Temperature dependence of gate–leakage current in AlGaN/GaN high-electron-mobility transistors

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We report on the studies of the temperature dependence of gate–leakage current in AlGaN/GaN high-electron-mobility transistors (HEMTs) for the temperature range 20–400 °C. The results show that the temperature dependence of gate–leakage current for AlGaN/GaN HEMTs at subthreshold regime ($V_{GS} = -6.5$ V) have both negative and positive trends. It has been observed that the leakage current decreases with the temperature up to 80 °C. Above 80 °C, the leakage current increases with the temperature. The negative temperature dependence of leakage current with the activation energy +0.61 eV is due to the impact ionization. The positive temperature dependence of leakage current with the activation energy −0.20 eV is due to the surface related traps, and the activation energy −0.99 eV is due to the temperature assisted tunneling mechanism. The drain voltage at a fixed drain–leakage current reveals the occurrence of both positive (+0.28 V/K) and negative (−0.53 V/K) temperature coefficients.
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Recently researchers have demonstrated very impressive state of the art AlGaN/GaN microwave power high-electron-mobility transistors (HEMTs) as high as 11.2 W/mm (Ref. 1) and power added efficiencies ranging from 25% to 40%. Many authors have tried to find out the mechanism of breakdown voltage (V_B) of GaN-based devices. Researchers have observed positive[2–5] or negative[6–9] temperature coefficients of V_B for GaN-based devices. Dyakonova *et al.*[3] observed the impact ionization of V_B in AlGaN/GaN HEMTs with a positive temperature coefficient for the temperature range of 17–43 °C. Dang *et al.*[4] have also observed a positive temperature coefficient of V_B in AlGaN/GaN HEMTs for the temperature range of −100 to 100 °C. However, Tan *et al.*[8] observed a negative temperature coefficient of V_B and positive temperature dependence of leakage current in AlGaN/GaN HEMTs for the temperature range of 20–200 °C. Until now, the exact mechanism of V_B in GaN devices is not very clear. The observation of drain– and gate–leakage currents at different temperature will help in understanding the breakdown mechanism. Many authors have observed the drain– and gate–leakage current of AlGaN/GaN HEMTs at subthreshold regime increases with the increase of temperature. The increase of drain– and gate–leakage currents with the temperature is a clear disadvantage of devices operating at elevated temperatures.[6,7] We are only aware of two reports which discuss the decrease of drain– and gate–leakage currents with the increase of temperature.[3,4] High-temperature (up to 500 °C), low-voltage (0–20 V), drain-biased dc characteristics of AlGaN/GaN HEMTs on both sapphire and semi-insulating-SiC substrates have already been reported elsewhere.[10] In this letter, we report the temperature dependence of gate–leakage current (I_{GLeak}) of AlGaN/GaN HEMTs on sapphire measured from high-voltage drain-biased characteristics at subthreshold regime ($V_{GS} = -6.5$ V) for the temperature range of 20–400 °C. The breakdown mechanisms of AlGaN/GaN HEMTs are also reported.

The AlGaN/GaN HEMT structures were grown on (0001)-oriented 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 ($n = 4 \times 10^{18}$ cm^{-3}), a 7 nm undoped AlGaN spacer layer, and a 3000 nm insulating GaN (*i*-GaN) layer on a buffer layer [GaN (30 nm)]. The Al content of AlGaN layers

