Challenges and Solutions in Ultra-Wide Bandgap Semiconductors

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AlGaN spans a wide bandgap range from 3.4-6.1 eV and is a crucial compound for the realization of deep-UV optoelectronics and future high-power, high-voltage electronics. Although most challenges in the growth and composition control of high crystalline quality AlGaN alloys grown on native substrates have been overcome, achieving control of n and p electrical conductivity in high and low doping regimes of technological interest has proven to be challenging, particularly for high Al-content alloys and AlN. The incorporation of unwanted extrinsic point defects and formation of energetically favorable native compensating defects significantly reduce the achievable free carrier concentrations and limit carrier mobility.

Generally, the formation energy of a point defect is a function of process conditions, as described by the chemical potentials of the species involved. In addition, the formation energy of charged point defects is a function of the Fermi energy, or electrochemical potential. Thus, controlling the chemical and electrochemical potentials during doping is crucial to achieve doping control. While the chemical potential can be controlled by adjusting process conditions, the control of the electrochemical potential requires a non-equilibrium process in which the minority carriers are generated in a steady state. We developed two theoretical frameworks, chemical potential and electrochemical potential control, to achieve predictive quantitative control of point defects in any semiconductor. The first framework is general and may be used to determine optimal growth conditions to achieve minimum compensation within any given constraint such as growth rate or crystal quality. The second framework addresses the energetics of charged point defects by manipulating their respective defect quasi Fermi levels (dQFL) via generation of excess minority carriers.

Both theoretical frameworks were corroborated experimentally in AlGaN and AlN and show excellent quantitative agreement with the theoretical predictions. They allow for orders of magnitude higher free carrier concentrations and conductivities than normal equilibrium processes. The presentation will focus on the details of the theoretical framework, experimental validation, and related phenomena. The proposed point defect control scheme is of great interest for all wide and ultra-wide bandgap materials for which compensation is the main fundamental limiting factor in obtaining semiconducting properties.