Single Crystal Diamond: An Ultimate Semiconductor

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Diamond is the ultimate extreme environment semiconductor with the lowest thermal expansion coefficient, the largest hardness value, and the highest chemical inertness. Coupled with a bandgap of ~5.4 eV, breakdown field strength of ~10 MV/cm, thermal conductivity of ~ 2,200 W/m·K, electron saturation velocity of ~ 2.7×10^7 cm/s, electron and hole mobilities of ~4,500 and ~3,800 $cm^2/V\cdot s$, respectively, diamond is poised to outperform its wide bandgap (WBG) (e.g. GaN) and ultra-WBG (UWBG) (e.g. Ga_2O_3, AlN) counterparts in terms of projected power-handling and power-switching performance.

Today, diamond is overcoming many historical challenges starting with its scalability. Thanks to improved microwave-plasma chemical vapor deposition (MP-CVD) systems, large area single crystal diamond materials are available. Figure 1 shows the 16×15 mm^2 single crystal diamond sample provided by Diamond Foundry. Figure 2 shows representative scanning electron microscopy (SEM) and cathodoluminescence (CL) images of an MP-CVD-grown diamond taken at the same location. The CL image, which is taken in panchromatic view with an acceleration voltage of 5 kV, is absent of any identifiable dislocations, indicating its high-quality. Figure 3 shows Raman spectroscopy comparison of the polycrystalline diamond (poly-diamond) and single crystal diamond samples. Single crystal diamond shows a single peak at 1331.7 cm^{-1} whereas poly-diamond shows multiple broad peaks between 1200–1600 cm^{-1}. Also shown in the poly-diamond Raman spectroscopy is the 521.95 cm^{-1} peak of the silicon used as the substrate for the growth of the poly-diamond. Figure 4 shows thermal conductivity measurement of the single crystal diamond using time-domain thermoreflectance (TDTR) technique. Open symbols show experimentally measured data, solid line shows model calculated fitting curve using parameters listed in the inset, and dashed lines show model calculations with ±10% diamond thermal conductivity. Model fitting shows the thermal conductivity measured is 2,189 W/m-K which is close to its theoretical value. Coefficient of determination R^2 is close to 0.98 indicating an excellent fit between experimental data and model calculation.

Diamond is gaining interest thanks to the highly-demanding operation of GaN RF devices. For the purpose of improving thermal budget of GaN RF device technology used for advanced high-power and high-frequency electronics, historically poly- and today single-crystal- diamond have been employed as a heatsink. Now GaN epilayers may be directly bonded to single crystal diamond substrates to remove heat efficiently. One critical understanding needed in this front is the surface activation and role of interlayers. Figure 5 shows contact angle measurement data for single crystal diamond and GaN/Si samples after plasma-surface activation using N_2 and O_2 plasma RIE. A contact angle smaller than 10° indicates the sample's high surface energy; a hydrophilic surface (low contact angle) typically implies that the material surface is free from contamination and that it is ready-to-bond to other material. Novel interlayers between GaN and diamond materials are needed as studies suggest thermal boundary resistance is responsible up to 40% temperature drop in high performance GaN RF devices.

Overall, single crystal diamond is on its way to become the ultimate semiconductor for ultra-high-performance and extreme environment devices.

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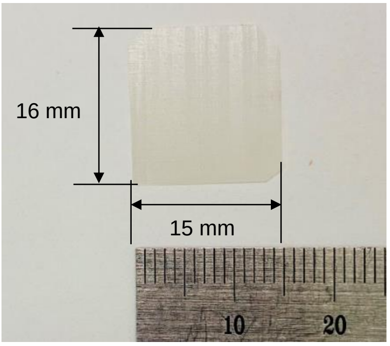

Figure 1. 16×15 mm^2 single crystal diamond sample provided by Diamond Foundry.

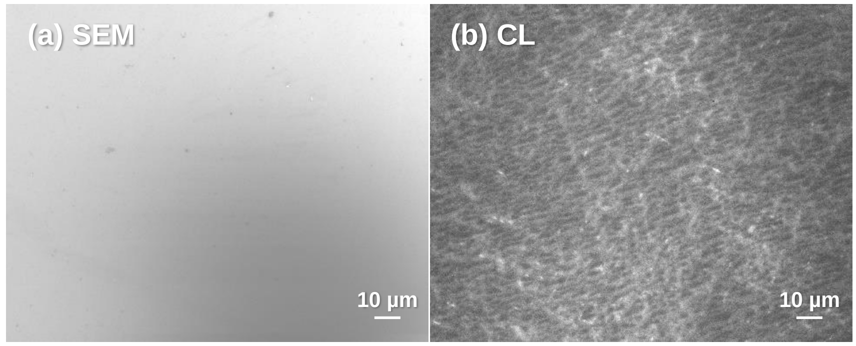

Figure 2. (a) SEM and (b) CL image of single crystal diamond sample taken at the same location are shown. No dislocations are observed in the CL image.

