Thermal Characterization of Mono and Multilayer Hexagonal Boron Nitride Heat Spreaders

Nur Julia Nazim Bulya Nazim
Universiti Teknologi Malaysia
Kuala Lumpur, Malaysia
nurjulianazim@graduate.utm.my

Mohd Faizol Abdullah
MIMOS Semiconductor (M) Sdn Bhd
Kuala Lumpur, Malaysia
faizol.abdullah@mimos.my

Mohd Rofei Mat Hussin
MIMOS Semiconductor (M) Sdn Bhd
Kuala Lumpur, Malaysia
rofei@mimos.my

Siti Aishah Mohamad Badaruddin
MIMOS Semiconductor (M) Sdn Bhd
Kuala Lumpur, Malaysia
aishahb@mimos.my

Muhamad Amri Ismail
MIMOS Semiconductor (M) Sdn Bhd
Kuala Lumpur, Malaysia
amris@mimos.my

Abdul Manaf Hashim
Universiti Teknologi Malaysia
Kuala Lumpur, Malaysia
abdmanaf@utm.my

Abstract—This article investigates the optimum number of hexagonal boron nitride (hBN) layers for the heat spreading application. The multilayer hBN films (up to 12L) are obtained by multiple wet transfers of monolayer hBN onto the Pt/Cu/Ti coil. The thickening of the hBN layer on the coil is verified based on optical microscopy images. Three figures of merit (FoM) are introduced; FoM 1 for the hotspot during transient-state (TS) Joule heating, FoM 2 for the hotspot during steady-state (SS) Joule heating, and FoM 3 for the lateral thermal resistance, \( \Theta \) also during the SS Joule heating. Based on the TS Joule heating analysis, 6L hBN was optimum for the hotspot reduction with FoM 1 of -22%. Based on the SS Joule heating, 7L hBN was optimum for the hotspot reduction with FoM 2 of -18.5%. The reduction in \( \Theta \) during the SS Joule heating is acceptably good when wet transferred hBN thickened up to 5L with FoM 3 of -35.4%.

Keywords—2D heat spreader, hBN, thermal characterization

I. INTRODUCTION

Hexagonal boron nitride (hBN) is a family member of two-dimensional (2D) materials. Monolayer hBN is an electrical insulator with a wide bandgap, \( E_g \) of 5.955 eV [1], and it is a good thermal conductor with thermal conductivity, \( \kappa \), up to 751 Wm\(^{-1}\)K\(^{-1}\) at room temperature [2]. The remarkably high \( \kappa \) from the electrically insulating hBN is attributed to its covalent B-N \( sp^2 \) bonding, which allows acoustic phonons to effectively carry the heat. Both properties speculated the perfect function of hBN as an on-chip direct-contact heat spreader for power electronics [3]. The function of hBN as a 2D heat spreader is slightly different compared to the conventional bulk heat spreaders, e.g. diamond, Cu, etc. The integration of a 2D heat spreader is objectively to carry heat from the hotspot to the nearest heat sinks, which are typically the local metalized areas on the chip (after the front-end-of-line process).

In actual application, hBN needs to be sufficiently thick to halt the tunneling current, which eventually will lead to short circuit complications in the device. Although \( \kappa \) values of 2D materials dropped when the number of layers increased, it did not prove the inferior heat spreading performance of the multilayer hBN. The thermal conductance is linearly dependent on the thickness of the heat spreader (mixed contribution of in-plane and out-of-plane thermal conductivity). A recent study highlighted the tradeoff between thickness and heat-carrying performance of hBN [4]. In this brief report, we discuss the heat spreading performance of mono and multilayer hBN. We precisely control the number of hBN layers by wet transfer and forming the van der Waals-layered films on the pre-fabricated thermal test structure.

