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High-temperature effects of AlGaN/GaN high-electron-mobility transistors on sapphire and semi-insulating SiC substrates

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The high-electron-mobility transistors (HEMTs) have been demonstrated on both sapphire and semi-insulating (SI) SiC substrates, and the dc characteristics of the fabricated devices were examined at temperatures ranging from 25 to 500 °C. The decrease in drain current and the transconductance with the increase of temperature have been observed. The decrease ratio of transconductance and drain current was similar for both the HEMTs on sapphire and SI–SiC substrates at and above 300 °C. The HEMTs on SiC substrates showed better dc characteristics after being subjected to thermal stress up to 500 °C. Although the SiC-based HEMTs showed better characteristics up to the temperature of 300 °C, compared with the sapphire-based HEMTs, similar dc characteristics were observed on both at and above 300 °C. For high-temperature applications ($\geqslant$300 °C), additional cooling arrangements are essential for both devices. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1461420]

Wide band gap AlGaN/GaN heterostructure offers the potential for high-electron-mobility transistors (HEMTs) suitable for high-power[1] and high-temperature operations.[2–4] Few authors have studied the high-temperature characteristics of AlGaN/GaN HFETs on sapphire[2–7] and silicon carbide (SiC)[8,9] substrates. The silicon doped metal semiconductor field-effect transistors on sapphire substrate have good pinch-off characteristics at 400 °C and are operational up to 500 °C.[3] Superior pinch-off characteristics at 400 °C in AlGaN/GaN HEMTs on SiC substrates have been observed by Maeda *et al.*[9] AlGaN/GaN HEMTs were tested up to 425 °C in an oxidizing environment[4] for reliability purposes. Daumiller *et al.*[6] evaluated the stability of AlGaN/GaN HFETs under high-temperature stress up to 800 °C. Recently, high-frequency measurements were carried out on AlGaN/GaN HEMTs at temperatures ranging from 23 to 187 °C.[2] Our previous devices were tested up to 350 °C.[7] So far, no reports are available on the comparative studies of sapphire- and semi-insulating (SI) SiC based AlGaN/GaN HEMTs at high temperatures (25–500 °C).

In this letter, the comparative study of high-temperature (25–500 °C) dc characteristics of AlGaN/GaN HEMTs on sapphire and SI-SiC substrates have been reported. We report the temperature dependent dc parameters of HEMTs on sapphire and SiC substrates. We also report the recovered $I_{\mathrm{DS}}-V_{\mathrm{DS}}$ characteristics of HEMTs upon cooling down to room temperature.

The AlGaN/GaN heterostructures were grown on (0001)-oriented SI-4H–SiC and sapphire substrates using atmospheric pressure metalorganic chemical vapor deposition (Nippon Sanso, SR-2000). The device structure consists of a 3 nm undoped AlGaN barrier layer, a 15 nm silicon-doped AlGaN supply layer ($n=4\times10^{18}$ cm^{-3}), a 7 nm undoped AlGaN spacer layer, and a 3000 nm insulating GaN (i-GaN) layer on a buffer layer. AlN (200 nm)[10] and i-GaN (30 nm)[7] buffer layers were used for SiC and sapphire-based HEMT structures, respectively. The Al content of AlGaN layers was maintained as 26%. Hall measurements were performed at different temperatures (8–300 K) on SiC-based AlGaN/GaN structures using the van der Pauw method. The growth and device fabrication steps were reported elsewhere.[10] Pd/Ti/Au (40/40/80 nm) gate metal was chosen because of its stability at high temperature up to 500 °C.[11] The Pt[5–7] and Ni[2,8,9]-based gate metals were examined by few authors. The devices were unpassivated. The device dimensions are as follows: source-drain distance (L_{sd}) = 8.5 μm; gate width (W_g) = 15 μm; gate length (L_g) = 3 μm, and source-gate distance (L_{sg}) = 2.0 μm. The device dc characteristics were performed at temperatures between 25 and 500 °C with an increment of 50 °C in N_2 ambient using HP4145B semiconductor analyzer. Capacitance–voltage ($C-V$) measurements were carried out at 1 MHz on Schottky diodes using a HP4845 *LCR* meter. To realize the gate-metal surface morphology, atomic force microscopy was used to probe on both as-fabricated and high-temperature stressed devices with the scan area of 1 μm^2.

