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Physics of GaN Based Electronic Devices

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GaN-InN-AlN based semiconductor materials and heterostructures differ form more conventional compound semiconductors, such as GaAs or InN, in many important ways, including crystal symmetry, much wider energy gaps, larger band discontinuities in heterostructures, much heavier electrons and holes, much stronger piezoelectric effects, and pyroelectric effects. All these differences impact the device physics of electronic and optoelectronic devices bases on this materials system, and the application of unique properties of GaN-based semiconductors and heterostructures to electronic and optoelectronic devices necessitates novel approaches to the device design based on the new materials and device physics specific for III-N compounds. In this talk, we discuss the physics of the electron transport in GaN in low and high electric fields with the emphasis on the properties of two-dimensional electrons and the physics of pyroelectric and piezoelectric effects in GaN-based heterostructures. We will link these effects to new approaches in designing GaN-based devices, including piezoelectric and pyroelectric gauges, field effect transistors, heterostructure bipolar transistors, and induced base transistors. We will also consider how these new approaches affect the design of optoelectronic device including UV photodetectors and visible and UV light emitters.

A large conduction band discontinuity and a large density of states in two dimensional systems in GaN-based heterostructures lead to an extremely high concentration of 2D electrons, up to an order of magnitude higher that in more conventional AlGaAs/GaAs heterostructures. This high electron density is very effective in screening the ionized impurity and other charges, such as dislocation charges and is sufficient for filling a fairly large concentration of surface states. This allowed us to develop new device concepts, such as a Doped Channel AlGaN/GaN High Electron Mobility Transistor and an AlGaInN/GaN Metal Oxide Heterostructure Field Effect Transistor with many characteristics (such as extremely low leakage current) superior to those for the conventional GaN-based Heterostructure Field Effect Transistors. Our analysis and our data for electronic devices fabricated at different substrates show that the substrate thermal impedance plays a more importance role in determining the device characteristics than the substrate dislocation density. On the other hand, the electron transfer from 2D states into 3D states in GaN at high electron densities plays a very important role in contrast to GaAs-base heterostructures, where the real space transfer takes place into a wide band gap semiconductor barrier layer.

In GaN-based heterostructures, up to $2x10^{13}$ cm^{-2} electrons can be induced by the polarization charges alone. Hence, the control of strain and of the strain profile plays a key role in the optimization of the device design. This is evidenced both by the data on the performance of the electronic devices and by the photoluminescence data for InGaN quantum wells. We will discuss our novel approach of Strain Energy Band Engineering (SEBE), which allowed us to independently control strain and energy band offset in these heterostructures. This control is achieved by using quaternary AlGaInN semiconductors, where each atom of In roughly compensates strain created by six Al atoms. This approach is especially important because it allow us to tailor polarization field profiles, which play a dominant role in determining the characteristics of nitride-based devices. SEBE is very promising for optoelectronic devices, including light emitters and photodetectors. Polarization effects also determine the design of vertical devices, including Heterostructure Bipolar Transistors and Induced Base Transistors. Finally we review models for GaN-based electronic and optoelectronic devices, which take into account the new device physics.

Other important characteristics of GaN-based materials include nonlinear optical properties that have been used for waveguiding and a high acoustic wave velocity. These properties can be used for developing blue and UV optoelectronic and acousto-optical devices.

Finally, we will discuss interesting plasma effects in GaN heterostructures. An extremely high density of 2D electrons in these heterostructures leads a very high velocity of the surface plasma waves. Hence, these heterostructure might find applications in terahertz plasma wave electronics devices, such as detectors and emitters of terahertz radiation.