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Laser lift-off transfer of AlGaN/GaN HEMTs from sapphire onto Si: A thermal perspective

Hangfeng Ji [a,*], Jo Das [b], Marianne Germain [b], Martin Kuball [a]

[a] H.H. Wills Physics Laboratory, University of Bristol, Bristol BS8 1TL, United Kingdom
[b] IMEC – NEXT, Kapeldreef 75, B-3001 Leuven, Belgium

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ABSTRACT

We report on the thermal study of AlGaN/GaN high electron mobility transistors (HEMTs) after substrate transfer from the original sapphire substrate onto Si using laser lift-off and metal bonding. Raman thermography determined a thermal resistance of about 8 °C/(W/mm) for these devices, which is similar to that for devices grown directly on Si substrates, and significantly improved over devices grown on sapphire substrates. The effective thermal boundary resistance between GaN and the new Si substrate was determined to be $(1.0–2.5) \times 10^{-8}\ m^2\ K/W$ at 145 °C, comparable to that in the GaN/Si system. These results illustrate that bonding layers between AlGaN/GaN HEMTs and the substrate can be as good as as-grown GaN/Si interfacial layers. This approach points to the potential benefit to devices transferred onto even higher thermal conductivity substrates such as diamond.

1. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) are very promising for radio-frequency (RF) applications where high power and high frequency are required [1]. Long time reliability of these devices remains a key concern, partially due to the high temperature within the device active area arising from Joule self-heating [2]. Therefore, proper and efficient thermal management is of great importance for reducing device failure rates. Since commercial bulk GaN substrates are currently not readily available, AlGaN/GaN HEMT devices are mostly grown on foreign substrates such as SiC and sapphire. Devices grown on sapphire substrates have the advantage of lower cost over devices grown on the more expensive SiC substrates. However, they have unsatisfactory thermal performance compared to devices on SiC, due to the relatively low thermal conductivity of sapphire ($\kappa \sim 35$ W/mK), although this can be improved using flip–chip mounting [3,4]. Compared to SiC ($\kappa \sim 350$ W/mK), diamond ($\kappa \sim 1200–1500$ W/mK) is an even higher thermal conductivity substrate, but direct GaN epitaxy on diamond is not a straightforward option. Transferring HEMTs onto highly thermally conductive substrates including diamond after the removal of the original substrate either by etching [5] or laser lift-off (LLO) [6,7] has been demonstrated, however, it is unclear at present how much the bonding layer, needed to attach the HEMT to the new heat sink, hinders heat transfer from the device into the substrate [7].

In this paper, as a model system, we study the thermal performance of AlGaN/GaN HEMTs transferred from sapphire onto Si, a higher thermal conductivity substrate ($\kappa \sim 150$ W/mK) than sapphire, using LLO and metal bonding processes. We compare their thermal performance to devices grown directly on Si substrates, and assess the effective thermal boundary resistance of the bonding layer. This substrate transfer approach also addresses the lattice mismatch between GaN and Si, which commonly has to be solved with superlattice or graded buffer layers [8]. Use of Raman thermography enabled assessing device peak temperature within the small device source–drain openings as spatial resolutions of better than 1 μm are required [9,10].

2. Experimental details

AlGaN/GaN heterostructures, with undoped 2.6 μm thick GaN buffer layer and 22 nm thick $Al_{0.3}Ga_{0.7}N$ layer, grown by metal organic chemical vapour deposition (MOCVD) on a sapphire substrate, were fabricated into HEMT devices. Standard Ti/Al/Ti/Au ohmic contacts were deposited by lift-off, and subsequently annealed at 850 °C for 60 s in N_2 ambient. Ni/Au gates and TiW/Au

* Corresponding author. Tel.: +44 117 928 8734.
E-mail addresses: hangfeng.ji@gmail.com (H. Ji), martin.kuball@bristol.ac.uk (M. Kuball).

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contact metals were also deposited. Finally, the devices were passivated with SiO_2. LLO transfer of the devices from the sapphire substrate onto the Si substrate was performed, as illustrated in Fig. 1. Firstly the processed wafer was bonded onto a temporary carrier using thermoplastic adhesive. Afterwards, the sapphire substrate was removed using LLO [6,11]: a 355 nm Nd:YAG pulsed laser was scanned over the sapphire substrate through its polished backside. After substrate removal, the wafer was diced into single HEMT devices which were then bonded onto a Si substrate (~300 μm thick) using Au/In/Au bonding layers. The metal bonding layers were deposited with thickness of 0.5/1.0/0.5 μm. Note that the bonding layer was deposited directly onto the GaN layer. For future applications it might be necessary to include diffusion barriers to prevent long term metal diffusion into the GaN buffer layer. We note alternative bonding layers such as a SU-8 layer were also investigated, however, were found to be less suitable, as the Au/In/Au metal bonding layer is a much better heat conductor, of benefit for efficient heat extraction from the device into the heat sink. The investigated HEMT devices had a total gate width of 100 or 150 μm. The source–gate and gate–drain openings were 1–2 μm and gate length of 2–2.5 μm. For comparison, temperature measurements were also performed on HEMT devices fabricated using similar LLO transfer processes but transferred onto a new sapphire substrate after the removal of its original sapphire substrate.

