GaN HEMT Near Junction Heat Removal

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Abstract

GaN HEMT technology is transforming applications in communications, radar, and electronic warfare by offering more than 5x higher RF transmit power over the existing GaAs-based technologies[1]. The high breakdown voltage and current handling capability of GaN HEMTs enables a 5x increase in RF power using GaN-based devices in place of conventional GaAs-based devices. However the ultimate power and performance of GaN technology cannot be exploited due to thermal limitations on performance and reliability. The research in this work demonstrates a novel method of directly depositing high quality, high thermal conductivity diamond within a micron of the GaN HEMT device channel to significantly improve near junction thermal transport to fully exploit GaN technology.

INTRODUCTION

The high power density in GaN HEMTs translates to mega-watts/cm^2 heat dissipation at the device gate region. Thermal simulations of GaN HEMT 2-stage MMIC power amplifier illustrate the device self heating as shown in Figure 1a. The temperature rise profile versus depth, shown in Fig. 1b, is taken from the device hot spot at the channel, through the substrate and down into the housing backside. The device temperature rise peaks at 231°C and a majority of the temperature rise occurs within the first 10 microns of the gate. Improved thermal transport solutions within microns of the GaN HEMT device channel are key to reducing GaN power amplifier self heating for peak performance and reliable operation.

Diamond substrates have been reported to offer high thermal conductivities exceeding 2000 W/mK which is more than 5 time greater than SiC (~380 W/mK)[2]. Replacing the SiC substrate less than a micron beneath the GaN HEMT device channel with low defects, high thermal conductivity diamond materials can significantly increase the thermal conductance and reduce the device junction temperature.

Substrate transfer and bonding methods have been reported to successfully integrate diamond with GaN HEMT materials[3]. Developing transition layers with reduced interfacial resistance and high conductivity is key area of focus with the transfer and bonding approaches. In this work direct growth of high quality CVD diamond films within a micron or less from the device junction is presented as a method to integrate diamond with GaN HEMT technology.

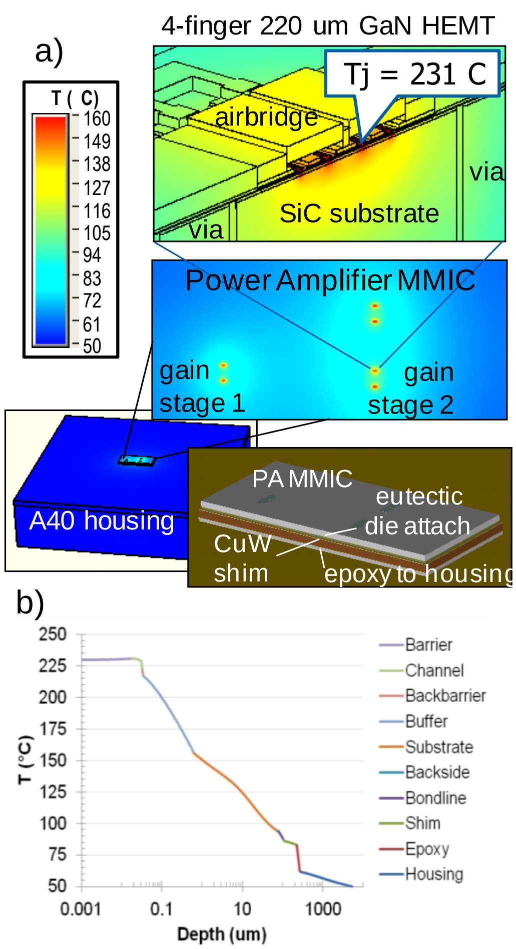

Fig. 1 a) Simulated thermal map of 2-stage GaN MMIC PA mounted on an A40 fixture. b) Temperature vs. depth from device peak temperature from device channel to the housing backside (50°C ambient).

