Material Studies of GaN on Diamond

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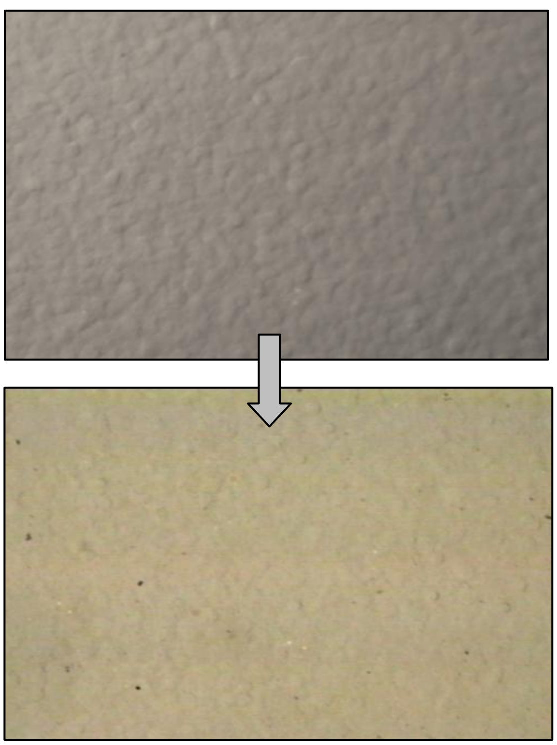
Abstract

Group4 Labs has developed and made commercially available for the first time, a composite semiconductor wafer that comprises of heteroepitaxial Gallium Nitride (GaN) compound semiconductor films atomically attached to polycrystalline chemical vapor deposited (CVD) diamond substrate. This GaN-on-Diamond wafer system enables extremely rapid, efficient, passive, and cost-effective heat extraction from the heat-generating heteroepitaxial device layers since the GaN heating layers are less than twenty nanometers from the highly thermal conductive diamond.



a

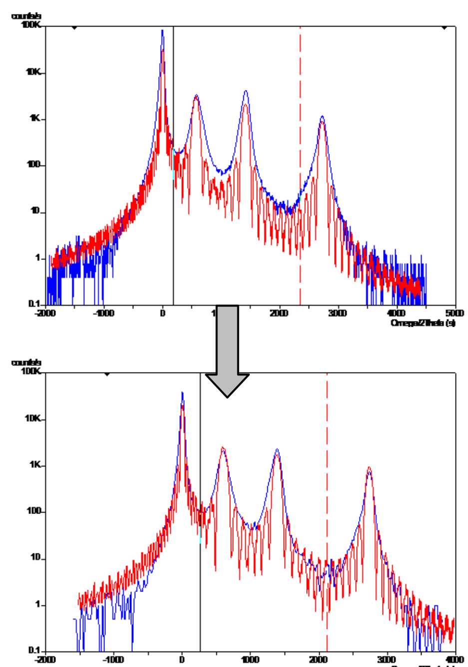
b

Figure 1. Nomarski micrographs (20x lens)of epi surface before (a) and after (b) transfer to diamond.

It is essential for the device manufacturing that the epitaxial layers have same level of quality after bonding to diamond substrate as they had on the original growth substrate. In this work we present results of comparative material property analysis for similar epitaxial layers as grown on silicon substrates and transferred to diamond substrates.

Experimental Results

Optical, X-ray, CL, and Hall effect measurements have been performed and analyzed. Figure 1 a, b show Nomarski microscope images of the wafer surface before and after transfer with high sensitivity to flatness. They indicate similar surface morphology with no specific features or cracks introduced during processing.



a

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Figure 2.Experimental (blue) and calculated (red) ω-2θ rocking curves for (0002) reflection, measured in the vicinity of GaN/AlN peaks before (a) and after transfer to diamond.

