

## High-temperature effects of AlGaIn/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 ( $\geq 300$  °C), additional cooling arrangements are essential for both devices. © 2002 American Institute of Physics. [DOI: 10.1063/1.1461420]

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

In this letter, the comparative study of high-temperature (25–500 °C) dc characteristics of AlGaIn/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  $I_{DS}-V_{DS}$  characteristics of HEMTs upon cooling down to room temperature.

The AlGaIn/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 AlGaIn barrier layer, a 15 nm silicon-doped AlGaIn supply layer ( $n=4\times 10^{18}$  cm<sup>-3</sup>), a 7 nm undoped AlGaIn spacer layer, and a 3000 nm insulating GaN (*i*-GaN) layer on a buffer layer. AlN (200 nm)<sup>10</sup> and *i*-GaN (30 nm)<sup>7</sup>

buffer layers were used for SiC and sapphire-based HEMT structures, respectively. The Al content of AlGaIn layers was maintained as 26%. Hall measurements were performed at different temperatures (8–300 K) on SiC-based AlGaIn/GaN structures using the van der Pauw method. The growth and device fabrication steps were reported elsewhere.<sup>10</sup> Pd/Ti/Au (40/40/80 nm) gate metal was chosen because of its stability at high temperature up to 500 °C.<sup>11</sup> The Pt<sup>5-7</sup> and Ni<sup>2,8,9</sup>-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<sub>2</sub> 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<sup>2</sup>.

The room temperature Hall measurement shows mobilities of 1163 and 1281 cm<sup>2</sup>/V s and sheet carrier densities of  $1.0\times 10^{13}$  and  $1.2\times 10^{13}$  cm<sup>-2</sup> for AlGaIn/GaN heterostructures on sapphire and SI-SiC substrates, respectively. Two-dimensional electron gas (2DEG) densities of  $4.2\times 10^{13}$  and  $4.8\times 10^{13}$  cm<sup>-2</sup> were obtained from AlGaIn/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.<sup>5</sup> 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 AlGaIn/GaN HEMTs on sapphire and Si-SiC substrates.

$T$ (°C)	$g_{m\max}$ (mS/mm)		$I_{d\max}$ (A/mm)		$R_s$ ( $\Omega$ mm)		$R_d$ ( $\Omega$ 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 <sup>a</sup>	140	201	0.36	0.55	4.7	3.5	9.5	6.5

<sup>a</sup>Parameters of high-temperature stressed (500 °C) device measured at 25 °C.

behavior has also been observed on sapphire substrate.<sup>7</sup> The 2DEG mobility above room temperature is limited by LO-phonon scattering.<sup>12</sup> 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 AlGaIn/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.<sup>10</sup> 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 AlGaIn/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).<sup>9</sup> Similar behavior was observed for 2DEG mobility decrease ratio by Maeda *et al.*<sup>12</sup> 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.*<sup>8</sup> 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.*<sup>8</sup> 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.<sup>6</sup>

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.<sup>13</sup> Maeda *et al.*<sup>9</sup> 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 AlGaIn/GaN HEMTs.<sup>6</sup> Both the substrate devices were operational even at 500 °C. Daumiller *et al.*<sup>6</sup> reported that the AlGaIn/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 AlGaIn/GaN HEMTs on sapphire and SiC measured at room temperature, respectively. The  $V_{gs}$  ranges from –3.0 to 1.5 V

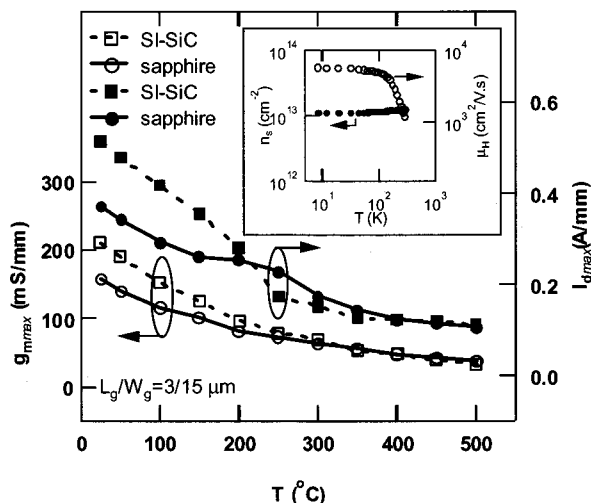


FIG. 1. Maximum transconductance ( $g_{m\max}$ ) and drain current ( $I_{d\max}$ ) of AlGaIn/GaN HEMTs on sapphire and Si-SiC substrates as a function of temperatures. The  $g_m$  was determined at  $V_{ds}=6$  V and  $V_{gs}=0.8$  V. The inset shows the 2DEG mobility ( $\mu_H$ ) and sheet carrier density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

