Polarization technology for HEMTs and LEDs

University of Notre Dame researchers have been developing techniques to use the spontaneous and strain-dependent polarization electric fields in nitride semiconductor to positive effect in transistors and light-emitting diodes. Mike Cooke reports on two pieces of work in this direction.

Polarization in nitride semiconductor devices is often seen as a problem, particularly where light emission is required (lasers, light-emitting diodes). By contrast, University of Notre Dame researchers see opportunities to create highly insulating layers [Yu Cao et al, Appl. Phys. Lett., vol96, p042102, 2010] and p-type doping [John Simon et al, Science, vol327, p60, 2010] for use in high-electron-mobility transistors (HEMTs) and deep-ultraviolet (DUV) devices.

Nitride semiconductor HEMTs are being widely developed for high-speed and high-power applications. The Notre Dame work on insulating layers has focused on blocking leakage through the buffer layer of the HEMT that arises through shallow dopant impurities such as silicon (Si) or oxygen (O) at the interface with the substrate, which can be made of silicon carbide (SiC) or semi-insulating gallium nitride (Si GaN). The presence of this conducting region under the buffer impacts both on/off ratios for digital applications and device speed where high performance is needed.

Notre Dame produced two HEMTs — one designed to show the problem of buffer leakage and the other a solution that uses giant polarization fields in nitride semiconductors to create a highly insulating layer (Figure 1). The devices were grown using radio-frequency (RF) plasma-source molecular beam epitaxy (MBE) on commercial Ga-face GaN templates (2μm iron-doped Si GaN layer on sapphire substrate).

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**Figure 1.** Leakage current density in the buffer vs applied voltage for control sample (a, inset shows SIMS atomic concentrations against depth with strong impurity peaks of silicon, oxygen and carbon at re-growth interface). Using ultra-thin AlN nucleation layer (b) gives much lower buffer leakage. Energy-band diagrams of the two structures from AlN top barrier (left end of diagrams) down to Si GaN template (right end). Adding AlN nucleation layer at right end (d) removes unwanted conduction path in (c).
For the leaky device (Figure 1, left), two monolayers of gallium were deposited on the Ga-face to create a metal-rich nucleation layer under the ~234nm of unintentionally doped GaN, followed by a 3nm aluminum nitride (AlN) cap. A two-dimensional electron gas (2DEG) forms through polarization effects at the GaN/AlN interface.

For the measurement of buffer leakage, the region of the 2DEG between the electrodes is cut with a reactive ion etch (RIE) so that current must flow through the unintentional paths such as the buffer/template interface. The leaky device has a current flow of 40mA/mm at ±5V. This flow is a factor of 25 smaller than that typical in an on-state GaN HEMT and hence would significantly limit on/off ratios. Secondary-ion mass spectrometry (SIMS) reveals large peaks for carbon, silicon and oxygen — the latter two elements are known to be n-type dopants in GaN.

An insulating device is created by growing an ultra-thin AlN nucleation layer (NL) before the GaN buffer (Figure 1, right). This cuts the leakage to less than 20nA/mm at 20V. At 4V, the leakage is reduced by seven orders of magnitude (a factor of 10^5) compared with the leaky set-up.

It was found in further experiments that nitrogen-rich growth conditions of the AlN were critical to insulating properties. A metal-rich AlN layer leads to leakage, possibly due to diffusion of oxygen and silicon dopant atoms from the re-growth interface into the buffer layer. Actual HEMTs were built with and without the AlN NL (Figure 2). The on/off ratio improves from about 100 for the leaky device to 10^6 for the device with the AlN NL. The researchers point out that this is a desirable feature for both analog (RF) and digital (power-switching) applications, adding: “In addition, the natural back-barrier introduced due to the band offsets and polarization dipole — as shown in the energy band diagram in Figure 1(d) — can potentially enable reduced short-channel effects for shorter-gate-length HEMTs”. The sub-threshold slope is also steeper with the AlN NL: 300mV/dec rather than 650mV/dec.

Among the advantages that Notre Dame sees for its approach are the absence of a dopant, and savings on source materials and in growth time.

Another application of polarization effects being worked on at Notre Dame could be improved p-type doping for nitride semiconductors [John Simon et al, Science, vol327, p60, January 2010]. Although magnesium is commonly used to create such hole conduction in nitride semiconductors, it is generally not as good as the n-type doping achieved with silicon. One particular problem is that the holes have a large activation energy from Mg acceptor levels (~200meV in GaN), meaning that these impurities are inefficient dopants at room temperature (300K ~26meV). Worse, as the bandgap...
energy is increased (usually by adding aluminum), the Mg activation energy also increases (~630meV in AlN). The corresponding activation energy values for Si n-doping are 15meV (GaN) and 282meV (AlN).

The Notre Dame work aims at encouraging dopant ionization using the built-in electric polarization fields. The technique has been applied to improving the optical emission from prototype ultraviolet LEDs. The researchers also see application opportunities for bipolar electronic devices.

To avoid the high p-type resistivity (and hence Joule heating) that occurs at higher Al-doping levels, one is usually restricted to Al_{x}Ga_{1-x}N compositions with Al fractions less than 20%. It is not uncommon to use pure GaN (0% Al) to avoid these effects in p-type layers. However, this comes at a cost for the emission efficiency of UV, since pure GaN becomes highly absorbing of radiation with photon energies greater than ~3.4eV (wavelengths shorter than ~365nm). Also, the use of p-GaN on AlGaN suffers from reflection from band-structure discontinuities that tends to block holes from entering the active region for UV electron-hole recombination.

Polarization effects are widely used to create two-dimensional (2D) electron gases (and even hole gases) with high sheet densities — these are the basis of high-electron-mobility transistors. These 2D gases have high conductivity in the plane transverse to the epitaxial growth. However, vertical devices such as LEDs need
high conductivity in the growth direction. To create 3D electron gases using polarization effects, Notre Dame has in the past used materials with varying composition (grading). In principle, reversing the growth polarity (N [0001] instead of the usual Ga [0001]) and the composition grading (GaN to AlGaN rather than AlGaN to GaN) should result in similarly produced 3D hole gases. One difference however is that, while 3D electrons are easily sourced from the III-nitride surface levels, deep-level traps localize surface holes. These would need to be removed to achieve dopant-free hole conductivity.

To overcome this problem, Notre Dame uses an intentional Mg-acceptor doping of the N-face graded AlGaN layer as a hole source for the 3D hole gas (Figure 3). The holes are required to balance the unbalanced polarization charge in the graded AlGaN layer. One sign of the successful creation of such a hole gas is a weaker temperature dependence of its properties compared with thermally activated Mg-doped p-type ungraded layers.

Notre Dame has carried out growth of such layers and compared their performance with traditional p-type nitride layers using secondary-ion mass spectrometry and Hall measurements. Further characterization involved x-ray diffraction, in-situ reflection, high-energy electron diffraction patterns and atomic force microscopy.

In addition, LED structures were produced and sub-bandgap emission (Figure 4) was observed (i.e. <3.4eV, >365nm). These emissions are attributed to transitions from deep acceptor levels. One added advantage of the graded structure is that it acts as a natural electron-blocking layer (EBL) (Science Figures 4C and D). In normal LEDs, EBLs are used to avoid over-spill of electrons from the active layer into the p-type layers. Recombination of electrons in p-type GaN is usually non-radiative, reducing the optical output. The graded solution also avoids raising barriers to hole injection into the active layers. These properties may also be useful in future UV laser diode development.

The researchers also see prospects for using the polarization doping methodology with the more general AlInGaN system, which would allow more variety for growth direction choice and strain management.