White paper technical area: Extreme Environments

Energy-efficient, harsh environment compatible electronics based on diamond

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Diamond has many superior physical properties such as an ultrawide bandgap (5.5 eV), high thermal conductivity (2200 W/m-K), high critical electric field (10 MV/cm), low dielectric constant (5.4), and high mobility and saturation velocity for both electrons and holes. Apart from that diamond has excellent radiation hardness and ability to work at high temperatures (~500^{o}C), making it an excellent semiconductor material that is compatible to work in harsh environmental conditions. Polycrystalline diamond films may be used as heat sinking material for other high-power-density devices such as GaN-based power electronics. Several approaches were demonstrated either by bonding thick polycrystalline diamond plate or by depositing a thin layer of polycrystalline diamond on top of GaN high-electron-mobility transistors (HEMTs). In both cases, either bonding layer or a buffer layer is needed with reasonable thickness, which acts as a thermal interface and therefore adds thermal barrier resistance and thus affecting the thermal performance such that maximum temperature could be reduced of the device. Argonne researchers have developed a unique technology that allows direct deposition of polycrystalline diamond on GaN at lower substrate temperature (450^{o}C) thus preserving the GaN without any degradation during diamond deposition and thus enabling seamless integration with GaN demonstrating good thermal performance. Figure. 1(a) shows SEM cross-section of the diamond-GaN interface and Figure 1(b) shows effective thermal conductivity of the diamond/GaN composite and reference GaN substrate alone. It is interesting to note that the effective thermal conductivity of the diamond/GaN composite increases with temperature indicating better thermal performance at higher temperatures even at diamond layer thickness of 150 nm. The thermal performance could be significantly improved by optimizing the thickness of the diamond layer. We believe that expertise at Argonne in diamond synthesis and expertise in the GaN synthesis and device performance studies at UIUC will be valuable in developing high-performance GaN HEMT devices integrated with diamond for 5G electronics.

Another interesting approach that we would like to propose is in developing high-frequency diamond field effect transistors (FET) based on H-terminated diamond. It is well-known that hydrogenation of the diamond surface creates two-dimensional hole gas layer with p-type conductivity, which exhibits a high hole-density (10^{14} cm^{-2}) and reasonably high breakdown field (1 MV/cm) and high hole mobility of >300 cm^2/V-s and is stable up to 500^{o}C. However, the stability of the H-terminated layer and surface defects at the diamond and high-K dielectric layers degrades the performance of these devices with time. We propose to use 2D materials such as h-BN at the diamond/high-k dielectric interface (shown in Fig.2a and b), which not only protects the H-terminated layer underneath but also provides a smooth interface for the deposition of dielectric materials providing a defect-free interface. Our preliminary studies in this direction have demonstrated much-improved performance in terms of reducing leakage current density at higher electrical field with at least 10 times lower thickness of the dielectric layer that is reported in the literature.

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Diamond synthesis and nanofabrication facilities at Argonne combined with UIUC's expertise on device physics and testing will be well suited for collaborative efforts on developing energy-efficient and harsh environmental compatible devices based on the diamond for 5G electronics.

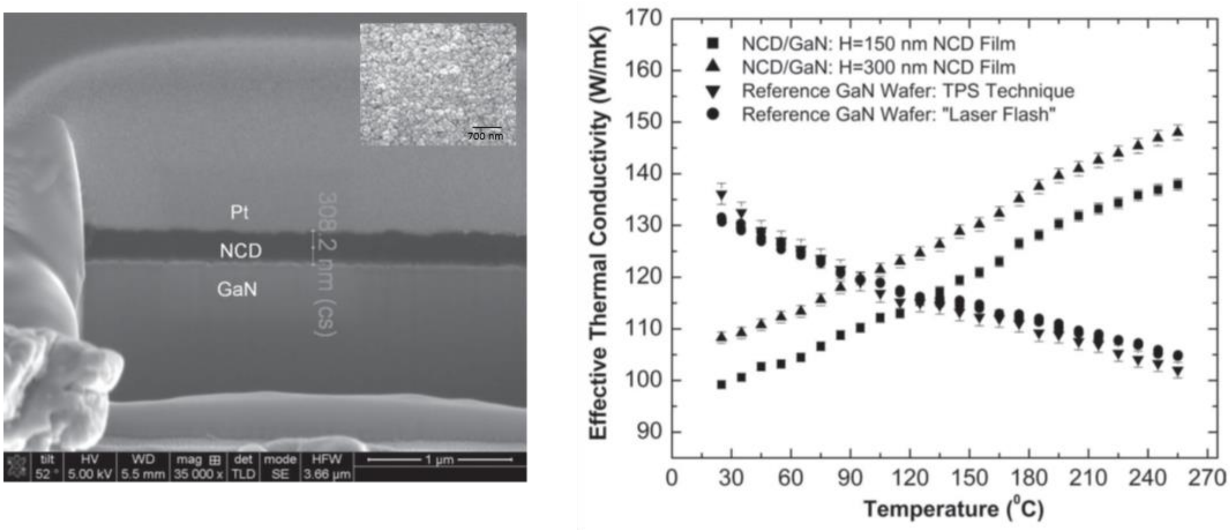

Figure 1(a): Cross-section SEM image showing diamond-GaN interface and the inset shows the morphology of the polycrystalline diamond. In (b), effective thermal conductivity as a function of temperature for two diamond/GaN composite substrates and the reference GaN wafer. The effective thermal conductivity in the case of a diamond/GaN interface increases with temperature(ref. Adv. Funct. Mater. 22 (7), 1525–1530 (2012).

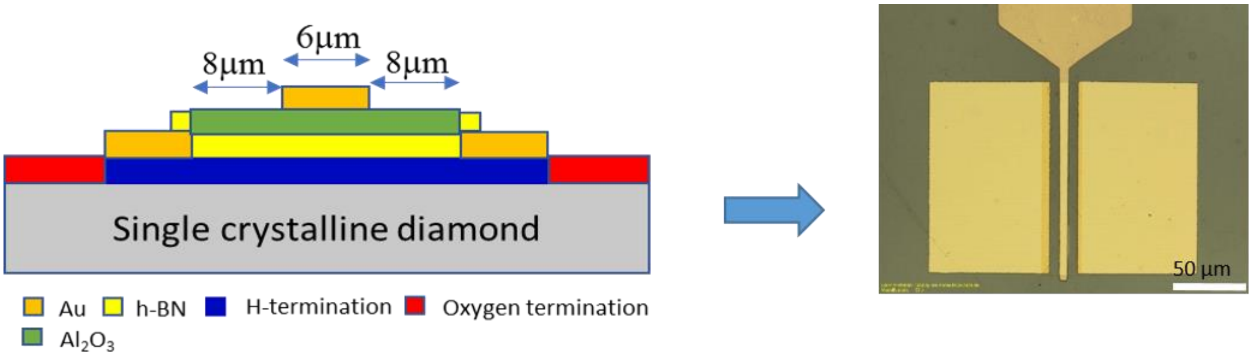

Figure 2(a) Schematics cross-section of the diamond based FET structure and (b) is the top view of the fabricated device (credit: Argonne National Laboratory)