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Thermal characterization of MBE-grown GaN/AlGaN/GaN device on single crystalline diamond

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Self-heating effects in a molecular beam epitaxy-grown GaN/AlGaN/GaN structure on a single crystalline diamond is investigated. A transient interferometric method, in combination with a three dimensional model, is used to describe a pulsed operation of a transistor-like heater, and a micro-Raman technique is used in a steady state. Good agreement is found between the techniques. The thermal conductivity of the diamond is found to be 2200 W/m K, and the thermal boundary resistance to the III-N epi-structure is $< 1 \times 10^{-8}$ m^2 K/W. The excellent cooling efficiency of the diamond is manifested by the fast saturation of the temperature at 1 μs and by a record low normalized thermal resistance of 3.5 K mm/W. © *2011 American Institute of Physics*. [doi:10.1063/1.3581032]

As the power density of state-of-the-art GaN-based amplifiers increases, device cooling and heat removal into a substrate becomes crucial. The material parameters of the substrate, such as thermal conductivity, k, and the thermal boundary resistance (TBR) at the substrate/III-N junction determine the level of the device self-heating.[1] TBR may arise due to an acoustic mismatch at the junction[2] and reported TBR values for SiC and Si substrates range from 1×10^{-8} to 1×10^{-7} m^2 K/W (see Refs. 1, 3 and 4). With respect to k, diamond offers the highest value of up to 2200 W/m K [see Ref. 5] from all the known substrate alternatives. Consequently, using diamond may be the best choice to limit device self-heating. AlGaN/GaN HEMTs fabricated on the GaN buffer which was atomically attached to the diamond substrate was initially reported.[6] The first direct growth and electrical performance of AlGaN/GaN HEMTs on the single crystalline diamond has only recently been reported.[7] However, neither report analyzes the thermal performance of the devices. In the present study we investigate the thermal aspects of the GaN-based structures grown on the diamond.

A GaN/AlGaN/GaN heterostructure with a total thickness of 1.4 μm was grown on the single crystalline diamond supplied by Element Six Ltd. using a N-plasma MBE. A consecutively processed device is represented by a 50 μm wide heater which is composed of two ohmic contacts separated by a 3 μm channel ("ungated" transistor). We used an optical transient interferometric mapping technique (TIM) in combination with a three-dimensional thermal model[1,8] to investigate the transistor-like self-heating effects in the time domain. The optical signal of the TIM method is represented by the phase shift, $\Delta\varphi$, of a laser probing beam ($\lambda = 1.3$ μm), and $\Delta\varphi$ is proportional to the product of the dissipated heat and the material refractive index change with temperature dn/dT.[1,8] The heater is stressed by an 80 V rectangular pulse for 15 μs, giving us the dissipating power density, $P \sim 12.5$ W/mm. To extract the heater temperature increase, ΔT, in the channel and the thermal parameters of the diamond/GaN system (k_{diamond} and TBR), the model is fitted to the TIM optical signal. Next, the micro-Raman technique is used to measure T in the steady state as a function of P. We used a Labram system equipped with a 514 nm argon-ion laser and T is obtained from a calibrated GaN phonon frequency. The device thermal resistance, $R_{\mathrm{th}} = \Delta T/P$, normalized to the channel width, is extracted from both of these experimental methods.

To make the thermal model feasible, it was first necessary to determine dn/dT of the diamond. This was done by fitting the model to the optical signal under the conditions when the signal originates mostly from the diamond, i.e., for sufficiently long (100 μs) electrical pulses applied on the heater. Results of the procedure (not shown) indicate $(dn/dT)_{\mathrm{diamond}} = 8 \times 10^{-6}$ K^{-1} which is in good agreement with the data in the literature.[9] The relevant material parameters of GaN used in the model were: $(dn/dT)_{\mathrm{GaN}} = 4 \times 10^{-5}$ K^{-1} and $k_{\mathrm{GaN}} = 130$ W/m K [Ref. 1].

