Electric fields in nitrides: new perspective for physics & device applications

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Because of the broken inversion symmetry in the wurtzite crystal lattice, and the strongly polar metal-N chemical bonds, GaN, InN, and AlN exhibit strong electric spontaneous polarization fields. Under strain, a piezoelectric component adds to, or subtracts from the spontaneous polarization fields. A simple model of polarization is the presence of an electric dipole moment in every unit cell: the strength of polarization in the nitrides is roughly 10 times smaller than ferroelectric crystals, amounting to roughly 10 unit cells contributing 1 electron charge for polarization. Unlike ferroelectrics, the polarization in nitride crystals is frozen, and cannot be flipped by an external field. The polarization strengths go as AlN>GaN>InN. Gradual, or abrupt compositional gradients cause a spatially varying polarization, for example in an AlN/GaN heterojunction, or in a graded InGaN layer. This creates fixed charges by Maxwell's equation $\rho(r) = -\nabla \cdot P(r)$, which in turn creates internal electric fields along the c-axis of the crystal. The first uses of these fields were to create high density 2-dimensional electron gases at AlGaN/GaN heterojunctions, which now form the basis for GaN HEMTs that power the nitride microwave and power electronics industries. Polarization-induced n- and p-type doping is now successfully achieved in the nitrides, adding an exciting control of conductivity. In photonic LEDs and Lasers, the polarization induced electric fields cause the Franz-Keldysh effect in quantum wells, reducing the electron/hole wavefunction overlap and the oscillator strength, which is typically deleterious for efficient light emission. However, this is a problem only at low carrier injection densities; the internal fields are screened at typical operation current levels. As a result, though it is possible to eliminate the internal fields by growing nitride crystals along semi- or non-polar crystal orientations, most nitride LEDs and Lasers today are made on the c-plane polar orientation. So, everything seems to be solved! Is there anything new about internal fields in nitrides?

A lot of new phenomena were discovered in the last 2-3 years due to internal fields in nitrides. Resonant tunneling diodes in AlN/GaN/AlN double barriers revealed rich new physics such as visible light emission, strong asymmetries in operation, and provided a direct means of measuring the internal polarization fields. By understanding the intersubband transitions and resonant tunneling, the race for nitride quantum cascade lasers is heating up because they offer much higher photon energies by virtue of their larger optical phonon energies. Interband Zener tunneling has been used to demonstrate nitride tunneling field-effect transistors (TFETs) for the first time. 2D hole gases with the highest densities in all known semiconductors, the dual of 2D electron gases, have been discovered this year in GaN/AlN heterojunctions, after nearly 3 decades of search. What's more, 2D Electron-Hole Bilayers have been observed in AlN/GaN/AlN quantum wells, where high density 2DEG and 2DHG are present simultaneously in close proximity in the same quantum wells. These structures promise an exciting new playground for low-dimensional junctions, Coulomb drag, and correlated transport physics. Because of the close proximity of the 2D electron and hole gases and the hybridization of their wavefunctions, topological insulators are being searched in nitride quantum wells. What is provided by spin-orbit interaction in heavy-element semiconductors is provided for by the Rashba effect due to the massive internal electric fields in the nitrides. I hope to share some of these exciting new findings on internal electric fields in nitrides with you and provide some perspectives on how we may use them for device applications.