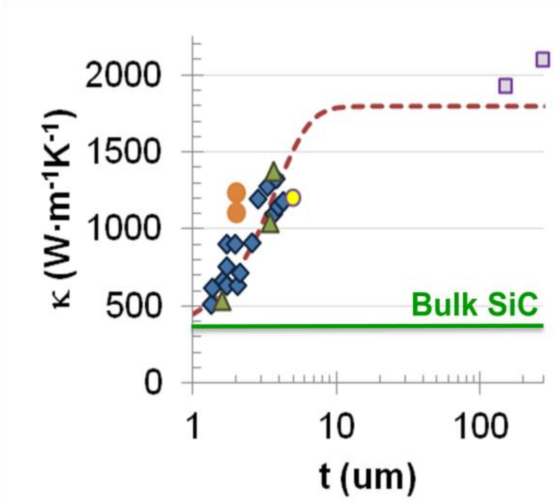

Fig. 2 CVD diamond film thermal conductivity plotted as a function of film thickness.

CVD diamond films in literature demonstrate rapidly increasing thermal conductivities (κ) with distance from nucleation interface to local bulk κ >1300-2000 W/mK as shown in Fig. 2[4]. Achieving high thermal conductivity > 1300 W/mK diamond films in thickness of 1 um or less is a key area of focus in this work. Experiments were designed to explore wafer surface preparation, diamond nucleation conditions, and diamond film growth parameters to achieve optimal film coalescence & growth for increased thermal conductivity with low interfacial boundary resistance.

EXPERIMENTAL

The diamond films were fabricated on Si wafers in a microwave plasma deposition system using purified methane and hydrogen as reactants. The Si wafer surface was seeded with nanocrystalline diamond (NCD) seeds. The NCD process conditions were optimized for rapid film coalescence and growth. Diamond films of 0.5, 1, and 5 microns in thickness were grown to study the thermal characteristics of the diamond film coalescence and bulk regions as shown in the top picture of Figure 3.

To fully characterize the thermal characteristics of the diamond growth process, diamond windows were etched into the Si to stop selectively on the backside of the diamond film with a high selectivity etch process as shown in the middle picture of Figure 3. Aluminum metal transducers were deposited on both the top and bottom sides of the diamond films as shown in the bottom picture of Figure 3. Diamond films measured by highly surface sensitive depth resolved pico-second thermo-reflectance measurements[5]. Suspended diamond films were characterized from front and back for improving measurement sensitivity of diamond film bulk and coalescence region as shown in bottom picture of Figure 3.

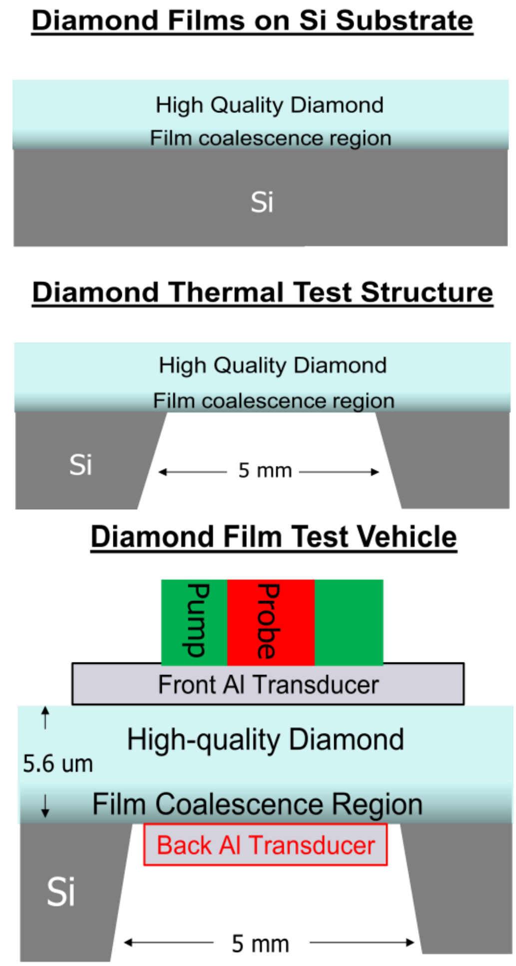

Fig. 3 Top: NCD diamond films grown on silicon substrates with 0.5, 1 and 5.6 um thickness. Middle: Selectively etched 5 mm wide windows in silicon substrate to form suspended diamond film. Bottom: Aluminum metal transducers deposited on both sides of the film for thermal measurements

RESULTS & DISCUSSIONS

Three diamond films of different thickness, 0.5, 1 and 5.6 microns, were measured using TDTR approach to better resolve the thermal characteristics of the films. TDTR of the thinnest, 0.5 micron, film was sensitive primarily to diamond heat capacity. The value measured was 1.98 MJ/m^{3}K. Measurements of the thickest, 5.6 micron, film are shown in Figure 4. A two layer model was fit to the measured results to extract characteristics of the low thermal conductivity film coalescence region and the high thermal conductivity bulk region. The best-fit model indicates a film coalescence region thickness of 760 nm with a thermal conductivity of 80 W/mK, leading to a total equivalent interface thermal resistance of 9.5 m^{2}K/GW. The bulk diamond region was found to have a thermal conductivity of 1340 W/mK through-plane and 965 W/mK in-plane.