The time evolution of the experimental $\Delta\varphi$ in the middle of the device channel, which is compared with the model with the best fitting, is shown in Fig. 1(a). Good agreement between the curves could be obtained for $k_{\mathrm{diamond}} = 2200$ W/m K without considering TBR. Inutility of the TBR indicates a low reflection of the heat at the III-N/diamond junction, despite the lattice-mismatch and inevitably low

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crystalline quality at the III-N/diamond junction. To establish the upper range of the possible TBR we calculated $\Delta\varphi$ for TBR $= 1 \times 10^{-8}$ m^2 K/W as shown in Fig. 1(b). A clear difference between the model and the experiment for this value allows us to suggest that TBR $< 1 \times 10^{-8}$ m^2 K/W.

The reason for an extremely low TBR is not known and may be unique to the diamond. Conversely, the heat reflection at the III-N/substrate junction is a complex effect depending upon various material parameters, as was recently pointed out.[2] As an example, for particular values of phonon group velocity and tangential correlation length and for a particular substrate choice, the transmission probability of the heat was shown to be alternatively insensitive, to decrease (at the GaN/SiC junction) or even increase (at the GaN/Si junction) with the roughness at the interface.[2]

In Fig. 2 we show the calculated time (t) evolution of the temperature in the heater for the two cases already analyzed, i.e., for (a) $k_{\text{diamond}} = 2200$ W/m K and TBR $= 1 \times 10^{-8}$ m^2 K/W, (b) $k_{\text{diamond}} = 2200$ W/m K and no TBR, and for (c) $k_{\text{diamond}} = 600$ W/m K and no TBR. We tested $k_{\text{diamond}} = 600$ W/m K which hypothetically corresponds to the poor quality diamond to see the impact of the substrate. Obviously, the lowest $\Delta T \sim 44$ K is obtained for case (b) which corresponds to our experiment. However, the difference between the cases became obvious only after about $t_1 = 100$ ns from the start of the pulse. Before that time instant, ΔT seems to be insensitive to the substrate quality as the heat wave only gradually penetrates to the substrate. Alternatively, at about $t_2 = 1$ μs the cooling effect from the substrate starts to dominate and ΔT saturates. While t_1 is obviously given by the thickness and k of the III-N epi-structure, the fast ΔT saturation at t_2 is due to the diamond substrate. This is also illustrated in the inset of Fig. 2 where we show our previous results (both experimental and the model) on a device grown on sapphire and dissipating about the same power density (11.9 W/mm).[10] No ΔT saturation can be observed for the sapphire substrate and ΔT steadily increases well above 200 K.

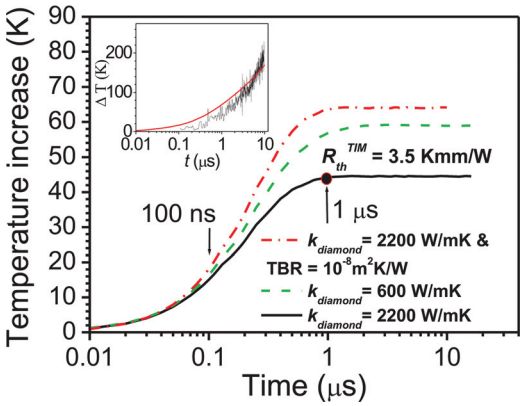

FIG. 2. (Color online) Calculated transient temperature increase in the middle of the heater channel for different diamond substrate parameters: $k_{\text{diamond}} = 2200$ W/mK and TBR $= 1 \times 10^{-8}$ m^2 K/W (upper curve), $k_{\text{diamond}} = 600$ W/mK and no TBR (middle curve), and $k_{\text{diamond}} = 2200$ W/mK and no TBR (curve on the bottom, corresponding to the parameters of the experiment). Arrows highlight 100 ns and 1 μs where $R_{\text{th}}^{\text{TIM}}$ is calculated for the experiment. Inset shows experimental and calculated ΔT for a device grown on sapphire (see Ref. 10).

