Effect of Manufacture on the Microstructure of GaN-on-Diamond

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Abstract

To achieve a robust GaN-on-diamond technology for reliable next-generation high-power electronics, it is important to understand the correlation between the manufacturing process and the resulting microstructure. Here we examine GaN-on-diamond samples produced using diamond seeding particles of different sizes. Combining in situ focused ion beam cross-sectioning and x-ray computed tomography, we were able to evaluate the interfacial features and 3D microscopic defects in this multilayer structure. The sample seeded with a smaller diamond particle size is free of microscopic defects.

INTRODUCTION

The reliability of current GaN microwave technology is predominantly limited by the lack of optimal heat dissipation. A potential solution to this problem is to integrate diamond, whose thermal conductivity is typically 5-6 times higher than SiC, with GaN to produce GaN-on-diamond devices. Various approaches have been proposed, including growing the diamond onto the GaN layer after removal of the original substrate, or wafer bonding. The former approach has been, to date, the most scalable approach for GaN-on-diamond wafer manufacturing. This enabled the successful fabrication of GaN-on-diamond devices with 3× greater power than GaN-on-SiC [1-3]. However, the reliability of these devices with excellent performance has rarely been studied, although it is critically important for a manufacturable and commercial next-generation high-power electronics technology. As yet, only data on the strength of the GaN-diamond interface has been published [3]. It has shown that a robust interface between GaN and diamond is possible, despite the significant thermal mismatch between the two materials. In this paper, we use in situ focused ion beam cross-sectioning and x-ray computed tomography to study the microstructure of GaN-on-diamond to show that wafers free of microscopic defects can be manufactured with optimized diamond seeding. However, if non-optimal seeding is used, defects detrimental for the reliability of GaN-on-diamond devices can be formed.

MATERIALS AND MEASUREMENT TECHNIQUE

The process of manufacturing samples is as follows, Fig. 1: first, remove the Si substrate of an AlGaN/GaN heterostructure grown by metal-organic chemical vapor deposition (MOCVD); deposit diamond particles as seeds onto an amorphous layer onto the GaN prior to the growth of a 100 µm thick polycrystalline diamond layer by microwave (MW) plasma chemical vapor deposition (CVD). Two conditions were studied here, one with less than 0.5 µm diameter diamond seeding particles (referred to as 'large' seeding in the following text) and the other one with seeding particles less than 50 nm in size (referred to as 'small' seeding). The use of different sizes of seeding particles is the most straightforward way to adjust the diamond grain size near the GaN-diamond interface to modify the thermal conductivity in this region [5]. Further details on the GaN-on-diamond material fabrication can be found in Ref. [6,7]. For each seeding condition, both as-made GaN-on-diamond samples, and those annealed at 825ºC, a typical condition used for ohmic contact formation, were studied.

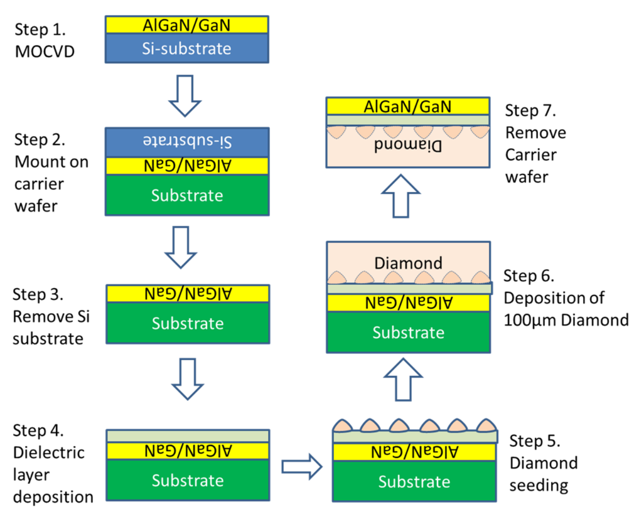

Fig. 1. Schematic of the primary process steps for the manufacture of GaN-on-diamond wafers.