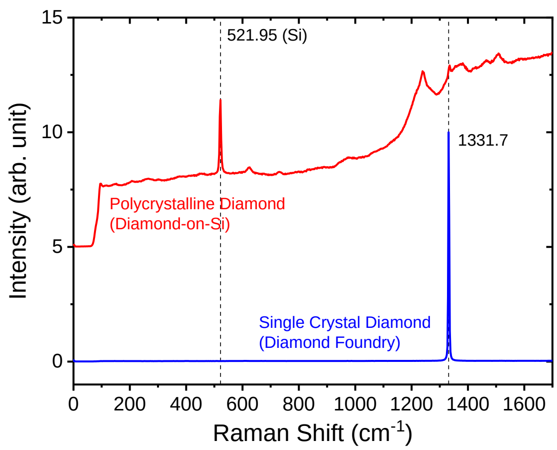

Figure 3. Raman shift comparison of polycrystalline diamond and single crystal diamond. Polycrystalline diamond is grown on Si wafer.

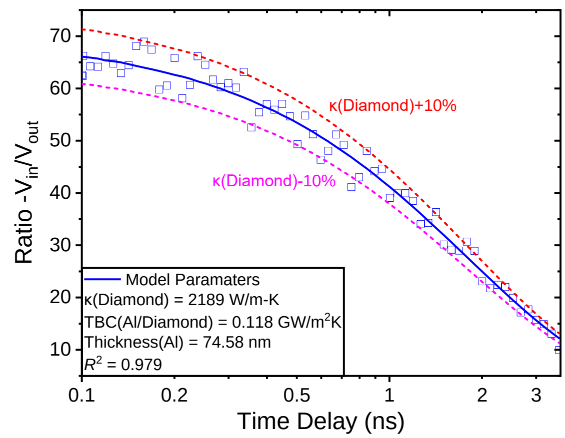

Figure 4. Thermal conductivity of single crystal diamond is measured using TDTR technique. Open symbols and lines indicate measured data and model calculation, respectively.

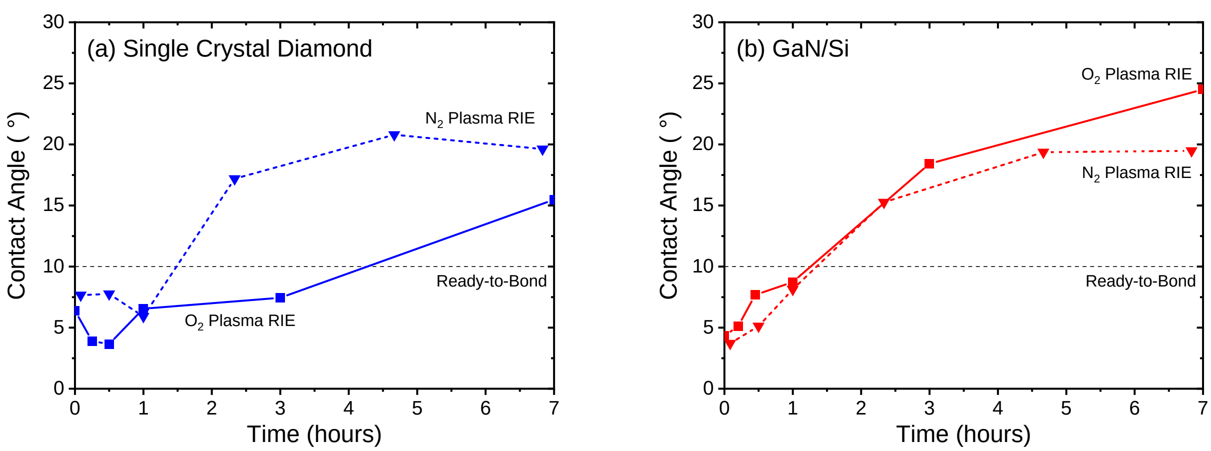

Figure 5. Contact angle measurements on (a) single crystal diamond and (b) GaN/Si samples. Samples were treated with N_2 (dashed lines with triangle symbols) and O_2 (solid lines with square symbols) plasma RIE before measurements. Angle being less than 10° is considered ready-to-bond.