The excellent performance of GaN materials including wide bandgap, high thermal conductivity, high electron saturation drift velocity makes it very suitable for the development of high-frequency, high-power microwave and millimeter-wave device and circuit applications. SiC material is presently a major choice to implement high-performance GaN HEMT due to its high thermal conductivity that is an order of magnitude greater than that of other materials such as sapphire. However, the heat dissipation issue appears more and more prominent with the development to direction of smaller size, greater output power and higher frequency. Therefore, to solve the degradation of device performance and reliability caused by heat dissipation, it is of utmost importance to reduce thermal resistance to get good thermal management.

Recently, GaN HEMT devices fabricated on diamond substrate (GaN-on-diamond) have been developed due to its high thermal conductivity (2000 W/m·K) that is three to four times that of SiC. The application of diamond substrate can significantly reduce the temperature rise of device, which is expected to solve the performance degeneration under conditions of high bias and power drive.

Accurate device model, especially physical model, is essential for predicting device performance and guiding process development. This paper discusses the comparison result of performance between GaN HEMTs fabricated on SiC and diamond substrates based on the SP model. The paper is organized as follows. In Device structure and fabrication section, the structure and fabrication process of GaN-on-Diamond HEMTs are described in detail. Then the 3D FEM model and SP model are described briefly in Thermal analysis setup and results section and SP model description for following performance verification and discussion in RF Performance verification section. Finally, Conclusion section is the conclusion.

Device Structure and Fabrication

The cross-section view of AlGaN/GaN HEMT on diamond substrate in this work and the under-gate energy-band diagram are shown in Fig. 1. It is fabricated on 500 μm diamond substrate. From bottom to top, the epitaxial layers are constituted by 1 nm AlN nucleation layer, 2 μm Fe-doped GaN buffer, 20 nm AlGaN barrier layer and 2 nm GaN cap layer. The Al-mole is 0.3 in AlGaN barrier layer. The gate is written by E-beam lithography. Gate-drain spacing (Lgd) and gate-source spacing (Lgs) are 2 μm and 1 μm, respectively. The each gate finger width Wg is 100 μm with gate number Ng = 2. Gate length L is 0.25 μm. The GaN-on-diamond device is first fabricated on epitaxial substrate (SiC) before being removed from the original substrate and bonded onto a high thermal-conductivity chemical vapor deposition (CVD) polycrystalline diamond substrate. Fig. 2 shows the details of low-temperature GaN-on-Diamond device substrate transfer process and each processing step is described as follow. Firstly, the GaN device wafer was inverted bonded onto a temporary carrier wafer. Then SiC substrate was removed using plasma etch process. The etched and chemical-mechanical polished (CMP) were further applied on the exposed bottom surface of the GaN epitaxial layer to reduce surface roughness to nanometer-level. After the preparation for wafer bonding, a thin layer of bonding adhesive was deposited on the GaN surface and the polished surface of diamond substrate. Finally, below the 150°C temperature, the two sides were brought into contact and subsequent curing was performed. The bonding temperature, pressure and time conditions are optimized to solve the problem of poor bonding quality and the epitaxial layer detachment after transfer process due to the thickness of bonding layer is too thin.
Thermal Analysis Setup and Results

The channel temperature has a significant influence on the device reliability and performance and several reports have investigated the temperature effect on devices, such as the variation of dc and equivalent circuit parameters with temperature, the dependence of small and large signal output characteristics on temperature. Since temperature rise of a power transistor is mainly dependent on the thermal conductivity of internal material, the application of high thermal conductivity diamond material can reduce device thermal resistance remarkably, making device more cooler, reliable and efficient even at increased power dissipation.

In this work, 3D electro-thermal finite element modeling is performed using ANSYS (v.15.0) to compare thermal performance of novel GaN-on-Diamond process to that of conventional GaN-on-SiC technology, due to its advantages of more convenience, better accuracy and time-saving. Compared with other approaches which set thermal resistance $R_{th}$ as a constant or linear function of dissipated power $P_{diss}$, it is more reasonable to perform the relationship between $R_{th}$ and $P_{diss}$ as a nonlinear function which is helpful to establish more accurate device model. In order to simplify the FEM simulation, only the main layers including 20 nm AlGaN barrier layer, 2 $\mu$m GaN buffer layer and 500 $\mu$m diamond substrate are investigated, since other layers (e.g., space layer) are considered too thin to affect thermal conduction within the device. And the temperature dependent heat conductivities of main layers materials are expressed as

$$K_{AlGaN}(T) = 30 \cdot \left(\frac{T}{300}\right)^{-1.5} (W/m \cdot K)$$  \[1\]

$$K_{GaN}(T) = 160 \cdot \left(\frac{T}{300}\right)^{-1.4} (W/m \cdot K)$$  \[2\]

$$K_{Diamond}(T) = 2000 \cdot \left(\frac{T}{300}\right)^{-1.15} (W/m \cdot K)$$  \[3\]