Figure 2 a, b show results of X-ray studies. High-resolution X-ray diffraction (XRD) measurements were performed using a PANalytical X'Pert MRD diffractometer at The LeRoy Eyring Center for Solid State Science at Arizona State University equipped with a multilayer focusing mirror and a 4-bounce Bartels Ge

(220) symmetrical single-crystal incident beam monochromator (Cu $K_{\alpha l}$ radiation, 12 arc.sec divergence) and a 3-bounce Ge(220) single-crystal analyzer (12 arc.sec acceptance angle). In triple-axis configuration this optic enables effective separation of coherent and diffuse scattering, thereby providing comprehensive information on elastic strain and types, densities, and spatial locations of crystal defects in epitaxial layers. Both symmetric (00.2) and asymmetric (10.5) or (11.4) reflections were used. Presented curves show no measurable impact of the transfer process on crystalline quality of the epitaxial layers.

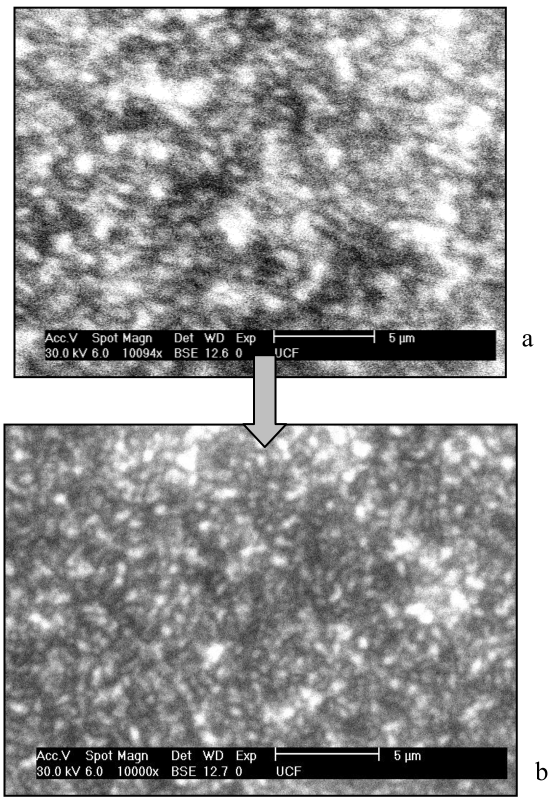

Figure 3. Show the CL map of the GaN epi surface before (a) and after (b) transfer to a diamond substrate.

In order to study internal strain of the epi layers, CL measurements were performed on GaN layers on silicon and on diamond (figure 3). Cathodo-luminescence tests were carried out using Philips XL30 TMP SEM under a 30kV electron beam accelerating voltage under room temperature with a vacuum of 10-5 mbar. Firstly, luminescence images of the sample were taken with SEM „s background scattering mode. Then different bright and dark spot on the picture are chosen to be measured with SEM integrated Gatan MonoCL3 system using its spot scan function. A series of spectra in several bright and dark regions were assembled. Results suggest that the transfer of epi layers from Si to diamond substrate does not cause noticeable strain or cracks in the layers.

Hall measured mobility and sheet concentration show that epitaxial layers transferred onto diamond substrate have retained the as-grown values. The typical measured Hall mobility for before and after epi transfer is in the 1600-1850 $cm^2/V.s$ range. Meanwhile the sheet concentration stayed steady within a very typical $-6x10^{+12}$ to $-8x10^{+12}$ $1/cm^2$ window.

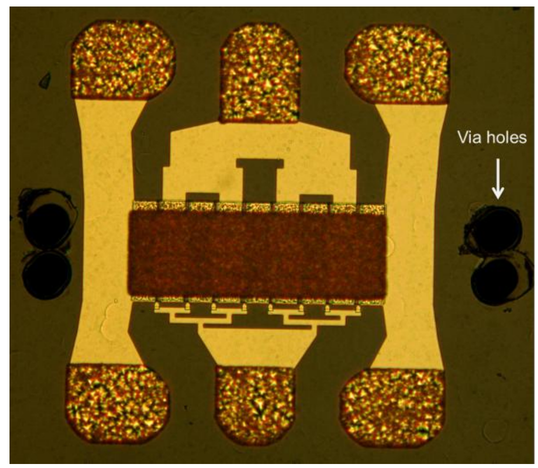

Figure 4. An eight finger device prior to via metallization.