The surface of the as-manufactured wafer samples and the cross-sectional microstructures were studied by a FEI Helio NanoLab 600i Dualbeam workstation. Trenches were milled by focused ion beam (FIB) Ga^+ beam at a number of locations across the samples and subsequently imaged by scanning electron microscopy (SEM) at a stage tilt of 52° to allow the *in-situ* observation of the surface features as well as the cross-sections. To obtain 3D microstructural information on the

GaN-on-diamond wafers, x-ray computed tomography (XCT) was performed on a ZEISS Xradia 510 Versa microscope with voltage of 80 kV, field of view of 1.6×1.6 mm and a voxel size of 0.65 μm^3. 3201 radiographs were taken as the specimen was rotated by 360°. These radiographs were then processed by computer algorithm to reconstruct the three-dimensional volume of the material.

Results and Discussion

Fig. 2a shows the typical surface appearance of the GaN in the sample made with large diamond seeding particles (after step 7 in Fig. 1). Different types of microscopic defects are visible, in particular dark dots arranged in straight lines. These lines are randomly distributed on the surfaces. While these are clearly apparent on the surface in the SEM micrographs, we note they tend to be less visible in optical microscopy images. FIB milled cross-sections of these dark dots, Fig. 2b, reveal that they are actually voids. Most of these voids are concentrated near the GaN-diamond interface, however, a few selected ones penetrate the full GaN layer and form through-holes. The most likely reason for the formation of the voids is damage introduced to the amorphous dielectric layer during the diamond seeding (step 5 in Fig. 1) and the subsequent etching of the GaN in the harsh environment of diamond growth. Annealing at 825 ^{o}C for 20s (after step 7 in Fig. 1), Fig. 2c, resulted in an increase of the density and size of these dark dots, possibly due to etching of the GaN by hydrogen or other radicals stored near the GaN-diamond interface. Cracks also formed linking up a line of dark dots as a consequence of the annealing, Fig. 2d.

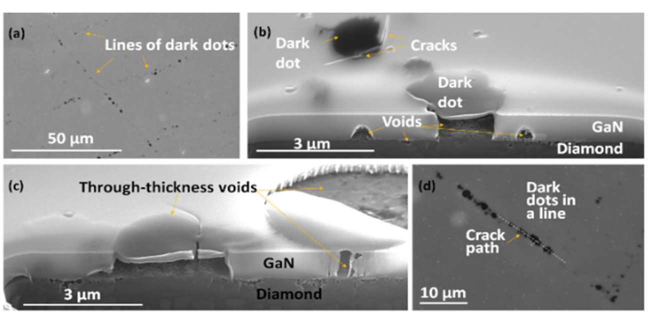

Fig. 2. SEM images of (a) the surface and (b) a FIB milled cross-section of as-manufactured GaN-diamond seeded with 'large' particles; (c) a FIB milled cross-section and (d) crack linking dark dots on this GaN-on-diamond after annealing at 825°C for 20s.

Lab-based x-ray computed tomography was employed for non-destructive imaging of the GaN-on-diamond structure. Fig. 3a shows a reconstructed 3D view of the GaN-on-diamond sample. Since the scanning resolution is about 0.65 μm^3, this technique was able to distinguish the 1 µm thick GaN layer from the diamond as indicated in the graph. The field of view is about 1.6×1.6 mm; therefore, the studied volume of material is sufficient to demonstrate the population and distribution of micrometer-size defects in the GaN. At the resolution adopted in the present work, XCT was able to capture the presence of voids in the GaN layer and those at the GaN-diamond interface, Fig. 2a.

