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## High-power and efficiency W-band InAlGaN/AlN/GaN high-electron-mobility transistors for future high-capacity wireless communications

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This study describes high-power and high-efficiency W-band InAlGaN/AlN/GaN high-electron-mobility transistors (HEMTs) for future sub-terahertz wireless communications. A low-thermal-budget selective-area growth (SAG) process was developed to obtain low contact resistance with low trap states. Transmission lines and substrate structures were optimized to obtain high-thermal conductivity and low substrate resonance. Consequently, a high output power of 28.7 dBm (742 mW), output power density of 4.6 W mm<sup>-1</sup>, and power-added efficiency (PAE) of 28.0% were achieved with pre-matched InAlGaN/AlN/GaN HEMTs at 90 GHz, which were superior combination of output power and PAE compared to the conventional high-temperature SAG process. © 2024 The Author(s). Published on behalf of The Japan Society of Applied Physics by IOP Publishing Ltd

The rapid spread of smartphones and Internet-of-things devices has led to an ever-increasing data traffic.<sup>1)</sup> Expected use cases, i.e. extended reality, wireless robotics, fully autonomous vehicles/robotics, and telepresence, will demand extremely low latency, ultra-high reliability, and data rates for future wireless communications.<sup>2–4)</sup> Although the sub-6 GHz and millimeter-wave bands are specified as 5 G new radio (NR),<sup>5)</sup> the requirements of above use cases have not yet been met partially because of the limited bandwidth and number of channels. A sub-terahertz range (90–300 GHz) is abundant in unoccupied frequency resources and thereby can provide enormous network capacity.<sup>6)</sup> The 100 GHz band (e.g. 92–100 and 102–109.5 GHz, allocated for land mobiles and fixed wireless access by the International Telecommunication Union Radiocommunication Sector<sup>7)</sup>) is one of the expected frequency bands utilized for future wireless communication because their features include wider bandwidth than each of 5 G NR frequency bands<sup>8)</sup> and less atmospheric attenuation than upper sub-terahertz bands.<sup>9)</sup> However, compared with sub-6 GHz and millimeter-wave band PAs, the 100 GHz band is hindered by limited power amplifier (PA) performance.<sup>10)</sup> GaN-based high-electron-mobility transistors (HEMTs) are promising for their high-performance 100 GHz band PAs because they can realize high-voltage/high-current operations and high-frequency signal amplification simultaneously.<sup>11–13)</sup> Our group previously presented a high output power density of 3.6 W mm<sup>-1</sup> at 86 GHz by InAlGaN/AlN/GaN HEMTs and 4.6 W mm<sup>-1</sup> at 94 GHz by integrating a selective-area growth (SAG) ohmic contact and an InGaN back barrier;<sup>14,15)</sup> however, power-added efficiency (PAE) was below 15%, which must be improved for practical use. The PAE  $\eta_{\text{add}}$  with a class A operation can be expressed as follows:<sup>16)</sup>

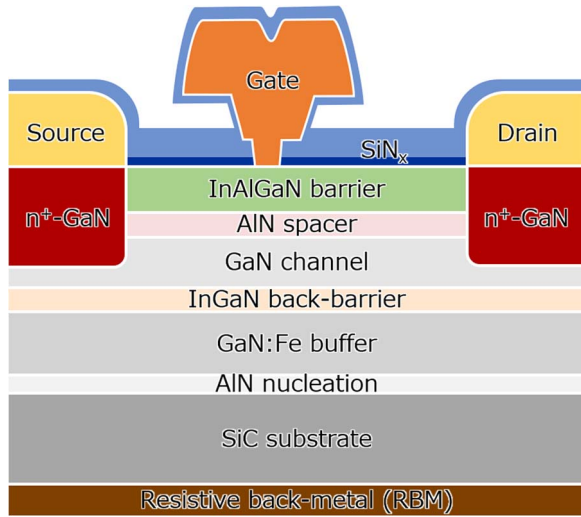
$$\eta_{\text{add}} = \eta_{\text{D}} \left( 1 - \frac{1}{G_{\text{P}}} \right) = \frac{1}{2} \left( 1 - \frac{V_{\text{min}}}{V_{\text{DS}}} \right) \left( 1 - \frac{1}{G_{\text{P}}} \right), \quad (1)$$

where  $\eta_{\text{D}}$  is the drain efficiency;  $G_{\text{P}}$  is the power gain,  $V_{\text{DS}}$  is the DC drain voltage, and  $V_{\text{min}}$  is the instantaneous minimum drain voltage under radiofrequency operation. The PAE can be affected by  $V_{\text{min}}/V_{\text{ds}}$  and power gain, and they are deteriorated by trap-related transient behavior, called current collapse. We confirmed that a high-temperature (HT) SAG process induced trap states and enhanced current collapse.<sup>17)</sup>