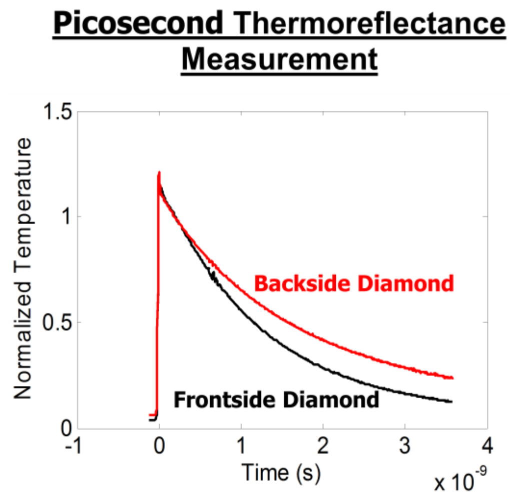

Fig. 4 Picosecond time domain thermal reflectance measurements of the front and backside for 5.6 micron thick CVD diamond film on Si substrate.

Several Si wafers were treated with different NCD seeding and diamond film growth conditions to explore methods for reducing thermal resistance of the diamond film coalescence region while improving the bulk film conductivity. In Figure 5 results from TDTR measurements from 5.6 um thick CVD diamond films with baseline growth conditions vs. the optimized high κ growth process are shown. The optimized growth conditions demonstrate a drastic improvement in thermal properties for the high κ process. The thermal conductivity increased from 80 (±10)

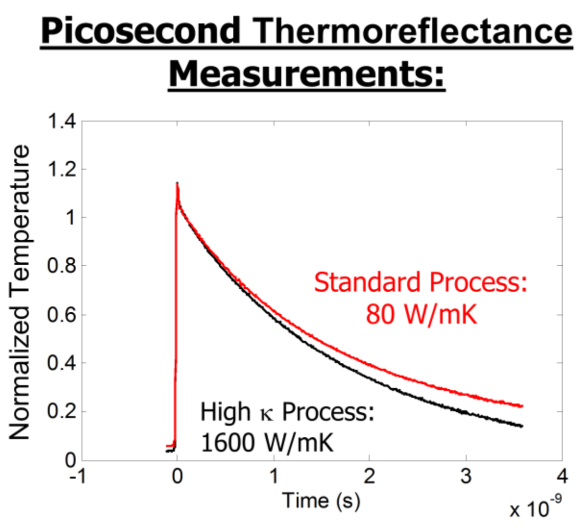

Fig. 5 Picosecond time domain thermal reflectance measurements of 5.6 micron thick CVD diamond films on Si substrates with varying growth conditions.

to 1600 (±300) W/mK in the diamond film coalescence region with the high κ process. Also the bulk film thermal conductivity was indistinguishable from the 'bulk' thin-film conductivity1600 (±300) W/mK for the high κ process.

CONCLUSIONS

Selective etching of Si substrates to stop on diamond films combined with innovative picosecond pulsed thermal characterization methods has allowed for depth resolved thermal characterization of high thermal conductivity diamond films. The investigation of advanced diamond seeding methods with optimized growth parameters has demonstrated diamond films with 1600 W/mK thermal conductivities for the film coalescence and bulk regions. The measurement results of this work report high thermal conductivity diamond within thickness less than 5 um. The results from this work demonstrated direct diamond growth as a promising approach for near junction heat removal of GaN HEMT devices.

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ACRONYMS

CVD: Chemical Vapor Deposition
HEMT: High Electron Mobility Transistor
MMIC: Monolithic Microwave Integrated Circuit
NCD: Nano-Crystalline Diamond
TDTR: Time Domain Thermal Reflectance