The room temperature Hall measurement shows mobilities of 1163 and 1281 cm^2/V s and sheet carrier densities of 1.0×10^{13} and 1.2×10^{13} cm^{-2} for AlGaN/GaN heterostructures on sapphire and SI-SiC substrates, respectively. Two-dimensional electron gas (2DEG) densities of 4.2×10^{13} and 4.8×10^{13} cm^{-2} were obtained from AlGaN/GaN heterostructures on sapphire and SiC substrates, respectively, using $C-V$ measurements. Table I shows the extrinsic transconductance (g_m), the maximum drain current (I_{dmax}), source resistance (R_s) and drain resistance (R_d) values of HEMTs on sapphire and SI-SiC substrates, respectively. The g_m and I_d decreasing trend with the increase of temperature (Fig. 1) is due to the decrease of both 2DEG mobility and electron velocity.[5] The decrease in 2DEG mobility of HEMTs on SiC substrate with the increase of temperature has been confirmed with the Hall measurements (inset of Fig. 1). Similar

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TABLE I. Device dc parameters of AlGaN/GaN HEMTs on sapphire and SI-SiC substrates.

T (°C)	g_{mmax} (mS/mm)		I_{dmax} (A/mm)		R_s (Ω mm)		R_d (Ω mm)	
	Sapphire	SI-SiC	Sapphire	SI-SiC	Sapphire	SI-SiC	Sapphire	SI-SiC
25	158	210	0.37	0.51	4.1	2.6	8.7	8.4
500	38	33	0.10	0.11	16.3	12.8	42.8	35.0
25[a]	140	201	0.36	0.55	4.7	3.5	9.5	6.5

[a]Parameters of high-temperature stressed (500 °C) device measured at 25 °C.

behavior has also been observed on sapphire substrate.[7] The 2DEG mobility above room temperature is limited by LO-phonon scattering.[12] Little low g_m decreasing trend with the increase of temperature (25–500 °C) has been observed for HEMTs on sapphire (78%) compared with the HEMTs on SiC (84%) substrates. The device g_m values depend on the quality of AlGaN/GaN heterostructure, device intrinsic transconductance (g_{m0}), and source resistance (R_s). With the help of g_m and R_s, g_{m0} have been estimated.[10] The decrease in g_{m0} with the increase of temperature (25–500 °C) was also observed for both sapphire- (449–100 mS/mm) and SiC- (463–57 mS/mm) based AlGaN/GaN HEMTs. From this, we confirmed that, the channel mobility decreases with the increase of temperature. The decrease ratio of g_m and I_d is low at and above 300 °C (see Fig. 1).[9] Similar behavior was observed for 2DEG mobility decrease ratio by Maeda *et al.*[12] The low degradation rate in g_m at high temperatures is a favorable characteristic for high-temperature operating devices.

At and above 300 °C, g_m and I_d of both device structures showed similar values (see Fig. 1). Gaska *et al.*[8] claimed, due to the high thermal conductivity, the SiC-based HEMTs exhibited better device characteristics at elevated temperatures (300 °C) compared with sapphire-based devices. Our results are in agreement with Gaska *et al.*[8] up to 300 °C. Above 300 °C, both devices have exhibited similar characteristics (see Fig. 1). At and above 300 °C, it is difficult to explain the SiC-based device characteristics with the help of substrate thermal conductivity. Drastically enhanced leakage-current activation energy (1.0 eV) above 400 °C on sapphire substrate supports the above argument.[6]

The R_s and R_d values were extracted from I_{DS}–V_{DS} characteristics. The increase R_s and R_d with the increase of temperatures was observed on both the HEMTs (see Table I and Fig. 2). The increase ratio is similar for both the substrate HEMTs. Threshold voltages (V_{th}) of the devices were extracted from $I_D^{1/2}$ vs V_G plot. Sapphire-based devices exhibited small variations in V_{th} values (−2.8 to −2.0 V) with the measurement temperature (see Fig. 2). Except the measurement temperature of 500 °C, V_{th} is ranging from −2.9 to −2.0 V. Due to the increase of drain leakage current, SiC-based HEMTs exhibited a low V_{th} value of −4.5 V at 500 °C. From this, we understand that the HEMTs on sapphire show better high-temperature dc characteristics with small V_{th} shift.[13] Maeda *et al.*[9] observed superior pinch-off characteristics with the threshold voltage of −7.0 V at 400 °C. We have also observed good pinch-off characteristics up to the temperature 400 °C in both the substrate HEMTs. Above the temperature of 450 °C, the increase of leakage current has been observed from SiC-based AlGaN/GaN HEMTs.[6] Both the substrate devices were operational even at 500 °C. Daumiller *et al.*[6] reported that the AlGaN/GaN HEMTs on sapphire substrate are operational even up to 750 °C with Pt/Au gate metal.

