3D diamond growth for GaN cooling and TBR reduction

Daniel Francis[1], Sai Charan Vanjari[2], Xiaoyang Ji[2], Tatyana Feygelson[3], Joseph Spencer[3], Hannah Masten[4], Alan Jacobs[3], James Spencer Lundh[4], Marko Tadjer[3], Travis Anderson[3], Karl Hobart[3], Bradford Pate[3], James Pomeroy[2], Matthew D. Smith[2], Martin Kuball[2]

[1]Akash Systems (Daniel.Francis@AkashSystems.com), [2]University of Bristol, [3]Naval Research Laboratory, [4]National Research Council Postdoctoral Fellow, residing at NRL

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Abstract: We demonstrate three methods to increase heat extraction from semiconductors. These are demonstrated on GaN HEMTs with the goal of improving the heat extraction in GaN-on-diamond structures. The methods are: 3D diamond growth on all sides of a GaN HEMT making a GaN-in-diamond structure; 3D diamond growth doubling the thermal conductivity of diamond thin films; and adhesion layer annealing which can reduce the TBR between GaN and diamond.

INTRODUCTION

As the world strives to develop increasingly high-power-density devices, the efficient extraction of heat from semiconductors becomes progressively more critical. This paper explores multiple techniques for improving heat extraction from GaN.

GAN-IN-DIAMOND

When removing heat from the active junction through the substrate [1] or via top-side flip-chip bonding [2], it's beneficial to establish a high thermal conductivity pathway that directly links the top and sides of a semiconductor to a highly thermally conductive substrate. Heat could then be efficiently extracted from this pathway. In this context, we demonstrate such a structure using a GaN HEMT (High Electron Mobility Transistor) encased in diamond.

Figure 1 shows a GaN-in-diamond structure, demonstrating that it is possible to encase the active semiconductor within diamond. While having diamond on top, unattached to a heat extraction path, is not particularly useful, constructing a fully connected diamond path can significantly reduce thermal resistance. Close thermal contact between the top diamond and the backside diamond is crucial because even if the diamond has high thermal conductivity, a path that spans microns in length can still result in considerable thermal resistance.

The sample shown in figure 1 was prepared starting with a GaN-HEMT on diamond where the GaN thickness was 400nm and the SiN adhesion layer between the GaN and the diamond was 18nm thick. The GaN HEMT was patterned by etching off the GaN in selective areas exposing the substrate diamond under the GaN epi. Another protective SiN coating was deposited by PECVD at 600°C with a thickness of 20nm. The entire substrate was seeded and 1.3 microns microwave-plasma CVD diamond film was grown over the GaN epi using the following conditions: power 800 W, pressure 15 Torr, 750 °C, 0.3% CH_4/H_2.

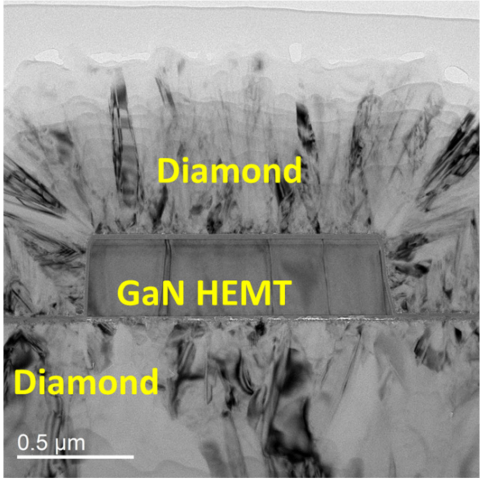

Fig. 1. TEM image of a GaN-in-diamond structure.

DIAMOND LATERAL REGROWTH

Another consideration when integrating diamond on the top side of a semiconductor device is that the diamond, near the growth surface (near-junction diamond) has thermal conductivity that is proportional to the grain size. Since the grains as grown start out small, the near-junction diamond has poor lateral thermal conductivity [3].