Fig. 3 shows the temperature profiles for $2 \times 100$ $\mu$m GaN-on-Diamond and $4 \times 50$ $\mu$m GaN-on-SiC HEMTs with 0.8 W heat load. The GaN-on-Diamond HEMT achieved a 15°C lower channel temperature than SiC substrate with same heat flux. The relationship between channel temperature increment $\Delta T$, thermal resistance $R_{th}$ and dissipated power $P_{diss}$ can be described as $\Delta T = R_{th} \cdot P_{diss}$. 

![Figure 2. Fabrication flow for GaN-on-diamond devices using low-temperature substrate bonding technology.](image-url)
Figure 3. Thermal conduction temperature contours of modeled (a) $2 \times 100 \ \mu m$ GaN-on-Diamond HEMT; (b) $4 \times 50 \ \mu m$ GaN-on-SiC HEMT. Module baseplate temperature is 300 K.

Fig. 4 shows that the $\Delta T$ and thermal resistance $R_{th}$ increases with the $P_{diss}$, which can be attributed to the nonlinear thermal conductivity of the device with respect to the temperature. Moreover, it is obvious that GaN-on-diamond device achieves lower temperature and thermal resistance compared to that on SiC. This thermal improvement is a direct result of better heat spreading in diamond. The relationship function between $R_{th}$ and $P_{diss}$ in Fig. 4b can be expressed through three-order polynomial as

$$R_{th}(P_{diss}) = \sum_{i=0}^{3} k_i P_{diss}^i, \quad i = 0, 1, 2, 3$$  \[4\]

**SP Model Description**

Many research works on GaN HEMTs equivalent circuit modeling and parameter-extraction method have been done in the past decade. Moreover, the major influence of trap and thermal effects on the device performance has been studied and discussed.

In this paper, the large signal equivalent circuit topology of proposed model is shown in Fig. 5. The interior of red box is intrinsic part, and exterior is the parasitic part. The parasitic elements are developed based on the analytic SP solution. The accurate and analytical calculation of SP and core models in all regions of device operation for GaN HEMTs was presented in our earlier paper. For the sake of completeness, the core $I_d$ model derivation is described briefly here. The drift-diffusion model is applied to describe carrier transport process. Under the assumption of the gradual channel approximation, the drain current can be obtained...
Table I. The extracted parasitic parameters for the $2 \times 100 \mu m$ GaN-on-diamond device.

| Parameter | Value   |
|-----------|---------|
| $C_{pdg}$ | 13.97 fF |
| $C_{pg}$  | 0.30 fF  |
| $C_{pd}$  | 0.37 fF  |
| $L_{g1}$  | 0.016 pH  |
| $L_{g2}$  | 98.16 pH |
| $L_{d1}$  | 0.081 pH |
| $L_{d2}$  | 77.76 pH |
| $L_s$     | 7.60 pH  |
| $R_s$     | 4.88 Ω   |
| $R_d$     | 4.72 Ω   |
| $R$       | 0.03 Ω   |

Table II. Parameter values used in the model.

| Parameter | Description | Value     |
|-----------|-------------|-----------|
| $W$       | Gate width ($\mu m$) $W = W_g \times N_g$ | 200       |
| $L$       | Gate length ($\mu m$) | 0.20      |
| $d_d$     | Doped AlGaN layer thickness (nm) | 0         |
| $d_s$     | Undoped AlGaN spacer layer thickness (nm) | 20        |
| $N_d$     | Doping concentration of the n-AlGaN layer (cm$^{-3}$) | 0         |
| $x_{Al}$  | Al mole fraction | 0.3       |
| $\varepsilon(x_{Al})$ | Permittivity of the AlGaN layer (F/m) | 9.12e-11  |
| $\phi_B(x_{Al})$ | Schottky barrier height(V) | 1.23      |
| $\Delta E_C(x_{Al})$ | Conduction band offset at the AlGaN/GaN interface(V) | 0.422     |
| $\sigma(x_{Al})$ | Polarization charge density (cm$^{-2}$) | 1.1e13    |
| $v_s$     | Saturation velocity (m/s) | 1.2e5     |
| $v_T$     | Thermal voltage(V) $v_T = kT/q$ | 0.026     |
| $\lambda$ | Channel length modulation parameter (1/V) | 1.0e-6    |
| $\eta$   | Temperature dependence of mobility(K) | 6.0e2     |
| $\mu_1$  | Low-field mobility (m$^2$/V·s) | 0.035     |
| $m_1$     | Mobility degradation coefficient first order(1/V) | 20.0e-7 |
| $m_2$     | Mobility degradation coefficient second order(1/V$^2$) | 15.0e-14 |
| $T_0$     | Ambient temperature (K) | 300       |