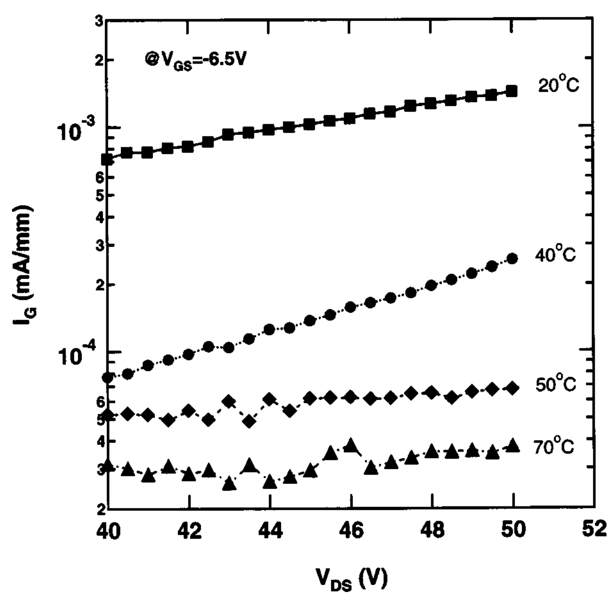

FIG. 1. I_G–V_{DS} characteristics of AlGaN/GaN HEMTs for the gate voltage $V_{GS} = -6.5$ V at different temperatures (20, 40, 50, and 70 °C). I_G values are negative.

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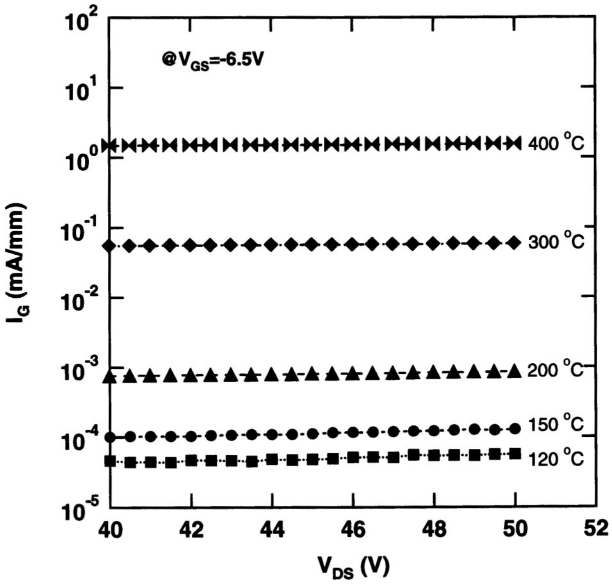

FIG. 2. I_G-V_{DS} characteristics of AlGaN/GaN HEMTs for the gate voltage $V_{GS}=-6.5$ V at different temperatures (120, 150, 200, 300, and 400 °C). I_G values are negative.

was maintained as 26%. The AlGaN/GaN heterostructures growth, electrical properties, and device fabrication steps have already been reported elsewhere.[11] The device dimensions used for this study are as follows: source–drain distance $(L_{sd})=8.0\ \mu$m; gate width $(W_g)=15\ \mu$m; gate length $(L_g)=2\ \mu$m, and source–gate distance $(L_{sg})=3.0\ \mu$m. The device dc characteristics were performed at different temperatures in the range between 20 and 400 °C in a N_2 ambient using Agilent 4156c semiconductor parameter analyzer. All the dc measurements were carried out in the dark. To avoid the destruction of the device, the gate voltage $V_{GS}=-6.5$ V and drain voltage $V_{DS}=50$ V were chosen as the optimal testing regime for the observation of leakage current dependence in the temperature range of 20–400 °C (even at an elevated temperature). The maximum drain current density of the fabricated devices was 320 mA/mm and the maximum transconductance was 118 mS/mm. The room-temperature threshold voltage of this device is −1.67 V. Three-terminal breakdown voltages of the HEMTs in the OFF state were close to 120 V.

