMO effusion cells for the group III elements, cracker cells for As and Sb, and a Veeco Uni-bulb RF plasma source for N incorporation. The nominal In composition was fixed to 15% for all the samples and the nominal N compositions were 5%, 6% and 8%.

The photoluminescence (PL) spectra (Fig. 1) shows a tenfold decrease for the PL intensity and increase in the full width at half-maximum (FWHM) from ~57 meV to ~76 meV when N composition is increased from 5% to 6%. For the sample with 8% N content, we could not measure a PL, partially due to the limited sensitivity and range of the InGaAs detector (~1700 nm) of the PL-mapper used. Bandgap energies estimated from the PL peaks are 0.86 eV and 0.80 eV for 5% and 6% N, respectively. Based on band anti crossing model and material composition, $E_g$ for the sample with 8% N is estimated to be closer to 0.75 eV. Although the PL properties degrade with higher N content, the surface morphology does not show significant degradation even for the sample with N concentration of 8%. X-ray diffraction (XRD) rocking curves reveal that samples with 5% and 6% N contents are compressively strained but that the 6% sample is close to full lattice matching. Conversely, sample with 8% nominal N is under tensile strain, yet, the diffraction peak for is clearly visible and remains relatively sharp, signifying good crystalline quality. The reciprocal space map (RSM) measured from asymmetric (224) reflection for the sample with 8% N (Fig. 2) indicates good crystalline quality as the GaInNAsSb peak is not significantly broadened but it also shows excellent coherence between the epilayers and substrate. The sample with 6% N also exhibits good quantum efficiency performance (Fig. 3); the peak internal quantum efficiency (IQE) was 0.90, respectively. With further optimization of the growth parameters, a significant increase in the material quality could be realistically expected enabling practical use as narrow bandgap bottom junctions in lattice-matched multijunction solar cells with up to 6 junctions and over 50% efficiency.

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[2] S.L. Tan et al., Proc. SPIE 8256, Physics, Simulation, and Photonic Engineering of Photovoltaic Devices, 82561E (2012).

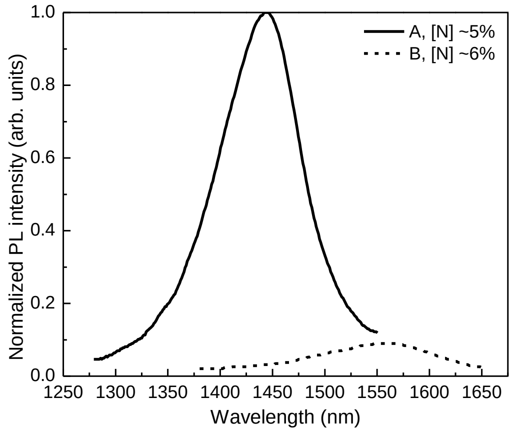


**Fig. 1** Normalized room temperature PL spectra measured from the GaInNAsSb layers with 5% and 6% nitrogen concentrations.

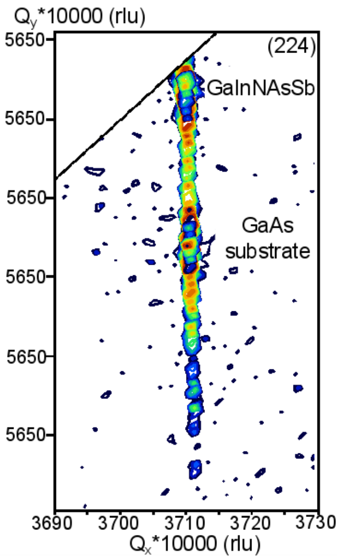


**Fig. 2** RSM measured from asymmetric (224) reflection for GaInNAsSb with 8% N. The peaks are vertically aligned revealing coherence between the substrate and epilayer lattices. The GaInNAsSb peak is not significantly broadened compared to the substrate peak indicating good crystalline quality.

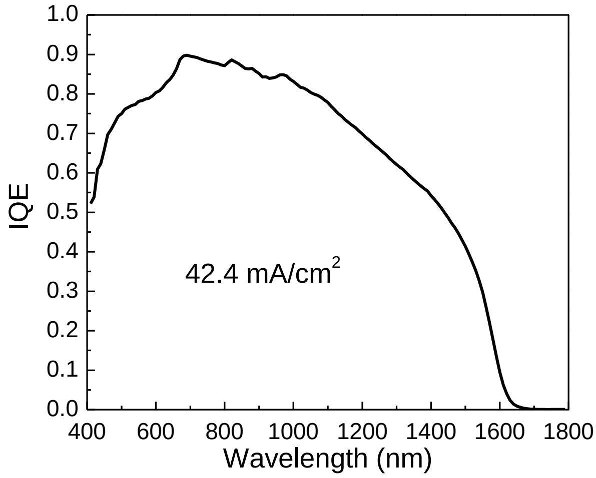


**Fig. 3** IQE for structure with 6% N concentration. The current density potential was estimated using ASTM G173-03 AM1.5D (1000W/$m^2$ normalization) as the reference spectrum.