Failure Mechanisms in AlGaN/GaN HEMTs Irradiated with 2MeV Protons

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Gallium nitride high electron mobility transistors (HEMTs) have shown the potential to be highly resistant to radiation damage, making them ideal for use in microwave power amplifiers and DC/DC converters in space-based applications. To investigate the mechanisms of radiation-induced degradation in AlGaN/GaN HEMTs, 2MeV protons were used to simulate the space radiation environment. The initial material quality was intentionally varied by studying HEMTs on sapphire, Si, and SiC substrates. The Hall mobility and 2DEG density was measured on Van der Pauw structures before irradiation and incrementally at each dose, up to up to a fluence of 6x10¹⁴ cm⁻² (Figure 1). The decrease in mobility can be attributed to increased carrier scattering in the 2DEG as a result of radiation-induced defects while the decrease in sheet carrier density is attributed to screening of the 2DEG from charged trap formation [1]. The magnitude of change in the 2DEG density is the same for all substrate materials (1x10¹² cm⁻²), though the percent change varies due to different initial values. A representative set of FET I-V curves from the HEMT on SiC before and after irradiation is shown in Figures 2 and 3. It is clear from Figure 2 that the ON-resistance increases and saturation current decreases, following the Hall data, and from the inset of Figure 3 that the OFF-state leakage decreases. TEM imaging was employed to directly probe the mechanisms suggested by the electrical measurements. A new, radiation-induced void at both edges of the gate in the Ni region of the Ni/Au gate metallization was revealed, shown in figure 4c [2]. EDS line scans (Figure 4b,d) indicate that, after radiation, the 20 nm Ni layer diffused up into the Au, and to a lesser extent, into the AlGaN, leaving voids protruding ~300 nm under the gate edges. The mechanism of the void formation shows all features of Ni/Au inter-diffusion through vacancy exchange, known as the Kirkendall effect. The exact process is still under investigation. It is particularly rare that such pronounced diffusion occurs at room temperature. Since the voids only occur at the gate edges, an additional electrochemical or strain-induced driving force is likely present. Therefore the role of the SiNx, passivation layer, as well as strain, at the gate edge will be factor in this ongoing research.

References
Figure 1. Hall characteristics as a function of proton fluence.

Figure 2. Change in threshold voltage and saturation current as a function of proton fluence.

Figure 3. Transfer curves for HEMT on SiC before and after irradiation. Inset: Before and after $V_G$-$I_G$ curves.

Figure 4. STEM images are shown (a) before and (c) after irradiation, as well as EDS line scans (b) before and (d) after irradiation, across the Ni gate region, into the AlGaN barrier.