Figures 3 and 4 show the I_{DS}–V_{DS} characteristics of as-fabricated and high-temperature (up to 500 °C) stressed AlGaN/GaN HEMTs on sapphire and SiC measured at room temperature, respectively. The V_{gs} ranges from −3.0 to 1.5 V

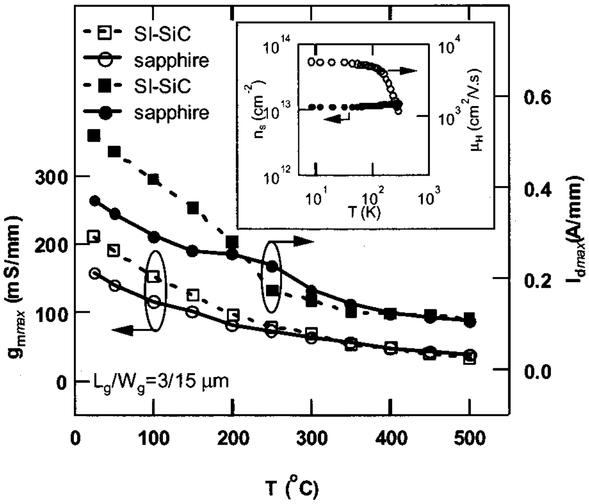

FIG. 1. Maximum transconductance (g_{mmax}) and drain current (I_{dmax}) of AlGaN/GaN HEMTs on sapphire and SI-SiC substrates as a function of temperatures. The g_m was determined at $V_{\text{ds}} = 6$ V and $V_{\text{gs}} = 0.8$ V. The inset shows the 2DEG mobility (μ_H) and sheet carrier density (n_s) of AlGaN/GaN structure on SI-SiC substrate as a function of measurement temperature (8–300 K).

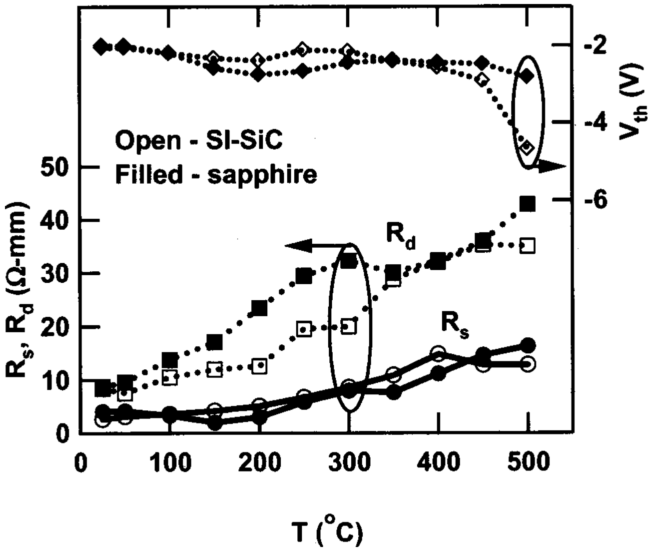

FIG. 2. Source resistance (R_s), drain resistance (R_d), and threshold voltage (V_{th}) of HEMTs as a function of temperature.

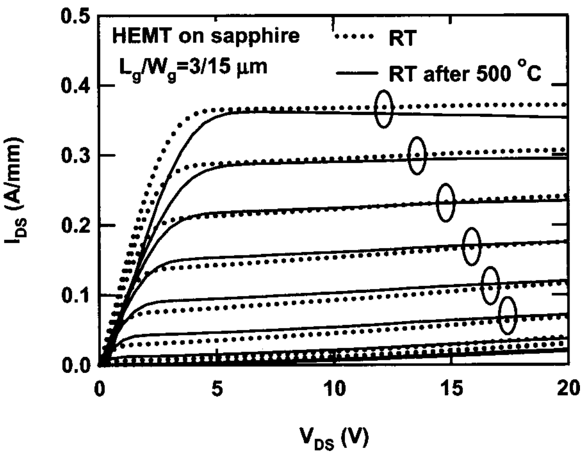

FIG. 3. $I_{DS}-V_{DS}$ characteristics of as-fabricated and high-temperature stressed (up to 500 °C) AlGaN/GaN HEMTs on sapphire substrate measured at room temperature. Top trace was at $V_{gs}=+1.5$ V and step was -0.5 V.