II. EXPERIMENTAL

The thermal characterization for hotspot and heat spreader was using a Pt/Cu/Ti micro-coil [5]. It was pre-fabricated using a standard lithography, metallization, and lift-off processes on SiO\(_2\)/Si (500 nm-thick SiO\(_2\)) substrate. The commercial monolayer hBN on Cu foil was obtained from ACS Material. We form an hBN heat spreader on a thermal test structure by a wet transfer process using polymethyl methacrylate (PMMA) as a carrier film. A single wet transfer resulted in a single layer (1L) hBN and the process was repeated until twelve layers (12L) hBN. The presence of hBN was verified using the fixed angle of 75° spectroscopic ellipsometry (SE) system (Semilab SE-2000). The morphologies of the hBN films-coated coil were investigated using an optical microscopy system (ZEISS LSM 800). Thermal characterization of the hBN heat spreader was using a four-wire Kelvin measurement. The

![Fig. 1](image-url) (a) Ellipsometry responses from the transferred 1L hBN film, and (b) extracted Tauc plot. Next are surfaces of 1L hBN on: (c) Cu foil, and (d) SiO\(_2\)/Si after wet transfer process.
thermal test setup consists of a probe chamber (NEXTRON mini probe station), a source meter (Keithley 2410), and an infrared (IR) thermal imaging camera (FLIR ETS320). More on the characterization method can be found elsewhere [6].

III. RESULTS AND DISCUSSION

The use of SE to verify the presence of hBN is an alternative method for Raman spectroscopy [7]. Often, the fingerprint of 1L hBN from Raman spectra is quite challenging to be observed due to the lack of interaction between the laser and the hBN [8]. Fig. 1a plots the SE responses in terms of \( \Psi(E) \) and \( \Delta(E) \) of 1L hBN on SiO\(_2\)/Si. The optical model was using a Tauc-Lorentz dispersion law [9]. It results in high fitting quality with R\(^2\) above 0.994. The thickness of 1L hBN was 0.333 nm. Fig. 1b is the Tauc plot for the 1L hBN, where the \( E_g \) was 5.96 ± 0.002 eV. The limitation of hBN verification using SE is that it cannot be done on Cu substrate. Hence we can only observe the surface condition of the 1L hBN on Cu foil as in Fig. 1c, while Fig. 1d shows the surface of 1L hBN on SiO\(_2\)/Si. The fitting of the optical model also suggests the thickness of PMMA residue (on hBN) was 3.31 ± 0.11 nm and air-void (under hBN) was 3.37 ± 0.06 nm.

The fabricated thermal test structure works both as a heater and a resistance thermometer. The calibration of the coil as a resistance thermometer was carried out using a controllable stage temperature, \( T_{\text{stage}} \) and IR thermometer. Fig. 2a is the temperature-resistance profile of the coil to determine the base temperature, \( T_0 \) and base resistance, \( R_0 \). The base point can be set at any reference temperature, e.g. at \( T_0 = 0 \) °C (\( R_0 \) is the intersection at the y-axis). Fig. 2b shows the plot of \( (R_\text{coil} - R_0)/R_0 \) against \( T_{\text{coil}} - T_0 \), where \( R_\text{coil} \) and \( T_{\text{coil}} \) are the coil resistance and temperature, respectively. The slope of this plot can be referred as the temperature coefficient of resistance, \( \alpha \) of the coil. For this device, the extracted value of \( \alpha \) was approximately 0.00637 K\(^{-1}\) and the same device will be used to evaluate the multilayer of hBN heat spreaders. Fig. 2c and 2d compare the photos of bare coil and coil with a maximum of 12L hBN heat spreader, respectively. The area of the central coil was 5 × 5 mm\(^2\) and the size of the hBN heat spreader needs to be larger than 7 × 7 mm\(^2\) to effectively bridge the heat between the central coil to the peripheral heat sinks. The central coil will act as a hotspot for this system and the metals will act as heat sinks (with heat sink temperature, \( T_{\text{sink}} \)).