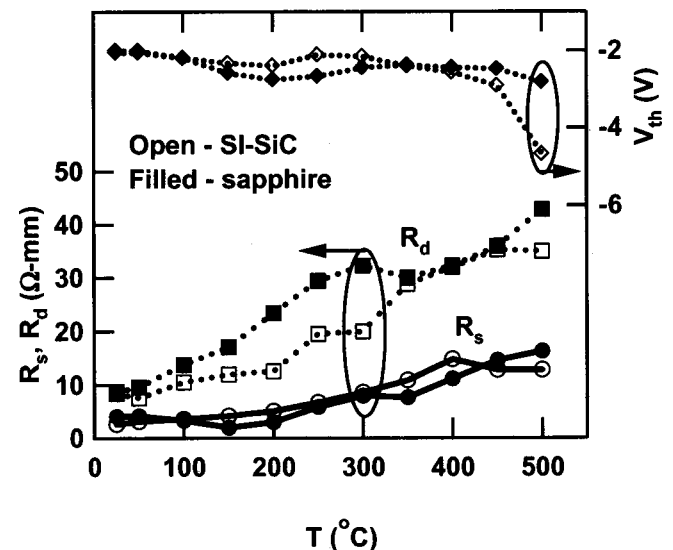


FIG. 2. Source resistance ( $R_s$ ), drain resistance ( $R_d$ ), and threshold voltage ( $V_{th}$ ) of HEMTs as a function of temperature.

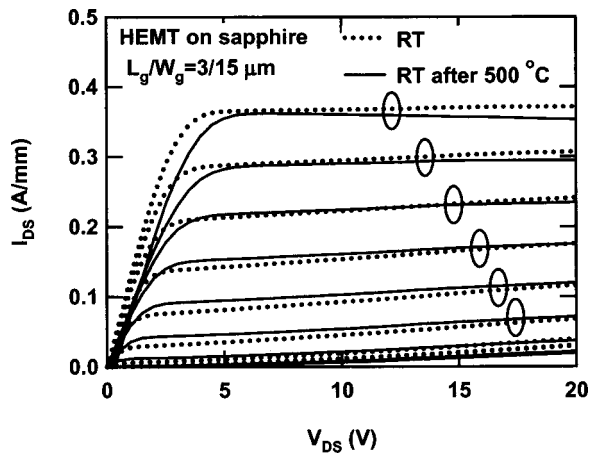


FIG. 3.  $I_{DS}$ - $V_{DS}$  characteristics of as-fabricated and high-temperature stressed (up to 500 °C) AlGaIn/GaN HEMTs on sapphire substrate measured at room temperature. Top trace was at  $V_{gs} = +1.5$  V and step was  $-0.5$  V.

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  $\Omega$  mm) was observed on sapphire-based HEMTs due to high-temperature stress. This degradation may be enhanced by the bias induced stress.<sup>6</sup> 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 ( $5.2 \times 10^{13}$  cm<sup>-2</sup>) 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 AlGaIn/GaN on sapphire and SiC samples are 4.0 and 2.9  $\Omega$  mm, respectively. Low values of  $R_c$  (3.4  $\Omega$  mm for sapphire and 2.0  $\Omega$  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/AlGaIn Schottky diodes.<sup>11</sup> The Pd/AlGaIn interface studies are reported elsewhere.<sup>11</sup> No delamination of Pd metal from AlGaIn surface was observed even after 900 °C

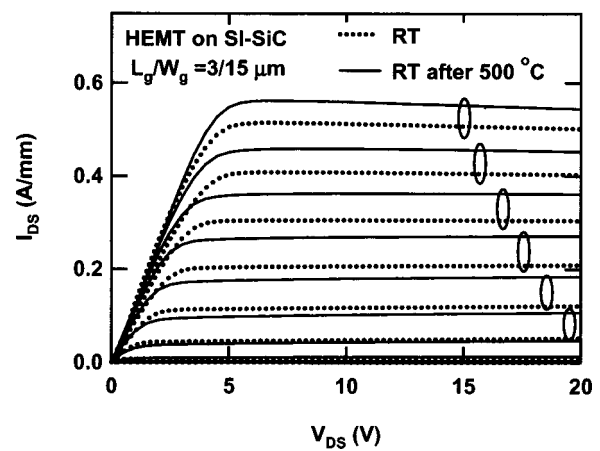


FIG. 4.  $I_{DS}$ - $V_{DS}$  characteristics of as-fabricated and high-temperature stressed (up to 500 °C) AlGaIn/GaN HEMTs on Si-SiC substrate measured at room temperature. Top trace was at  $V_{gs} = +1.5$  V and step was  $-0.5$  V.

annealing.<sup>11</sup> Moreover, no interfacial reactions were observed even at 750 °C annealed Pd/AlGaIn interfaces, which was confirmed using Auger electron spectroscopy. From this we conclude that Pd/AlGaIn interface is stable up to 500 °C.

In conclusion, comparative high-temperature (25–500 °C) dc characteristic studies of Al<sub>0.26</sub>Ga<sub>0.74</sub>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 ( $\geq 300$  °C), additional cooling arrangements are essential for both devices.

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