Thermal measurements were performed using Raman thermography, using the 488 nm line of an Argon ion laser as excitation source for the Raman measurements. This photon energy is below the GaN bandgap to prevent light absorption, i.e., the generation of electron–hole pairs in the device during the temperature measurements. Raman shift of the GaN E_2 phonon was probed to determine the temperature of powered devices, with 0.5–0.7 μm spatial resolution. Device peak temperature rise at different power densities was determined at the center of the gate-finger, on its drain side, where maximum temperature rise is present [9]. Only GaN Raman modes were visible from the LLO transferred devices, as the metal bonding layer blocks the incident laser beam. All measurements were performed with the devices thermally attached to a copper heat sink, kept at 25 °C using a Peltier cooled stage. More details on Raman thermography can be found in Ref. [9].

3. Results and discussion

Fig. 2 displays device peak temperature rise in an LLO transferred AlGaN/GaN HEMT onto Si, compared to AlGaN/GaN HEMTs directly grown on Si from Ref. [2]. LLO transfer from the original sapphire substrate onto Si reduces the device temperature significantly. Determined thermal resistances, i.e., temperature rise per

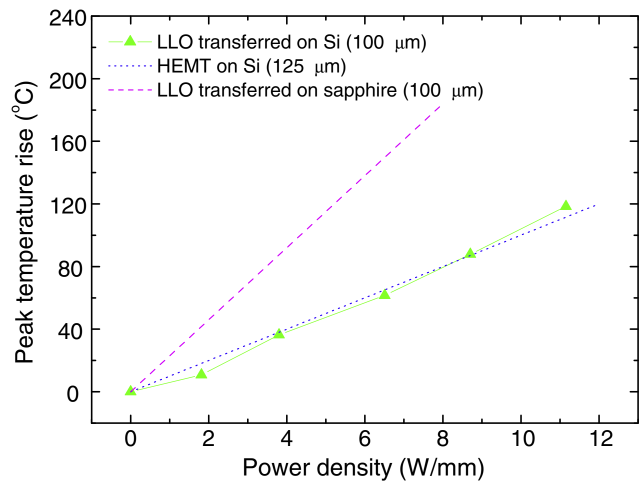

Fig. 2. Peak temperature rise in an LLO transferred AlGaN/GaN HEMT onto Si, compared to device directly grown on Si (from Ref. [2]). Results on an LLO transferred AlGaN/GaN HEMT onto a new sapphire substrate is also included. Gate width for all devices was 100 μm, apart from the device on Si which was 125 μm.

Table 1
Thermal resistance for different AlGaN/GaN HEMTs and TLM (transfer length method) structure. Gate lengths for HEMTs are given in parentheses.

Device structure	Thermal resistance [°C/(W/mm)]
LLO transferred on Si (100 μm)	~8
HEMT on Si (125 μm)	10[a]
LLO transferred on sapphire (100 μm)	~20
HEMT on sapphire (100 μm)	23[a]
TLM on Si	12[b]

[a] Ref. [2].
[b] Ref. [12].

power density, are given in Table 1. Thermal resistance of the LLO transferred HEMT on Si is as low as ~8 °C/(W/mm), comparable to that of the device grown directly onto a Si substrate. We note that GaN grown on Si does typically contain interfacial layers such as a graded AlGaN layer or superlattice structures which can increase thermal resistance near the interface. This results in a thermal boundary resistance (TBR), which was reported to be $3.3 \times 10^{-8}\ m^2\ K/W$ [12]. Using thermal analysis similar to Ref. [12], a TBR of $(1.0–2.5) \times 10^{-8}\ m^2\ K/W$ was determined for the bonding layer used here between the AlGaN/GaN HEMT and the Si heat sink. This is somewhat lower than the value reported in Ref. [12], but interface temperature was here 145 °C compared to 300 °C in Ref. [12], and TBR decreases with decreasing tempera-

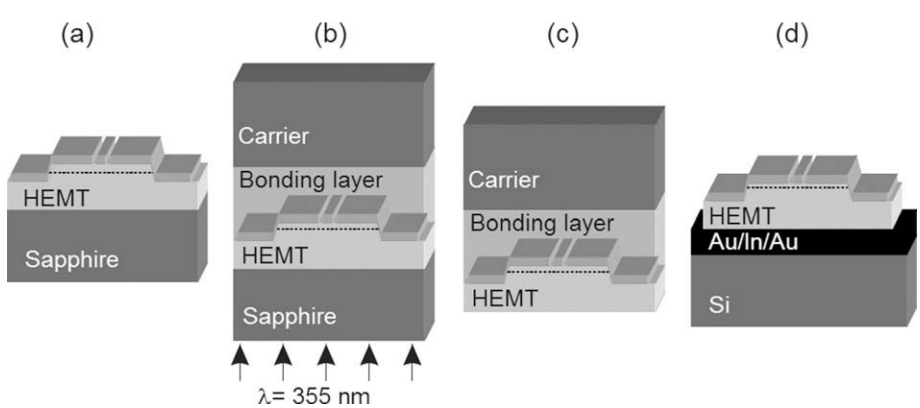

Fig. 1. Schematic of AlGaN/GaN HEMT LLO transfer process: (a) as-grown HEMT on sapphire substrate, (b) bonding to carrier and application of laser pulses to sapphire substrate backside, (c) removal of sapphire substrate, and (d) bonding to Si substrate and carrier removal.