Finally, in Fig. 3 we show steady-state ΔT values obtained for the GaN/diamond heater using our micro-Raman experiment which indicates that $R_{\text{th}}^{\text{Raman}} \sim 3.7$ K mm/W. The $R_{\text{th}}^{\text{Raman}}$ value can be correlated with the results of the TIM-related thermal model at the time instant when ΔT saturates. At $t_2 = 1$ μs, the TIM model (see Fig. 2) indicates $R_{\text{th}}^{\text{TIM}} \sim 3.5$ K mm/W. Thus the TIM experiment is in good agreement with the micro-Raman experiment. Additionally, in Fig. 3 we also show the values for an AlGaN/GaN/SiC HEMT reported by Simms *et al.*[11] Our values of R_{th} for the device grown on the diamond is less than half of what was obtained for the device grown on SiC.

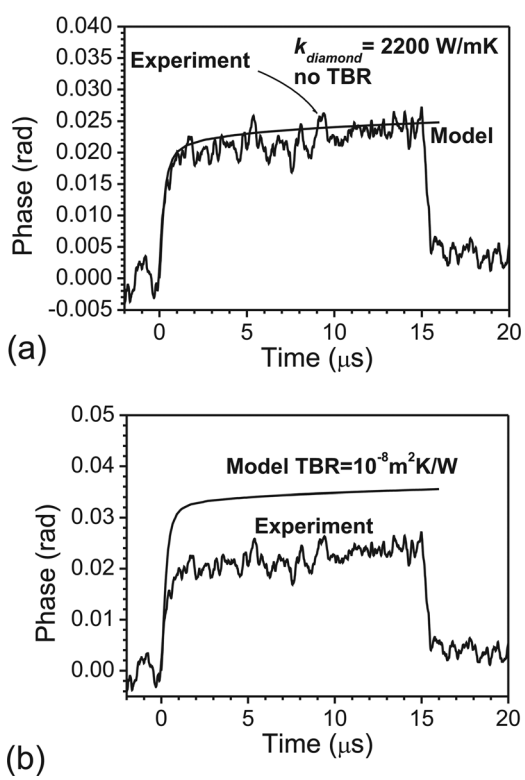

FIG. 1. Calculated and experimental TIM optical signal in the middle of the heater channel during a 15 μs electrical pulse. (a) Model is calculated to get the best fit and (b) for $k_{\text{diamond}} = 2200$ W/mK and TBR $= 1 \times 10^{-8}$ m^2 K/W.

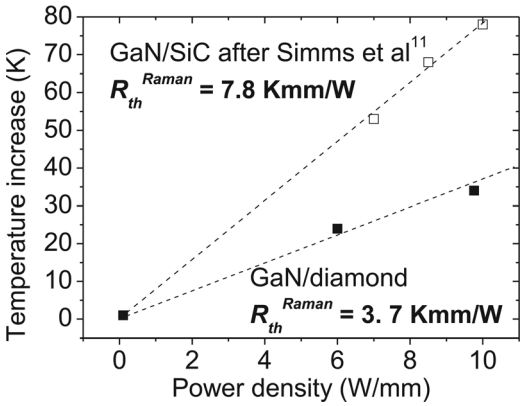

FIG. 3. Steady-state temperature increase obtained by the micro-Raman technique on the GaN/diamond transistor-like heater compared to the results on AlGaN/GaN/SiC HEMT reported by Simms *et al.* (Ref. 11).

We note that the precision of R_{th}^{TIM} and TBR extraction is limited by the simplifications introduced into the model, such as by the assumption of the isotropic k values, and by the limitations of the TIM method. A more precise value of the TBR could be expected by using 3-D confocal micro-Raman thermography.[4] Nevertheless, the coincidence between our TIM and micro-Raman experiments confirms the excellent efficiency of the heat transfer from GaN to the diamond.

In conclusion, using TIM, the three-dimensional thermal model, and the micro-Raman technique we analyzed the thermal behavior of the GaN-based device grown on the single crystalline diamond. Extremely high thermal conductivity of the diamond has been observed which, together with the negligible thermal boundary resistance, secures the unique cooling capability of the diamond substrate. The temperature increase in the device is already saturated after 1 μs from the start of the heat dissipation and we obtain the device normalized thermal resistance to be about 3.5 K mm/W. For GaN-based devices this is the lowest reported normalized thermal resistance ever.

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