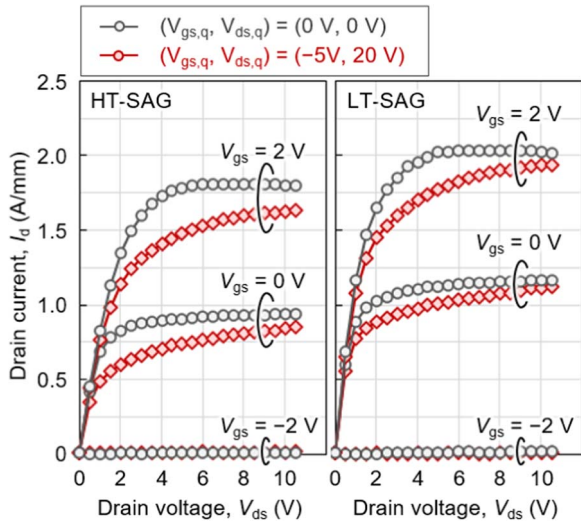
In the present study, high-power and high-efficiency W-band InAlGaN/AlN/GaN HEMTs with a low-thermal-budget (LT) SAG process were developed. The substrate structure was also optimized in terms of thermal management and propagation properties.

Figure 1 shows a schematic cross-section of InAlGaN/AlN/GaN HEMTs. The epitaxial structure was composed of one layer each of AlN nucleation, Fe-doped GaN buffer, InGaN back barrier, GaN channel, AlN spacer, and InAlGaN barrier, which were grown on a SiC substrate by metalorganic vapor phase epitaxy (MOVPE). The typical sheet resistance  $R_{\text{sh}}$ , carrier density  $n_{\text{s}}$ , and mobility  $\mu$  of epitaxial structures were 250  $\Omega$  sq<sup>-1</sup>,  $1.2 \times 10^{13}$  cm<sup>-2</sup>, and 2080 cm<sup>2</sup> V<sup>-1</sup> s<sup>-1</sup>, respectively. Device fabrication was initiated via electrical isolation of elements through ion implantation. Subsequently, a SiN<sub>x</sub> surface-protection layer was formed by plasma-enhanced chemical vapor deposition (PECVD), which acts as a mask for the subsequent SAG process. A part of SiN<sub>x</sub> mask and InAlGaN/AlN/GaN layers were removed through inductively coupled plasma reactive ion etching (ICP-RIE), and the n<sup>+</sup>-GaN was grown by MOVPE. In a previous study,<sup>15)</sup> the SiN<sub>x</sub> mask should be removed by wet chemical etching after the SAG process because a polycrystalline GaN was formed on a mask and the SiN<sub>x</sub> became defective after the SAG process because of the HT growth condition ( $\sim 750$  °C). In this study, the pattern layout and growth conditions were optimized for the LT-SAG process ( $\sim 630$  °C) without polycrystalline growth on the mask. Then, the Ti/Al metals were evaporated, and post-metallization annealing was conducted at 600 °C for 1 min, thus affording the source/drain electrodes with a typical contact resistance of 0.1  $\Omega$ ·mm. After the Ohmic contact formation, the second passivation layer was formed by PECVD. The gate footprint was defined by electron beam lithography, and the exposed SiN was removed through ICP-RIE. The Ni/Au-based gate electrode was formed through evaporation and a lift-off process using the trilayer resist technique. The gate length  $L_{\text{g}}$ , the source–gate spacing  $L_{\text{sg}}$ , and the gate–drain spacing  $L_{\text{gd}}$  were 0.08, 0.5, and 0.8  $\mu$ m, respectively. Figure 2 shows the pulsed  $I_{\text{d}}-V_{\text{ds}}$  characteristics of InAlGaN/AlN/GaN HEMTs with HT-SAG and LT-SAG processes. The quiescent gate and drain voltages ( $V_{\text{gs,q}}$ ,  $V_{\text{ds,q}}$ ) were (0 V, 0 V) and (–5 V, 20 V), respectively. The pulse



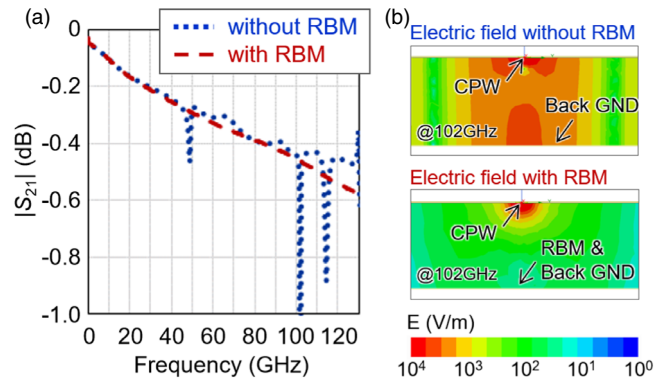


**Fig. 1.** Cross-sectional diagram of InAlGaN/AlN/GaN HEMTs with a selective-area growth (SAG) ohmic contact and a resistive back metal (RBM).