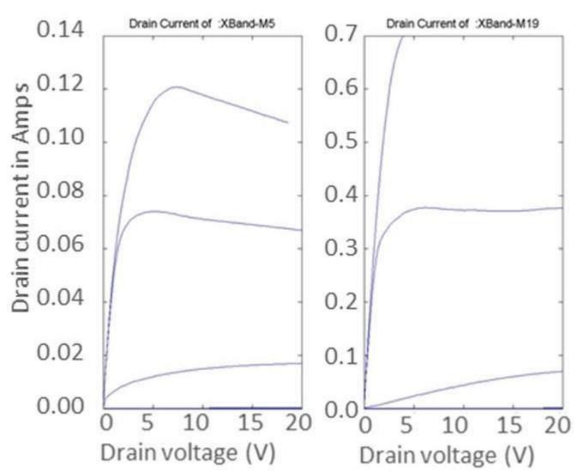

Figure 5. The IV characteristics of a two (left) and an eight (right) finger HEMT device on diamond.

Finally, as a demonstration multi-finger HEMT devices were fabricated starting from a GaN-on-diamond wafer. The epi was a 175Å thick $Al_{0.26}Ga_{0.74}N$ layer on a 0.8 µm GaN buffer. The epi had a 480 ohm/sq sheet resistance and the diamond had thermal conductivity of 800 - 900 W/mK. A Ta/Ti/Al/Mo/Au stack was used as the ohmic contact metal. After passivation with plasma enhanced CVD (PECVD) nitride, the ohmic contacts were annealed at a maximum temperature of 800C for 20 seconds. The gates, written in this project by e-beam, were 0.25 µm long and 100 to 150 µm wide. Contact metal and air bridges were formed after the gates. Source vias were used for each device. The source vias were laser drilled all the way through the diamond substrate from the GaN epi side. The vias were then metalized with sputtered Ti/W. Figure 4 shows an amplifier just prior to via metallization.

Devices with two, four, eight and sixteen fingers were tested. These tests were performed while the wafer was situated on a chuck. The IV characteristics for a two and an eight finger device are shown in Figure 5. They show stable performance up to I_{DSS} = 0.7 A and 20 V applied on the drain for the eight finger device.

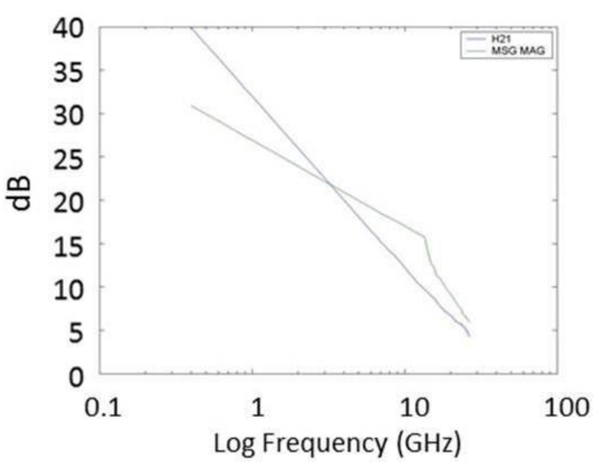

Figure 6. The small signal frequency response of an eight finger HEMT on diamond.

The frequency response of an 8 finger device is shown in Figure 6. The f_t and f_{max} were 42.4 and 41.5 GHz respectively. In previously and soon-to-be published papers [1,2], the authors show that the epi-transfer process used here does not affect the electrical characteristics of the GaN epitaxy. Indeed, the authors establish that the I_{DSS} values, for example, are inherited from the source GaN epi as it was originally grown on Si.

A summary of the electrical characteristics of various size HEMT on diamond devices is shown in the table below.

Table 1.

Fingers	I_{DSS} mA/mm	g_m mS/mm	f_{max} GHz	Breakdown V
2	570	340	38	100
4	675	350	40	Not meas.
8	650	350	41	Not meas.
16	600	310	39	Not meas.

Conclusions

Thus, the study shows that gallium nitride epi layers can be transferred onto highly thermal conductive diamond substrate without measureable structural damage. We also demonstrated that devices of various sizes can be fabricated without significantly impacting the localized descrete device performance. These developments show promise for the implementation of large area devices taking advantage of the passive cooling from the diamond substrates.

References

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