Figure 6. Measured (circles) and simulated (lines) I-V characteristics with SHE for (a) $V_{ds} = 0$ V to 35 V with step 1 V and $V_{gs} = -3.4$ V to 0 V, 0.2 V step from bottom to up of GaN-on-Diamond HEMT; (b) $V_{ds} = 0$ V to 35 V with step 1 V and $V_{gs} = -4$ V to 0 V, 0.2 V step of GaN-on-SiC HEMT (c) Transfer characteristics of two devices (d) Transconductance $g_m$ of two devices.
after integrating from source to drain,
\[ I_{ds0} = \frac{W}{L} \frac{\mu_{ss} C_0}{\delta} (v_{gs} + v_T - \phi_{oa})(\phi_{oa} - \phi_{sd})(1 + \lambda V_{ds}) \]  

\[ V_{th} = \varphi_B(x, \lambda) - \Delta E_C(x, \lambda) - \frac{q N_d d_d^2}{2\varepsilon(x)} = \frac{q s(x)}{\varepsilon(x)} (d_d + d_i) \]

where \( W \) and \( L \) are gate width and gate length, \( C_0 = \varepsilon(x)/d \) with dielectric constant \( \varepsilon(x) \), thickness of AlGaN barrier layer \( d = d_d + d_i \) and Al mole content \( x_{Al} \), \( v_{gs} = V_{gs} - V_n \) with \( V_n \) gate source voltage. \( v_{gs} \) is the threshold voltage expressed as (6) with Schottky barrier height \( \varphi_B \), doping concentration of n-AlGaN layer \( N_d \), polarization induced charge density at the interface \( \sigma \) and the conduction band offset at \( x_{Al} \), Al mole content \( x_{Al} \). \( \Delta E_C \) is the threshold voltage expressed as (6) with Schottky barrier height \( \varphi_B \), doping concentration of n-AlGaN layer \( N_d \), polarization induced charge density at the interface \( \sigma \) and the conduction band offset at \( x_{Al} \), Al mole content \( x_{Al} \). The drain current expression including self-heating effect is
\[ \mu(T) = \mu_{ss}(T_0/T)^\eta 
\approx \mu_{ss} [1 + \eta (1 - T/ T_0)] \]

\[ \mu_{ss} = \mu_1 \frac{1 + m_1 E_V + m_2 E_V^2}{1 + m_2 E_V^2} \]

where \( \eta = 6 \times 10^2 \) K for good approximation, \( \mu_{ss} \) is the original temperature-independent effective carrier mobility, \( \mu_1 \) is the low field mobility, \( m_1 \) and \( m_2 \) are fitting parameters to be extracted from experimental data to model the vertical field dependence of carrier mobility, \( E_V \) is the effective vertical electric field indicated as \( E_V = \varepsilon(x_{Al})/\delta \). Finally, through substituting (7) into (5), the final drain current expression including self-heating effect is
\[ I_{ds} = \frac{2 B \pm \sqrt{B^2 - 4AC}}{2A} \]

where \( A = V_d R_{th}, B = T_0 + [m(\eta/\eta_0) - 1]I_{i00}V_{ds}R_{th}, C = -T_0 I_{i00} \). The terminal charge model and nonlinear gate capacitances \( C_{gg0} \) and \( C_{gd0} \) adopted in this work can be obtained by following D.E. Ward channel charge assigning principle. The definitions and values of related model parameters are given in Table II.

Therefore, the DC-IV characteristics with self-heating effect of two devices are shown in Figs. 6a, 6b. The excellent agreement between model and measurement confirms the model effectiveness to predict AlGaN/GaN power HEMT DC behavior. Fig. 6c shows the comparison of transfer characteristics for these two devices. Threshold voltage \( V_n \) of GaN-on-diamond device drifts slightly to the forward direction compared to the GaN-on-SiC likely due to the decreasing of interface polarization induced charge density \( \sigma \) after transfer process. The drain current of GaN-on-diamond appears larger than that on SiC with the increasing \( V_{ds} \) indicating the lower self heating effect in GaN-on-diamond device. The \( g_m \) of GaN-on-diamond is also larger than that on SiC shown as Fig. 6d due to the thermal improvement which results in better gate controlling capability of device. However, there still exhibits negative output resistance in saturation region (Fig. 6a) in GaN-on-diamond HEMTs despite heat dissipation is improved, which likely due to the large number of dislocation defects in epilayer caused by relatively high lattice mismatch between diamond substrate and GaN material rather than heating effects.