**Fig. 2.** Pulsed  $I_d$ - $V_{ds}$  characteristics of InAlGaN/AlN/GaN HEMTs with high-temperature (HT) and low-temperature (LT) SAG processes.

width was  $1\ \mu\text{s}$  and a duty cycle was 0.1%. The HT-SAG device showed a maximum drain current  $I_{d,\text{max}}$  of  $1.78\ \text{A mm}^{-1}$  and on-resistance  $R_{\text{ON}}$  of  $1.35\ \Omega\cdot\text{mm}$  under non-stressed conditions, and the knee current  $I_k$  was reduced by 17.5% under stressed conditions. The LT-SAG device showed improved  $I_{d,\text{max}}$  of  $2.01\ \text{A mm}^{-1}$ , on-resistance  $R_{\text{ON}}$  of  $1.03\ \Omega\cdot\text{mm}$ , and  $I_k$ -reduction of 12.5%. According to Van der Paul method, the  $\mu$  and  $n_s$  were  $1570\ \text{cm}^2\text{V}^{-1}\text{s}^{-1}$  and  $1.4 \times 10^{13}\ \text{cm}^{-2}$  for HT-SAG devices, whereas those were  $1950\ \text{cm}^2\text{V}^{-1}\text{s}^{-1}$  and  $1.4 \times 10^{13}\ \text{cm}^{-2}$  for LT-SAG devices. As-deposited  $\text{SiN}_x$  used as the first passivation layer in HT-SAG devices included the amount of hydrogen impurities caused by insufficient ionization of monosilane. Fourier-transform infrared spectroscopy revealed that hydrogen bonds accounted for approximately 35% of Si-N bonds in as-deposited  $\text{SiN}_x$  and reduced to below 10% in  $\text{SiN}_x$  sintered at  $600^\circ\text{C}$ , which nearly corresponded to the thermal budget of the LT-SAG process. A study reported that hydrogen atoms at nitrogen vacancy were responsible for electron localization,<sup>18)</sup> which could cause potential fluctuations and reduce electron

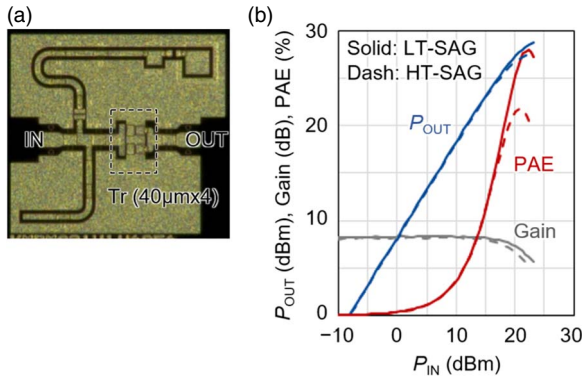


**Fig. 3.** (a) Simulated propagation losses and (b) electric field in the substrate of  $50\ \Omega$  coplanar waveguides with and without RBM.

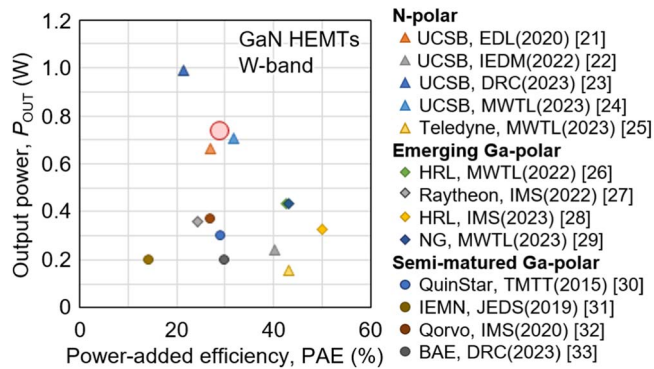
mobility by remote Coulomb scattering.<sup>19)</sup> In addition, the HT-SAG process includes the removal of the  $\text{SiN}_x$  mask and additional  $\text{SiN}_x$  deposition on the semiconductor surface by PECVD, which could induce damage at the interface between the  $\text{SiN}_x$  and the InAlGaN barrier layer. We believe that the improvement of pulsed  $I_d$ - $V_{ds}$  characteristics obtained with the LT-SAG process originated from the reduction of the trap states in the  $\text{SiN}_x$  film and interface.