The quality of the hBN wet transfer process was observed based on the coverage of hBN on the coil. Fig. 3a – 3l show the surfaces of hBN films-coated coil for the 1L – 12L hBN, respectively. It is noticeable that the contrast changed for each wet transfer of hBN and the coil appeared darker for the thickened hBN heat spreader. The grains of the polycrystalline hBN unfortunately were too vague to be distinguished. We found several stripes of residual PMMA on the wet transfer hBN and they may influence the performance of the hBN heat spreader. The transient-state...
(TS) Joule heating analysis was carried out by six-times cycling of $P_{coil}$ and the $T_{stage}$ was fixed at 30 °C to enable cooling of the coil during the removal of $P_{coil}$. Fig. 4a and 4b compare the temperature-power ($T$-$P$) profile of the coil with and without a 1L hBN heat spreader, respectively during the TS Joule heating. During the cycle, the coil withdraws ~8 W of dc power and the bare coil can reach up to 41.5 °C during the peak power. The presence of 1L hBN spread the heat on the thermal test structure and reduced the peak temperature down to 36 °C. The heating of $T_{coil}$ during the TS Joule heating can be translated into a form of $\frac{dT_{coil}}{dP_{coil}}$.

Fig. 4c and 4d show the heating of the $T_{coil}$ against time at the first heating cycle for the coil with and without a 1L hBN heat spreader, respectively during the TS Joule heating. During the cycle, the coil withdrawing ~8 W of dc power and the bare coil can reach up to 41.5 °C during the peak power. The presence of 1L hBN spread the heat on the thermal test structure and reduced the peak temperature down to 36 °C. The heating of $T_{coil}$ during the TS Joule heating can be translated into a form of $\frac{dT_{coil}}{dP_{coil}}$.

We introduce the second figure of merit (FoM 2) as the changes in $\frac{dT_{coil}}{dP_{coil}}$ during the SS Joule heating. Fig. 5c shows the changes in FoM 2 for the multiple wet transfers of hBN up to 12L. There is a clear trend in hotspot reduction for the thickening of the hBN heat spreader. In this case, 7L hBN is optimum for ~19.5% hotspot reduction, and further thickening results in inferior performance. The third figure of merit (FoM 3) is proper to quantify the changes in $T_{coil}$ during the SS Joule heating. Similarly, Fig. 5d tracks the changes in FoM 3 for the multiple wet transfers of hBN up to 12L. We found thickening of the hBN heat spreader for 5L was optimum for lowering the $\theta$ by approximately -35.4%. Even though the thicker hBN is expected to have a higher heat carrying capacity, our findings advise the wet transfer hBN should not be more than 9L to avoid degradation in FoM 3. The thermographs of bare coil and coil with optimum 7L hBN heat spreader (based on FoM 2) during SS Joule heating are provided in Fig. 6a – 6l. Nevertheless, the findings from the analysis of SS and TS Joule heatings may only be applicable for the case of turbostratic multilayer hBN. Our approach of multiple wet transfers cannot guarantee a Bernal stacking of each hBN layer.
Fig. 5 Steady-state Joule heating of: (a) bare coil, and (b) coil with 1L hBN heat spreader. Next is the heat spreading performance of multilayer hBN in terms of: (c) FoM 2, and (d) FoM 3.

Fig. 6 Thermographs of device during steady-state Joule heating at: (a) 10 V, (b) 12 V, (c) 14 V, (d) 16 V, (e) 18 V, and (f) 20 V applied bias on the bare coil. Next are the thermographs for the coil with optimum 7L hBN heat spreader at: (g) 10 V, (h) 12 V, (i) 14 V, (j) 16 V, (k) 18 V, and (l) 20 V.

IV. CONCLUSION

Based on the TS Joule heating, 6L hBN was optimum for the hotspot reduction as it demonstrated the highest FoM 1. Based on the SS Joule heating, 7L hBN was optimum for the hotspot reduction as it demonstrated the highest FoM 2. The reduction in $\Theta$ during the SS Joule heating was good when hBN is thickened up to 5L according to FoM 3. In conclusion, we recommend the suitability of 6L and 7L hBN (possibly mixed of turbostratic and Bernal-stacked films) for the 2D heat spreading application.

V. REFERENCES