**RF Performance Verification**

The developed model is embedded into Keysight Advance Design Systems (ADS v.2013) by using the Symbolically Defined Devices.
are listed at Table III. In addition, the large-signal performance of $4 \times 50 \mu m$ GaN-on-SiC device bias at $V_{ds} = 28 \text{ V}$, $V_{gs} = -2.5 \text{ V}$ is also incorporated, shown as Fig. 9c. Furthermore, to study the large signal performance difference of these two devices, the simulated results of $2 \times 100 \mu m$ GaN-on-Diamond HEMT is collected under identical bias ($V_{gs} = -2.5 \text{ V}, V_{ds} = 28 \text{ V}$) at 10 GHz, shown as Fig. 10. The large-signal load-pull simulation is performed as shown in Fig. 10a. Fig. 10b shows the device on SiC exhibits typical performance of 5.56 W/mm, 56.44% and 14.23 dB. The GaN-on-Diamond device averaged lower at 5.15 W/mm and 51.02% and 13.05 dB. The GaN-on-diamond HEMT appears slightly inferior performance. The reason can be attributed to the $V_{th}$ forward shift caused by relatively serious charge-trapping effect which is introduced in the transfer process. Therefore, the relatively lower current density is observed near the operation bias point which limits the output performance compared to the devices on GaN-on-SiC. Therefore, future work on the improvement of epi material quality needs to be ongoing.

Table III. (a) The optimal source and load impedances bias at $V_{GS} = -2.15 \text{ V}, V_{DS} = 20 \text{ V}$. (b) The optimal source and load impedances bias at $V_{GS} = -2.5 \text{ V}, V_{DS} = 28 \text{ V}$.

| Gate width(μm) | Source        | Load          |
|---------------|---------------|---------------|
| $2 \times 100 \mu m$ GaN-on-Diamond(@6 GHz) | $Z_s = 20.45 + j55.28 \Omega$ | $Z_l = 108.21 + j76.30 \Omega$ |
| $2 \times 100 \mu m$ GaN-on-Diamond(@10 GHz) | $Z_s = 9.70 + j29.50 \Omega$ | $Z_l = 71.34 + j81.10 \Omega$ |
| $4 \times 50 \mu m$ GaN-on-SiC(@10 GHz) | $Z_s = 10.51 + j21.18 \Omega$ | $Z_l = 43.12 + j98.23 \Omega$ |
| $2 \times 100 \mu m$ GaN-on-Diamond(@10 GHz) | $Z_s = 9.70 + j29.50 \Omega$ | $Z_l = 47.65 + j107.4 \Omega$ |
Conclusions

In this paper, performance comparison between $2 \times 100 \, \mu\text{m}$ GaN-on-Diamond HEMT and $4 \times 50 \, \mu\text{m}$ GaN-on-SiC HEMT is discussed based on the surface potential model. Through 3D FEM simulation, it is demonstrated that the heating dissipation is significantly improved for GaN-on-Diamond HEMT device and the thermal resistances are extracted for following modeling. The effectiveness and accuracy of SP model are validated through compared with measured DC-IV and RF performance. Then based on the SP model, the large signal performance between GaN-on-Diamond and GaN-on-SiC HEMTs are compared and discussed under identical bias and thermal

Figure 9. Single-tone power sweep simulations (lines) and measurements (symbols) for power characteristics ($P_{\text{out}}$, Gain and $P_{\text{AE}}$ versus input power $P_{\text{in}}$) (a) (b) $2 \times 100 \, \mu\text{m}$ GaN-on-Diamond HEMT(@6 GHz and 10 GHz) bias at $V_{\text{gs}} = -2.15 \, \text{V}$, $V_{\text{ds}} = 20 \, \text{V}$. (c) $4 \times 50 \, \mu\text{m}$ GaN-on-SiC HEMT(@10 GHz) bias at $V_{\text{gs}} = -2.5 \, \text{V}$, $V_{\text{ds}} = 28 \, \text{V}$.

Figure 10. (a) Loadpull simulation results and (b) Comparison of large-signal characteristics between $2 \times 100 \, \mu\text{m}$ GaN-on-Diamond and $4 \times 50 \, \mu\text{m}$ GaN-on-SiC HEMTs for $V_{\text{gs}} = -2.5 \, \text{V}$, $V_{\text{ds}} = 28 \, \text{V}$ at 10 GHz.
conditions. The results show that accurate predictions by using the proposed large-signal model are achieved. The future development direction of GaN-on-Diamond HEMTs still work on the reduction of lattice mismatch rate during transfer process to improve epi layer properties.

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