Diamond is typically seeded with 5 to 30nm grains. Although the diamond vertical thermal conductivity increases rapidly, horizontal grain size and corresponding thermal conductivity increases slowly. This small lateral grain size is seen in Figure 2. This image shows diamond grown on silicon about 1 micron from the silicon-diamond interface. The thermal conductivity of small grain diamond is dominated by the grain size [4] as a result the lateral thermal conductivity is severely impacted by the high density of grains.

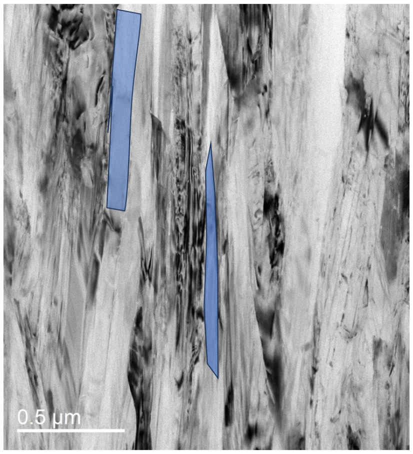

Fig. 2. Cross-section TEM image showing near junction diamond about 1 µm from the growth surface. The grains are tall in laterally narrow.

Typically, the diamond film grain size is about 1/10th the thickness of the diamond film. This corresponds to a thermal conductivity of 30 to 100 W/mK for a 1-micron thick film. If diamond is to be used to conduct heat laterally from the top surface of the semiconductor down to the substrate where the heat is extracted, the lateral thermal conductivity is critical. The ideal approach is to develop a way to increase the lateral grain size of the diamond and in doing so, increase the lateral thermal conductivity.

We demonstrate a method to enhance the thermal conductivity of near-junction diamond films through lateral diamond growth. In this approach, after a short diamond growth, we deposit and pattern a thin layer of nitride and continue diamond growth without seeding. The unseeded diamond begins in the exposed areas and spreads laterally to cover the patches of silicon nitride. Figure 3 illustrates the increase in the size of diamond grains that laterally grow over the silicon nitride.

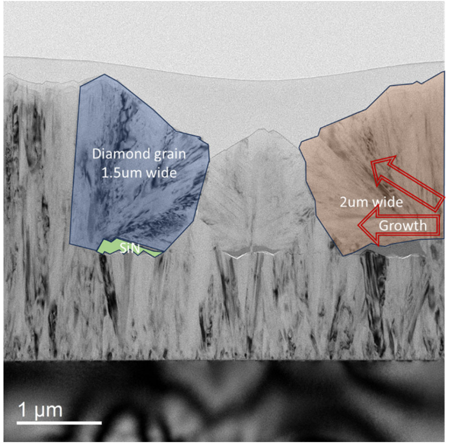

Fig. 3. Cross-section TEM image showing the lateral regrowth of diamond using patterned SiN.

~~We measured the thermal conductivity of the large-grain diamond area and compared it to the un-patterned areas. The thermal conductivity of the patterned diamond was 260W/mK, compared to 130W/mK for the diamond in the un-patterned areas and 100W/mK for the initial diamond growth. This demonstrates that by using lateral overgrowth, bulk-level diamond thermal conductivities can be achieved in much thinner films.~~

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To achieve bulk-level thermal conductivity (> 1000W/mK), diamond films typically need to be grown to a thickness of 25 to 50 microns. However, increasing the grain size near the boundary could potentially allow reaching bulk-level thermal conductivity with just 10 or 20 microns of diamond growth. Additionally, the proposed heat extraction path from a top-side diamond film involves lateral heat flow into the substrate. The horizontal thermal conductivity of thin films is notoriously low (because of the density of horizontal grains), but by increasing the thermal conductivity near the substrate, the thermal resistance for lateral heat extraction can be significantly decreased.

These measurements and images demonstrate that by utilizing lateral overgrowth, bulk-level diamond thermal conductivities can be achieved in much thinner films, and the lateral heat extraction through spreading into the substrate would likely be substantially improved.

Commented [A1]: I believe bulk diamond thermal conductivity is > 1000 W/mK. I suggest you instead say that using lateral overgrowth, thin film thermal conductivities can be “significantly improved.” Your following paragraph notes the limitations of the TTR technique for lateral thermal conductivity measurements. It isn’t clear how you are inferring you achieve bulk-level thermal conductivity with the measurement you are making, even if the reference states those larger grains, as observed in your TEM image, can have higher thermal conductivity. Please clarify how you arrive at that conclusion, as the measurement itself shows a lower value.

