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Challenging endeavor to integrate gallium and carbon via direct bonding to evolve GaN on diamond architecture

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ABSTRACT

This paper depicts efforts for fabricating GaN on diamond microstructure through direct bonding between Ga and C, while excluding the use of adhesive interlayer during spark plasma sintering (SPS) process. The resulting GaN on diamond architecture is seemingly successful, as suggested by macroscopic morphological observations. The microscopic inspection using high-resolution transmission electron microscopy (HRTEM), however, shows a unique, off-the-chart interlayer configuration, wherein the components are migrated, etched, or fused to tentatively form multiple crystal phases. These phases can be constructed based on their utmost stabilities among all possible phases thermodynamically driven under or near the SPS conditions.

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Gallium nitride (GaN) on diamond structure is deemed to be of substantial interests in multiple electronic applications including high electron mobility transistors (HEMT), light emitting diode (LED) devices, etc. [1–4]. This is because of the desired nature of GaN that provides wider band gap, higher thermal conductivity, and enhanced critical field strength/electron mobility compared to other semiconductors such as Si and SiC [5–8]. Such properties allows for the operation of GaN-based devices at greater voltage with lower leakage current [9–11]. However, in spite of offering the beneficial electronic properties, the GaN-based devices suffer due to non-uniform high heat generation in the active GaN layer during the device operation. The low thermal conductivity of GaN layer and its substrate suppresses the efficient dissipation of heat from the active GaN layer, leading to exhibit low performance of the resulting GaN-based high power devices.

To avoid this limitation, recent GaN-based devices incorporate a heat spread layer that is directly attached to the GaN device layers. This layer plays a key role in distributing the heat across the entire spread layer to some extent (Fig. 1a), yet, still opens a chance to further increase the efficiency associated with the heat elimination to reduce the temperatures near the device regions. It is suggested in the literatures that facilitated heat removal from the device can be realized by integrating materials with high thermal conductivity, among which diamond thin film is the most highly-preferred [12]. It should be noted that the production of active GaN layer on the thin diamond substrate is not an easy task and thus barely fabricated through the incorporation of an adhesion layer between GaN and diamond. Such example can be found on previous studies [13–16], wherein Cu heat sink is employed as an adhesion agent for the formation of the GaN on diamond architecture. In addition, recent works have also focused on developing a method denoted as top-down approach [17–19], which is typically initiated from the growth of the GaN thin film layer on a substrate such as SiC, Sapphire, or Si. Subsequently, a sacrificial wafer is used on the growth side of the GaN thin film layer, whereas the substrate present in the opposite side of the GaN thin film layer is removed through grinding and/or polishing [17–19]. The resulting, ground GaN surface is then attached to a diamond substrate [17–19]. On the other note, M. Kuball and coworkers recently produced GaN on diamond microstructure but still incorporated a dielectric interfacial layer for adhering the GaN to the diamond prior to removing the sacrificial wafer [19]. The utilization of the interfacial layer used in this binding interfacial or adhesive layer restricts the performance of the entire device because of the increase in the thermal resistance (Fig. 1a) [19]. Alternatively, diamond thin film is suggested to be directly deposited onto GaN layers but turned out to have internal stresses at the interface. In particular, these stresses are detrimental to achieve stable and feasible performance of the device

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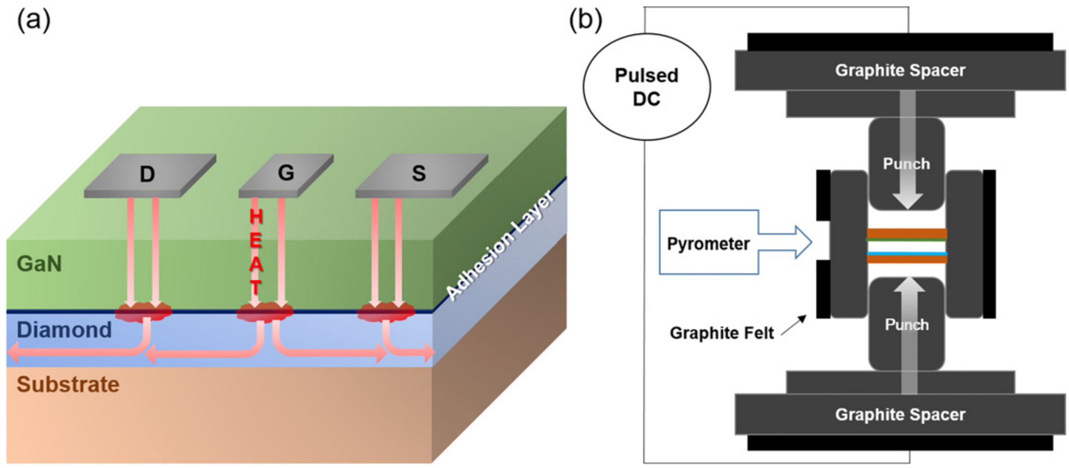