Figure 1 shows high-voltage drain-biased I_G-V_{DS} characteristics of AlGaN/GaN HEMTs measured at subthreshold regime (at $V_{GS}=-6.5$ V) for different temperatures 20, 40, 50, and 70 °C. The observation of a negative temperature dependence of the I_{GLeak} in AlGaN/GaN HEMTs is due to the occurrence of impact ionization phenomena.[2–5] Figure 2 shows high-voltage drain-biased I_G-V_{DS} characteristics of HEMTs measured at subthreshold regime (at $V_{GS}=-6.5$ V) for different temperatures 120, 150, 200, 300, and 400 °C. Above 80 °C, the I_{GLeak} current started increasing with the increase in temperatures. The positive temperature dependence of leakage currents are due to the temperature assisted tunneling phenomena.[6–9] A similar temperature dependence of I_D-V_{DS} characteristics (similar to Figs. 1 and 2) has also been observed (not shown here). The negative and positive temperature dependence of drain– and gate–leakage currents measured at $V_{DS}=50$ V and at subthreshold regime is shown in Fig. 3. An activation energy plot of the

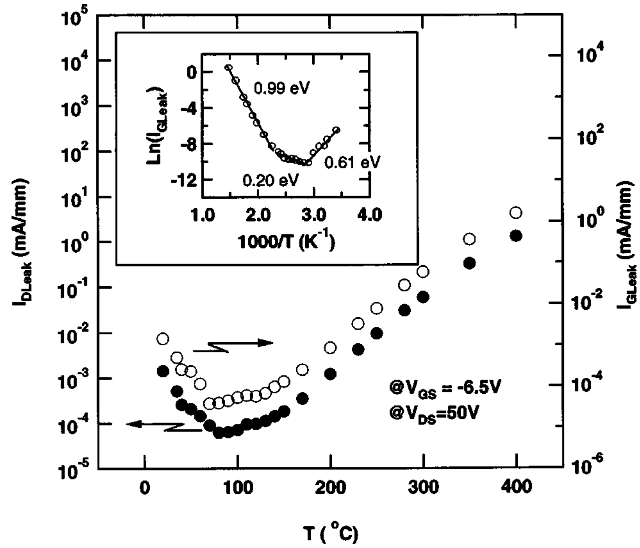

FIG. 3. Drain– and gate–leakage current of AlGaN/GaN HEMTs for $V_{DS}=50$ V and $V_{GS}=-6.5$ V (subthreshold regime). Inset figure activation energy plot of I_{GLeak} measured at $V_{GS}=-6.5$ V.

I_{GLeak}measured at subthreshold regime ($V_{GS}=-6.5$ V), is shown in the inset of Fig. 3. Up to the temperature of 80 °C, the leakage current decreases with the activation energy of +0.61 eV. This is due to the occurrence of deep acceptor initiated impact ionization.[12] Trivedi *et al.*[13] theoretically predicted the avalanche breakdown mechanism on wide band-gap semiconductors namely SiC and GaN. The I_{GLeak} increase rate is considerably small with the activation energy of −0.20 eV, at the temperature between 90 and 150 °C (See Fig. 3). A similar activation energy (see Table I) was observed for the temperature range of 20–200 °C by Tan *et al.*[8] The small increase of I_{GLeak} is responsible for surface related hopping conduction.[8] Above 150 °C, the leakage current increases exponentially with an activation energy of −0.99 eV. It is clear that the increase of I_{GLeak} is associated with the temperature assisted tunneling mechanism.[9]

In order to estimate the temperature dependence of the V_B, we used the drain voltage (V_D) at a fixed I_{DLeak}.[3] The temperature dependence of the V_D for a fixed I_{DLeak} of $6\times10^{-3}\ \mu$A/mm is shown in Fig. 4. Temperature coefficients were calculated and tabulated in Table I. Up to the temperature of 80 °C, a positive temperature coefficient +0.28 V/K

TABLE I. The temperature coefficient of breakdown values for different devices from previous reports. The values with an asterisk denote values obtained in this work.