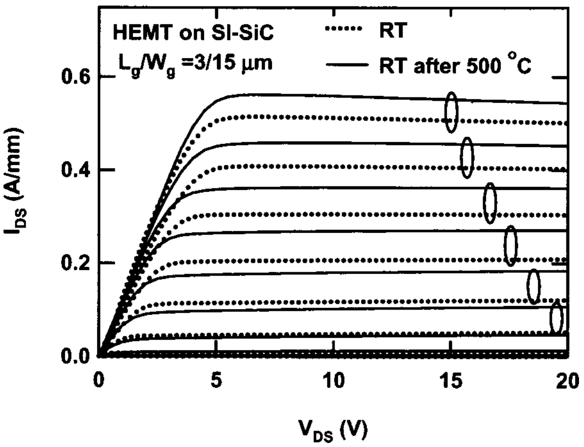

FIG. 4. $I_{DS}-V_{DS}$ characteristics of as-fabricated and high-temperature stressed (up to 500 °C) AlGaN/GaN HEMTs on SI-SiC substrate measured at room temperature. Top trace was at $V_{gs}=+1.5$ V and step was -0.5 V.

with $\Delta V_{gs}=0.5$ V. The dotted and solid lines represent as-fabricated and high-temperature (500 °C) stressed devices, respectively. A small increase in R_d (9.5 Ω mm) was observed on sapphire-based HEMTs due to high-temperature stress. This degradation may be enhanced by the bias induced stress.[6] About 7% high value of drain current has been observed on high-temperature stressed SiC-based HEMTs compared with the as-deposited HEMTs (Table I). An increase of drain current in the high-temperature stressed HEMTs is due to (i) the increase of 2DEG carrier density and (ii) the reduction of drain resistance. An increase of 2DEG carrier density (5.2×10^{13} cm^{-2}) and decrease of drain resistance (Table I) have been confirmed using $C-V$ and $I_{DS}-V_{DS}$ measurements, respectively. The contact resistance (R_c) of the ohmic contact was measured on as-fabricated and high-temperature stressed samples using transmission line model. The R_c values of AlGaN/GaN on sapphire and SiC samples are 4.0 and 2.9 Ω mm, respectively. Low values of R_c (3.4 Ω mm for sapphire and 2.0 Ω mm for SiC) were observed on the high-temperature stressed HEMTs. The decrease of R_c supports the enhanced dc characteristics of high-temperature stressed SiC-based HEMTs. Very little (2%) I_d reduction has been observed on high-temperature stressed sapphire-based HEMTs. Only 12% and 4% reduced g_m values were observed from the high-temperature stressed (500 °C) sapphire- and SiC-based HEMTs compared with the as-deposited HEMTs, respectively (Table I). The large g_m reduction percentage on sapphire based HEMTs may be due to the slow cooling rate compared with the SiC-based HEMTs (high thermal conductivity).

The device degradation is highly possible through Schottky/gate-metal contacts at high temperature. The rms roughness values of as-deposited and thermally stressed HEMTs on sapphire and SiC substrates are 4.1 and 2.1 nm and 7.0 and 13.3 nm, respectively. An increase of rms surface roughness has been observed on the thermally stressed HEMTs. Similar behavior has been observed on the annealed Pd/AlGaN Schottky diodes.[11] The Pd/AlGaN interface studies are reported elsewhere.[11] No delamination of Pd metal from AlGaN surface was observed even after 900 °C annealing.[11] Moreover, no interfacial reactions were observed even at 750 °C annealed Pd/AlGaN interfaces, which was confirmed using Auger electron spectroscopy. From this we conclude that Pd/AlGaN interface is stable up to 500 °C.

In conclusion, comparative high-temperature (25–500 °C) dc characteristic studies of $Al_{0.26}Ga_{0.74}N/GaN$ HEMTs on sapphire and SI-SiC substrates were demonstrated. The decreases in I_d, g_m, and g_{m0} with the increase of temperature are due to the limitations of 2DEG mobility and carrier velocity. Upon cooling after high-temperature stress (500 °C), HEMTs showed recovered $I_{DS}-V_{DS}$ characteristics. The HEMTs on SiC substrates have shown better dc characteristics after being subjected by thermal stress up to 500 °C. Although the HEMTs on SiC exhibited better dc characteristics up to the temperature of 300 °C compared with sapphire-based HEMTs, similar dc characteristics were observed on both the HEMTs at and above 300 °C. For high-temperature applications (⩾300 °C), additional cooling arrangements are essential for both devices.

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