Growth of High-Efficiency, Six-Junction, Inverted Metamorphic Solar Cells

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Six-junction (6J) solar cells have the potential to achieve over 50% solar conversion efficiency when operated at high concentration. Inverted metamorphic (IMM) solar cells designs enables the monolithic growth of multijunction solar cells with a broad range of bandgaps. We have demonstrated 6J IMM solar cells with record 39% efficiency at one-sun AM1.5G irradiance and 47.1% efficiency at 143 suns concentration. The metal organic vapor phase epitaxy (MOVPE) growth of 6J IMM solar cells is accomplished by growing the first three junctions (2.1 eV AlGaInP, 1.7 eV AlGaAs, and 1.4 eV GaAs) lattice-matched to GaAs, then step-grading the lattice constant progressively to 1.2 eV, 0.95 eV, and 0.69 eV compositions of $Ga_xIn_{1-x}As$. The fabrication of these complex solar cell devices presents severe MOVPE growth challenges to simultaneously achieve the high minority carrier quality needed for high efficiency and low resistive properties needed for high concentration operation.

We have achieved low threading dislocation densities ~1.0 x 10^6 cm^{-2} in all the mismatched $Ga_xIn_{1-x}As$ alloys grown on GaAs by optimizing the compositionally graded buffer growth conditions. Transmission electron microscopy (TEM), cathodoluminescence (CL) and cathodoluminescence spectral imaging (CLSI) were used to characterize defect densities. Growth temperature, substrate misorientation, alloy composition, and surfactants are key parameters that affect CuPt atomic ordering and the phase stability of optically transparent [1] GaInP or AlGaInP grading alloys to promote facile dislocation glide [2]. In our best devices, we have use 2°B miscut substrates to promote atomic ordering in $Ga_xIn_{1-x}P$ graded buffers. The ordering stabilizes metastable GaInP alloys within the metamorphic buffers and reduces the energies required for facile dislocation glide resulting in lower dislocation densities [3] and thus higher performance of the metamorphic junctions grown on 2°B. But we also require minimal ordering to achieve the high bandgap of the AlGaInP top junction, so an Sb surfactant was use to disorder the top junction.

The diffusion of Zn during subsequent growth from phosphide back-surface fields (BSF) into the tunnel junctions and junction bases presents a significant challenge for high concentration operation [4]. This redistribution of Zn dopants creates heterojunction barriers to conduction and degrades the peak tunneling currrent of tunnel junctions. A Ga-interstitial assisted mechanism of Zn results in long Zn diffusion distances [5] and higher temperature growth, which helps dislocation glide, can also promoting Zn diffusion. We have investigated various alternatives to Zn-doped phosphide BSF, such as C-doped and Zn-doped AlGa(In)As BSFs as well as spacer layers to reduce the effects of Zn diffusion. These studies were instrumental to enable the excellent high concentration performance of 6J IMM solar cells.

References:

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