Fig. 1. (a) Schematic representation of GaN on diamond architecture with the heat dissipation pathway shown as red arrows. D, G, and S denote drain, gate, and source, respectively. (b) Illustration of die assembly in spark plasma sintering (SPS) process. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

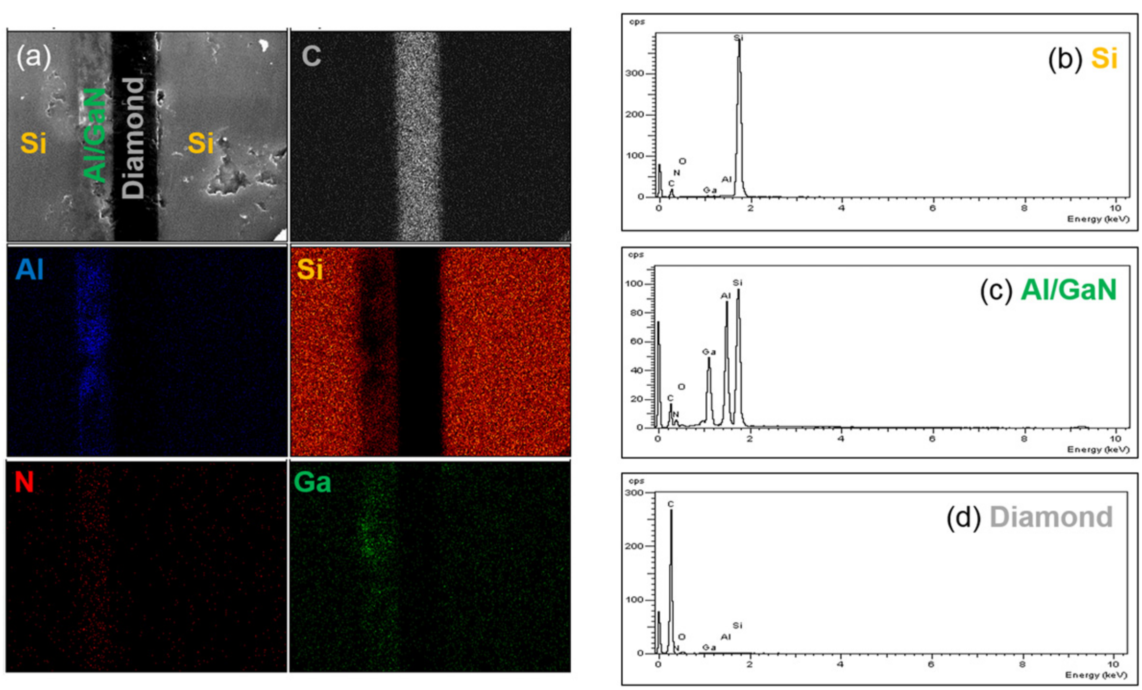

Fig. 2. (a) Cross-sectional SEM image of GaN on diamond microstructure and EDS analysis of each layer (C: grey; Al: blue; Si: orange; N: red; Ga: green). EDS elemental mapping of C, Al, Si, N, and Ga at each layer: (b) Si, (c) Al/GaN, and (d) Diamond. Al is also detected due to the presence of AlGaN buffer layer used for GaN growth on Si wafer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[20] and occasionally lead to the failure of the device due to the formation of stress based micro-cracks [21]. Apparently, GaN on diamond microstructure via direct bonding with no adhesive agent has been rarely reported, to the best of our knowledge, and it is our primary goal to elucidate our effort in this report.

For the creation of GaN-diamond architecture, we utilized spark plasma sintering (SPS) process at 1000 °C with an uniaxial pressure of 40 MPa for 2 min, as illustrated in Fig. 1b.[1] The resulting GaN-diamond microstructures were characterized using scanning electron microscope (SEM, JEOL-6400) for the observation of cross-sectional region to confirm the bonding between diamond ans GaN. It is clarified in Fig. 2a that the distinct layers are evident, while showing feature of Si-GaN-diamond-Si architecture (i.e., different surface textures). Also, energy-dispersive X-ray spectroscopy (EDX) mapping was used to investigate the elemental composition of each layer. As shown in Fig. 2b, c, and d, expected elements are found in corresponding interfacial regime, which can be another evidence to suggest the formation of Si-GaN-diamond-Si structure.

Further, high resolution transmission electron microscopy (HRTEM) was employed to validate the formation of GaN on diamond via chemical bonding between the element in GaN (i.e., Ga) and diamond (i.e., C)

[1] Experimental specifics can be found in a thesis (University of Florida at department of Materials Science and Engineering) by Dr. Kim, J. C., which is entitled as 'Processing and Characterization of Diamond Surfaces for Wafer Bonding Applications'.

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