Device	Temperature coefficient (V/K)	
	Positive	Negative
GaN and AlGaN diodes	~0.02,[a] ~0.20,[b] 0.0045[c]	0.34,[d] 6.0[e]
AlGaN/GaN HEMTs	~0.33,[f] 0.05,[g] 0.28*	0.11,[h] ~0.16,[i] 0.53*
AlGaAs/InGaAs HEMTs	⋯	~0.033[j]
InGaAsP APDs	~0.042[k]	~0.02[k]
InP APDs	~0.029[k]	⋯

[a]See Ref. 2.
[b]See Ref. 5.
[c]See Ref. 14.
[d]See Ref. 7.
[e]See Ref. 6.
[f]See Ref. 3.
[g]See Ref. 4.
[h]See Ref. 8.
[i]See Ref. 9.
[j]See Ref. 17.
[k]See Ref. 15.

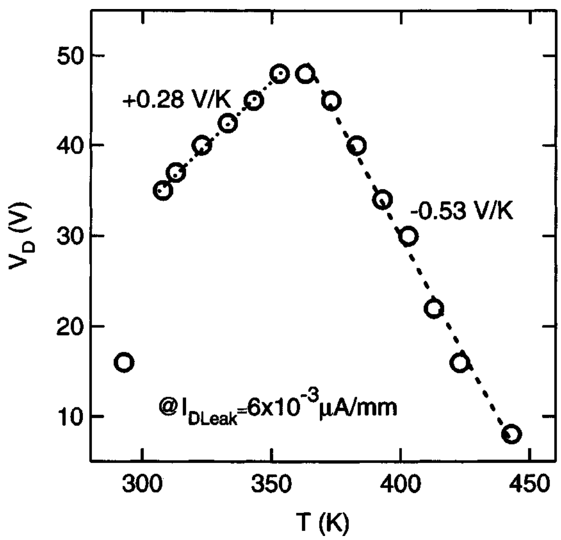

FIG. 4. Drain voltage (V_D) of AlGaN/GaN HEMTs at subthreshold regime ($V_{GS}=-6.5$ V) for a fixed I_{DLeak} of 6×10^{-3} μA/mm.

of V_D was obtained. Small values of the temperature coefficient, as obtained by other researchers[3,4,14] (see Table I) may be related to the presence of defect-related microplasmas.[2] However, Aggarwal *et al.*[5] predicted that the increase of V_B with temperature is ~0.20 V/K for the temperature $\geqslant$200 K. The positive sign of V_D temperature coefficient agrees with the results obtained for AlGaN/GaN HEMTs,[3,4] GaN *p*-*n* diode,[2] GaN *p*-*n*-n^+ diode,[5] GaN photodiode,[14] InP avalanche photodiodes (APDs),[15] and InPGaAs APDs.[15] This also agrees with the theoretical predictions for the impact ionization process in Si and Ge.[16] For temperatures greater than 80 °C, the devices exhibited a negative temperature coefficient of −0.53 V/K. The negative temperature coefficient of V_D agreed with the results obtained for AlGaN/GaN HEMTs,[8,9] AlGaAs/InGaAs HEMTs,[17] GaN Schottky, and GaN *p*-*i*-*n* diodes.[7] This suggests that impact ionization in the channel, rather than gate tunneling, is the dominant breakdown mechanism up to the temperature of 80 °C. Above 80 °C, gate tunneling is the dominant breakdown mechanism in the channel. Similar avalanche and tunneling breakdown mechanisms were observed on InGaAsP APDs by Takanashi and Horikoshi[15] for the temperature range of −190–23 °C.

In conclusion, positive and negative temperature dependences of drain– and gate–leakage currents have been observed in AlGaN/GaN HEMTs on sapphire. Up to the temperature 80 °C, the leakage current decreases with an activation energy of +0.61 eV. This decrease of leakage current is due to the deep acceptor initiated impact ionization. Above 80 °C, the leakage current increases with activation energies of −0.20 and −0.99 eV. This increase in leakage current in AlGaN/GaN HEMTs is due to the surface-related traps and temperature assisted tunneling mechanism. The positive (+0.28 V/K) and negative (−0.53 V/K) temperature coefficients of drain voltage have been realized at a fixed drain–leakage current (6×10^{-3} μA/mm) of AlGaN/GaN HEMTs.

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