A backside process comprises grinding and polishing of the SiC substrate, metallization, and dicing. Generally, the substrate is thinned to  $50$ – $100\ \mu\text{m}$  to obtain a characteristic impedance of  $50\ \Omega$  in microstrip transmission lines with comparable dimensions to transistors. On the contrary, thinning the SiC substrates leads to the degradation of heat transfer confirmed by a computational fluid dynamics solver.<sup>20)</sup> We employed  $350\ \mu\text{m}$  thick SiC substrates and a coplanar waveguide (CPW) whose characteristic impedance did not correlate with the substrate's thickness. Substrate resonance is another issue because the wavelength of a  $100\ \text{GHz}$  wave is close to the substrate thickness. We employed  $100\ \text{nm}$  thick Ni-Cr film as a resistive back metal (RBM) (Fig. 1) to attenuate the propagated signal. Figure 3(a) shows the transmission properties of  $50\ \Omega$  CPWs with a length of  $1\ \text{mm}$  calculated by electromagnetic-field simulation software. The CPW without RBM showed destructive interference because of substrate resonance, particularly at high frequency [Fig. 3(b)]. The CPW with RBM showed straightforward characteristics reflecting dielectric loss, indicating that an RBM is effective in suppressing the substrate resonance.

We designed pre-matching circuits as shown in Fig. 4(a) to evaluate the power performance of InAlGaN/AlN/GaN HEMTs. The gate periphery  $W_g$  of the transistor was  $0.16\ \text{mm}$  ( $4 \times 40\ \mu\text{m}$ ). The cut-off frequency  $f_T$  and maximum oscillation frequency  $f_{\text{max}}$  were estimated as  $89$  and  $310\ \text{GHz}$ , respectively. The reflection coefficient of source  $\Gamma_S$  and load  $\Gamma_L$  of transistors were  $0.71$  and  $0.43$  at  $90\ \text{GHz}$ , respectively. Because the  $\Gamma_S$  was too high to adjust the impedance precisely with our load-pull system, the input matching network was designed to transform the source impedance of transistor to approximately  $50\ \Omega$ . As for the output matching network, no passive components, except for short  $50\text{-}\Omega$  transmission lines, were embedded because the  $\Gamma_L$  of the transistor was in the adjustable range of equipment. The MAG values of the input and output matching networks



**Fig. 4.** (a) Micrograph and (b) large-signal characteristics of pre-matched InAlGaN/AlN/GaN HEMTs.



**Fig. 5.** Comparison of the load-pull power performance of W-band GaN HEMTs.

were  $-0.47$  and  $-0.02$  dB at 90 GHz, respectively, which was used for de-embedding the circuit loss and extracting the transistor power performance. Figure 4(b) shows the input–output power ( $P_{IN}$ – $P_{OUT}$ ) characteristics of pre-matched InAlGaN/AlN/GaN HEMTs at 90 GHz. The transistors were biased at the  $V_{gs}$  of  $-1.2$  V and  $V_{ds}$  of 20 V. The saturated  $P_{OUT}$ , power density, and PAE were 27.5 dBm (566 mW),  $3.5$  W mm $^{-1}$ , and 21.8% with HT-SAG devices and 28.7 dBm (742 mW),  $4.6$  W mm $^{-1}$ , and 28.0% with LT-SAG devices, respectively. Compared with our previous work,<sup>14,15</sup> we obtained a good combination of power density and PAE, which was mostly attributed to the suppression of the current collapse and increase of power gain by the LT-SAG process and optimized substrate structures. Figure 5 summarizes the current state-of-the-art W-band GaN HEMTs.<sup>21–33</sup> Our InAlGaN/AlN/GaN HEMTs demonstrated the highest output power among the semi-matured Ga-polar HEMTs, and good power performance enough to compete with emerging Ga-polar and N-polar devices.

In summary, high-performance W-band InAlGaN/AlN/GaN HEMTs were demonstrated. DC characteristics were enhanced by the LT-SAG process, which is likely caused by the reduction of defects in the SiN $_x$  film and interface. The CPWs with RBM were employed for transmission lines to obtain high-thermal conductivity with thick SiC substrates and suppress unwanted signal propagation in the substrates. Consequently, our InAlGaN/AlN/GaN HEMTs demonstrated higher PAE than our previous devices and the highest output power among the semi-matured Ga-polar HEMTs at W-band,

indicating that these technologies are beneficial for future sub-terahertz wireless communications.

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