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Physics of AlGaN/GaN Electronic and Photonic Devices

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1. Introduction

Unique properties of GaN/AlN/InN and related quaternary and ternary semiconductors make them superior for many device and system applications, including applications for solid state lighting [1], high power transistors, and blue and UV optoelectronics. The physics of nitride semiconductor devices is quite different from that of Si-based or GaAs-based devices because nitride semiconductors have hexagonal symmetry, large bandgaps (with an exception of InN), and large polar optical phonon energies. The key difference is a large spontaneous and piezoelectric polarization in hexagonal (wurtzite) semiconductors that can induce two dimensional electron or hole gases with very high sheet densities at the heterointerfaces in nitride semiconductors. The surface electron density in GaN-based Heterostructure Field Effect Transistors (HFETs) might exceed 2×10^{13} cm^{-2}, which is more than an order of magnitude higher than the electron concentration in GaAs-based HFETs. This increased carrier concentration translates into much larger current carrying capabilities of AlGaN/GaN transistors that demonstrate record powers at microwave frequencies (up to 30 W/mm compared with 1 to 2 W/mm powers for their GaAs-based counterparts.) Also, a large electron semiconductor HFETs alleviates the effect of surface states, allowing for the development of insulated gate HFETs that have many additional advantages concentration. Surface Acoustic Wave and pyroelectric devices are other examples, where superior properties of nitrides enable device applications.

Polarization induced fields also affect the performance of photonic nitride devices, such as deep UV Light Emitting Diodes (LEDs) and solar-blind photodetectors.

In this paper, we review the new physics of GaN/AlN/InN devices that still has to be fully understood.

2. Migration Enhanced Metal Organic Chemical Vapor Deposition – MEMOCVD

AlN/GaN/InN based devices are typically grown on hetero substrates, even though several electronic and optoelectronic devices on native GaN [2] or AlN [3, 4] substrates have been demonstrated. Growth on foreign substrates making the strain control (strain energy band engineering [5]) and innovative epitaxial growth techniques to be of the key importance, since growth defects propagate from the substrate and buffer layer into the device active channel. New epitaxial techniques (such as Lateral Epitaxial Overgrowth [6] and Migration Enhanced Metal Organic Chemical Vapor Deposition – MEMOCVD™) are needed to alleviate this problem. [7] As shown in [6], the lifetime of minority carriers in an AlGaN sample grown by MEMOCVD™ is a factor of 6 large than for similar samples grown by conventional MOCVD. Such lifetime increase is the evidence of improved material quality.

3. Physics of Electron Transport in InN/GaN/AlN alloys

Transport properties of AlN/GaN/InN-based semiconductors have unique features compared to more conventional semiconductors, such as Si or GaAs. In these materials, the polar optical phonon energy is large (much larger than the thermal energy at room temperature). As a consequence, the dominant optical polar scattering occurs in two steps: photon absorption and re-emission (resulting in an effectively elastic scattering process). [8] In high electric fields, an electron runaway plays a key role determining the peak field and peak velocity in these compounds. The runaway effects are further enhanced in 2D electron layers. [9]

4. Physics of AlN/GaN/InN Heterostructure Field Effect Transistors

As mentioned above and was first predicted in [10] spontaneous and piezoelectric polarization at AlGaN/GaN or AlGaInN/GaN leads to the formation of high density two-dimensional (2D) electron gas or 2D hole gas (depending on the surface polarities).

GaN has a relatively small mobility compared to GaAs (between 800 and 2000 cm^2/V-s at 300 K for 2D electrons at the AlGaN/GaN heterointerface) but a high peak and saturation velocity. This combination makes the velocity distribution in the field effect transistor channel to be extremely important making a variable threshold voltage approach useful and, possibly, even necessary for improving a high frequency response of the short channel HFETs. Such designs have been investigated for GaAs-based [11] and SiC based FETs [12] but still have to be explored for GaN-based FETs.

A field dependent penetration of the electron wave function from the device channel into the wide band gap barrier layer strongly affects the real space transfer and device breakdown voltage. [13] Quantum well designs (e.g. incorporating an InGaN quantum well between the wide band gap AlGaN barrier layer and GaN buffer) might be required to control this wave function penetration and the real space transfer. High electric field at the gate edges leads to the additional strain and hot electron effects causing the current collapse and gate lag. Optimized field plate and recessed gate designs (including the use of textured AlGaN for easily controlled etching) help solving this problem and improving the device reliability. Inverted HFET designs might result in reduced access resistance, a large current carrying capability, lower gate leakage and better thermal control. Large energy gap discontinuities at heterointerfaces allow for obtaining very large densities of 2D electrons (exceeding those at AlGaAs/GaAs heterointerfaces by a factor of 10 to 20) with a commensurate increase in the output power. Such large densities make the insulated gate design (with the dielectric layer separated from the active channel by the wide band gap barrier layer) practical, since one can tolerate a much higher density of the surface states. Large electron densities in the HFET channels also minimize the 1/f noise making it to be smaller than in doped GaN films.

5. AlGaN/GaN-BASED UV LEDs

AlGaN/GaN-based UV LEDs will find applications in bio-agents detection, water and air purification, food sterilization, UV curing, fire detection, non-line-of-sight short range communications, and in biomedical systems. Basic designs of GaN based UV LEDs use either sapphire or SiC substrate and rely on the emission through the sapphire substrate or on the edge emission, respectively. SiC substrates are inferior in terms of the light extraction but have a much larger thermal conductivity than sapphire. AlN bulk substrates combine both advantages and they are "native" substrate for AlGaN alloys with a high molar fraction of Al. Recently, we reported on high-efficiency 280 nm LEDs [14] and on 265 nm LEDs [15] with continuous-wave (CW) powers in excess of 1 mW. This progress has been achieved by using AlN/AlGaN strain-defects management superlattices [16] for defect filtration and by improved materials growth using Migration Enhanced Metalorganic Chemical Vapor Deposition (MEMOCVD).[5] Further improvements will have to rely on better understanding of device physics, including electron and hole transport, injection, radiative and non-radiative recombination, polarization effects, and the low frequency noise.

6. Conclusions

As discussed above, new physics of GaN-based devices affects their growth, carrier concentration profiles, transport and photonic properties. Deep understanding of new physics of GaN/AlN/InN devices is a prerequisite for the optimization of their design and improving their reliability and performance.

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