Commented [A2R1]: The paragraph now reads more explicitly that the bulk level of thermal conductivity would be achieved with thinner diamond -20 microns now compared to 50 microns without this technique. Not that you have bulk thermal conductivity at 2 microns of diamond thickness.
Though, the next phase of this development might get us there!

These thermal conductivity measurements are performed by transient thermal reflectance (TTR) (Described in more detail in the next section) This measurement is primarily sensitive to the vertical thermal conductivity. In this measurement, the spot size is much larger than the diamond grains and therefore the heat extracted is through the substrate rather than spreading within the diamond film. Given that the grains in the un-patterned diamond films are just as tall, but only 1/10th as wide, the vertical thermal conductivity is only marginally impacted by the small grains. In our measurement the impact to the vertical thermal conductivity is 2X. However, if you use the thermal conductivity graph in reference [4] figure 6B, you can see that a change in grain size from 0.1μm to 1.5μm would actually change the thermal conductivity from ~100 W/mK to nearly ~1000W/mK. This is the change one might expect for lateral diamond thermal conductance. If the heat extraction is vertical, as it is with a thick substrate this near-junction low thermal conductivity is not significant. However, if the heat extraction is lateral as would be the case for top-side diamond, then the low lateral thermal conductivity is a significant thermal barrier. Every micron of lateral heat path of diamond with a thermal conductivity of 100 W/mK is the equivalent of 10 m^2K/GW thermal boundary resistance (TBR). This TBR of each micron of lateral diamond heat spreading is comparable to the thermal resistance of the adhesion layer.

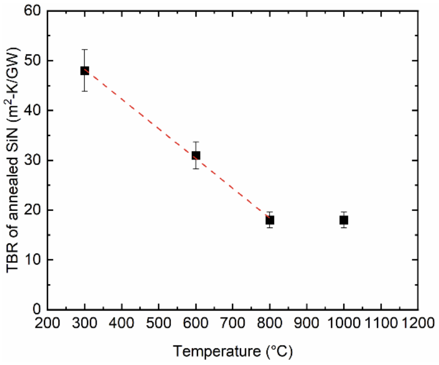

Fig. 4. TBR measurements of SiN on GaN-on-diamond samples annealed at different temperatures between 300°C and 1000°C.

ADHESION LAYER TBR REDUCTION

Finally, since diamond growth conditions typically damage most semiconductors, we use a protective layer of silicon nitride between the diamond and the semiconductor.

To minimize thermal resistance between the diamond and the semiconductor, minimizing the thickness of this layer is essential. Here, we introduce another parameter for minimizing thermal resistance: the densification of the nitride. Densifying nitride is a well-known technique for eliminating pinholes and generally improving the quality of the nitride. The thermal conductivity of the regrown large grain diamond and the TBR of the densified silicon nitride after annealing were measured by the transient thermoreflectance (TTR). In the TTR measurements, a 150-nm gold layer was coated as a transducer. The 532-nm pump beam generated a temperature jump on the sample surface with a repetition rate of 8 kHz, and the 488-nm probe beam was reflected back from the sample surface and collected by the detector for thermoreflectance signals. The thermoreflectance transient data was then fitted to the transient heat equation to determine the unknown TBR or thermal conductivity [5-6]. Results can be seen in figure 4. The uncertainty of TTR measurements was estimated to be ~10%. In our study, we treated four GaN-on-diamond samples with 25nm of PECVD silicon nitride and annealed the samples between 300°C and 1000°C. The results demonstrate that we were able to reduce the thermal boundary resistance between samples by a factor of more than three by thermal annealing the nitride.

CONCLUSIONS

In this paper we have shown the ability to grow diamond on all sides of GaN, that we can control the diamond thermal conductivity and the importance of adhesion layer densification to control the TBR between semiconductors and diamond.

ACKNOWLEDGMENTS

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