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Materials Issues for Vertical Gallium Nitride Power Devices

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In this paper we are addressing some fundamental materials issues for the development of vertical GaN-based power devices. Specifically, what is the most economical way to form n+GaN / n-GaN (~50 µm thick, low defect, and doping level 10^{16}cm^{-3} or lower), which is required for power devices rated up to 5kV.

Because of the low on-resistance, high breakdown field strength, and good thermal conductivity, GaN power devices are very promising to address a number of current day power electronic applications. The most GaN power devices reported in the literature are based on lateral geometry; however, the development of vertical power devices will lead to higher blocking voltage, lower parasitic inductance and current collapse-free operation. Although there are a number of reports on vertical GaN power devices they generally suffer from a number of problems, the most important of which is high leakage current due to the high concentration of extended defects, such as threading dislocations and basal plane stacking faults.

The requirement that the drift region of such vertical power devices has a thickness approximately 50 µm, rules out as uneconomical the traditional epitaxial methods of MBE and MOCVD because of the relatively low growth rates of 1-2 µm / h. Furthermore, commercially available GaN substrates for the growth of the GaN drift region are prohibitively expensive. In our laboratory we have developed the HVPE method for growing GaN at growth rates as high as 700 µm / h, which allows us to develop both inexpensive free standing GaN substrates, as well thick GaN films with low defect density and low carrier concentration [1].

Free standing GaN substrates were developed by growing a thick GaN film (>1 mm) on a sapphire substrate and allowing the GaN film to separate from the sapphire substrate during the cooling down. This natural separation mechanism of the GaN film from the sapphire substrate is the result of the thermal stresses due to the difference in the thermal expansion coefficient between the two materials. Specifically, the average in-plane thermal expansion coefficient in the temperature range 300 to 1000 K for sapphire (7.5×10^{-6} K^{-1}) is greater than that of GaN (5.6×10^{-6} K^{-1}) causing the sapphire to contract at a faster rate than GaN upon cooling. However, the sapphire is mechanically constrained by the GaN epi-layer, and therefore held at a length that is elongated compared to the length it would have achieved had it not been constrained. This results in a tensile stress in the sapphire substrate. The stress analysis of the GaN layer follows analogous logic. GaN would like to contract at a certain rate but is coerced to contract faster than normal under action of the sapphire substrate. The final length of the GaN layer is shorter than it would be had the layer contracted independently and is thus under compressive stress. Such stresses can be quantified utilizing the Stoney Equation (1), which expresses the thermal stress in the film as a function of fundamental parameters of the film and substrate. According to Eq. 1, the epitaxial film stress (σ_f) depends on the thermal expansion coefficients (α), Poisson's ratios (ν), Young's moduli (E), thickness (d), and the temperature change (ΔT). The subscripts "f" and "s" denote values for the film and substrate respectively. Figure 1 shows the theoretical thermal stress generated as a result of cooling GaN on sapphire from 1025˚C (GaN growth temperature) to 25˚C (room temperature) as a function of the GaN thickness, using known material properties [1]. It should be noted that what is plotted in Figure 1, is the magnitude of the stress and that the nature of the stress in the GaN layer is compressive and that of sapphire, tensile. According to these data the compressive stress of GaN is reduced by over two orders of magnitude as the film thickness increases to 1mm; correspondingly, the tensile stress of sapphire increases by over two orders of magnitude in the same range of film thickness. We observed that upon cooling the thick GaN film separates from the sapphire substrate, a result attributed to the formation of cracks on the sapphire substrate.

$$\sigma_f = \frac{(\alpha_s - \alpha_f)\Delta T}{[(1-\nu_f)/d_f E_f) + ((1-\nu_s)/d_s E_s)](d_f)} \quad (1)$$

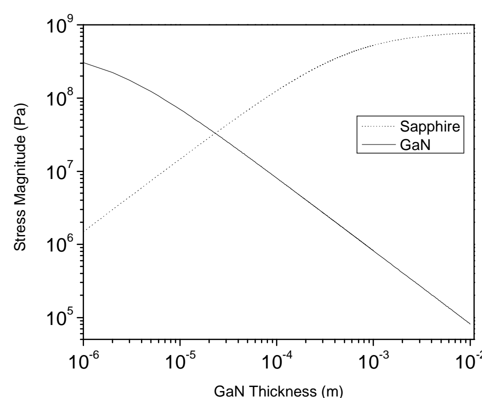

Figure 1 – Calculated thermal stress in sapphire and GaN as a function of GaN deposition thickness.

Using the HVPE method we have also produced GaN films on sapphire substrates with carrier concentration varying from 10^{20} to 10^{17} cm^{-3}. The evidence suggests that the electron concentration is due to accidental doping of the GaN films by oxygen, whose origin are oxygen impurities in the process gases or oxygen extracted from the quartz tube of the reactor. Thus, the incorporation of oxygen in the films can be minimized with the use of gas purifiers and the employment of appropriate liners in the reactor. Issues related to controlling extended defects in GaN produced by this method will be discussed.

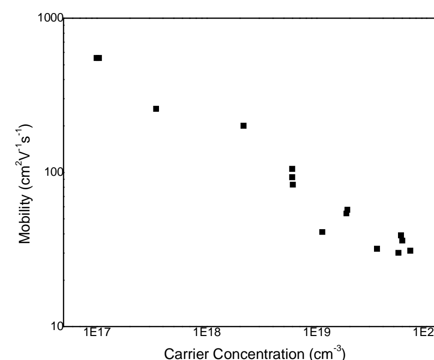

Figure 2: Electron mobility vs carrier concentration for a number of GaN films deposited by HVPE

[1] Adrian D. Williams and T. D. Moustakas, J. Crystal Growth **300,** 37 (2007)