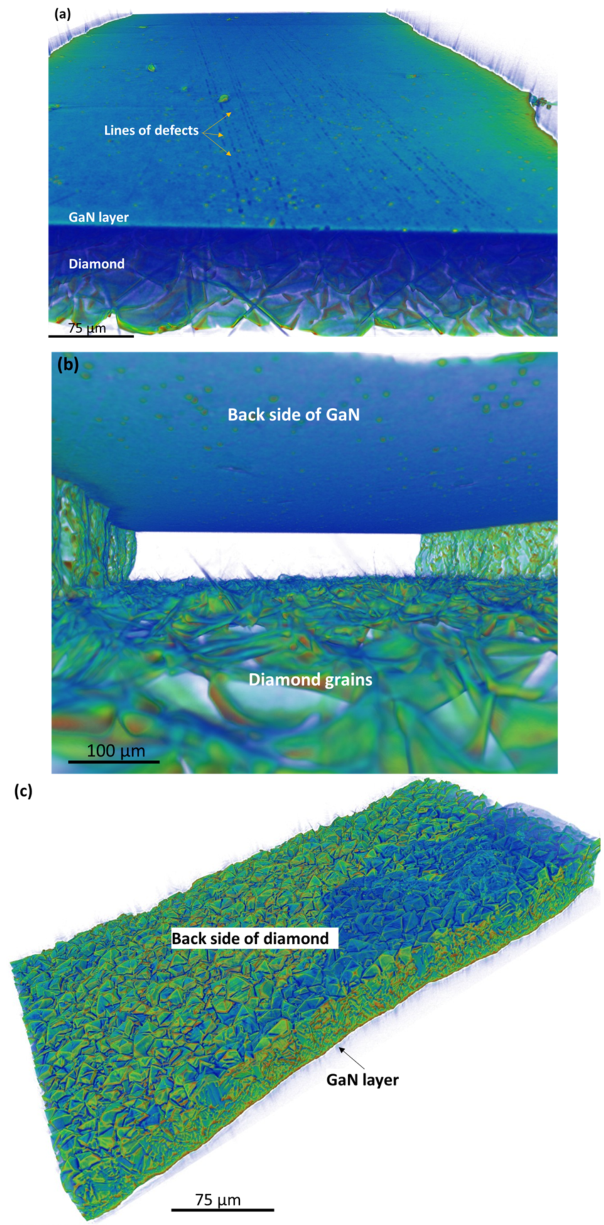

Fig. 3. X-ray computed tomography (XCT): (a) 3D reconstruction of GaN-on-diamond material, seeded with 'large' particles, showing the surface defects and a cross-section of individual layers; (b) graphical processing was applied to the computed volume to remove the diamond material next to GaN layer revealing the backside of the GaN; (c) backside of 100 µm thick diamond layer. False color is used in the x-ray tomography images to illustrate the different features.

The results also illustrate the homogeneity of the diamond, Fig. 3b, and the grain structure of the grown diamond layer at the back side of the wafer, Fig. 3c. It can be seen from Fig. 3c that the as-grown diamond has a high roughness, which is ultimately removed by polishing the finished wafer.

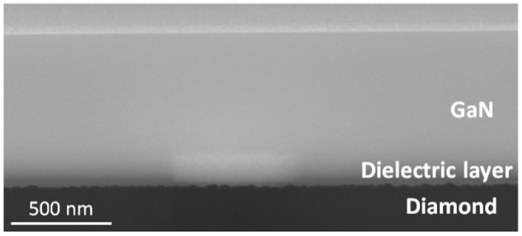

Fig. 4. SEM image of a cross-section of GaN-on-diamond seeded with ‘small’ size diamond particles, after annealing at 825°C.

For the sample seeded with ‘small’ diamond particles, no apparent microscopic defects were observed over the four inch wafer studied, except small undulations in the amorphous seeding layer. The diamond properties combined with the homogenous material structure provide thermal properties which allows three times greater power dissipation than in standard GaN-on-SiC devices. After annealing treatment at 825°C for 20s, no obvious changes in microstructure and corresponding properties were observed, Fig. 4. In general, in these samples, during diamond growth, the GaN is protected from the harsh diamond growth environment by the amorphous seeding layer, inhibiting the formation of voids and through-holes in the GaN. Changes in the seeding can therefore produce GaN-on-diamond wafers free of microscopic defects, which are stable up to temperatures commonly used for GaN microwave device processing.

Conclusions

Substantial progress has been made in recent years in GaN-on-diamond technology for high-power transistors, and it is of great importance now to study materials and device reliability related challenges. We demonstrated that GaN-on-diamond material free of microscopic defects can be manufactured with less than 50 nm diameter seeding particles.

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Acronyms

HEMT: High Electron Mobility Transistor
CVD: Chemical Vapor Deposition
FIB: Focused ion beam
SEM: Scanning electron microscopy