Comparative study of drain-current collapse in AlGaN/GaN high-electron-mobility transistors on sapphire and semi-insulating SiC

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The drain-current collapse at high drain voltage has been studied in AlGaN/GaN high-electron-mobility transistors (HEMTs) on both semi-insulating (SI)–SiC and sapphire substrates using small frequency (120 Hz) sinusoidal wave superimposed dc I_{DS}–V_{DS} characteristics. Low drain-current collapses were observed in AlGaN/GaN HEMTs on SI–SiC substrate when compared with the HEMTs on sapphire substrates. Two and three thermally activated deep traps were observed on SiC-based and sapphire-based HEMTs, respectively. The existence of an additional deep trap ($\Delta E = 0.61$ eV) could be associated with the material defects/ dislocations responsible for the severe drain current collapse in sapphire-based HEMTs. The white-light illuminated I_{DS}–V_{DS} characteristics support the existence of more number of deep traps in the sapphire-based HEMTs. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1512820]

Nitride-based field effect transistors are of great interest due to their capability of operating at high power, high temperature, and high frequency. An important problem facing nitride-based high power microwave electronics is the presence of drain current collapse while applying high drain voltage. Authors have discussed the current collapse mechanism of field effect transistors with the help of trap-related phenomenon,[1–6] piezo-related charge states,[7] and the source and drain resistances.[8] Until now, the exact current collapse mechanism of AlGaN/GaN high-electron-mobility transistors (HEMTs) is not very clear. Authors have studied the drain current collapse using high drain voltage dc characteristics[1,2,4,5] and also pulsed dc characteristics.[3,6–8] Recently, Kikkawa *et al.*[9] showed the drain current collapse using a 100 Hz curve tracer. So far, no comparative studies have been performed between the HEMTs on sapphire and SiC using small frequency (120 Hz) sinusoidal wave superimposed dc measurements. Because of the low dislocation density GaN buffer layers, the performance of AlGaN/GaN HEMTs on semi-insulating (SI)–SiC was superior to the HEMTs on sapphire substrates.[10] The comparative study may help to understand the drain current collapse mechanism. In this study, we report the lower drain current collapse of AlGaN/GaN HEMTs on SI–SiC when compared with the HEMTs on sapphire substrates using dc and 120 Hz sinusoidal wave superimposed dc measurements.

The device structures were grown by atmospheric pressure metalorganic chemical vapor deposition on (0001)-oriented SI–4H-SiC and sapphire substrates. The device structure growth and its fabrication details were reported elsewhere.[10–12] For this study, device dimensions are as follows: source-drain distance (L_{sd}) 10 μm; gate-width (W_g) 200 μm; gate-length (L_g) 2 μm, and source-gate distance (L_{sg}) 3.5 μm. Several devices with an identical dimension were used for this study. The dc and small frequency 120 Hz sinusoidal wave superimposed dc I_{DS}–V_{DS} characteristics (hereafter, it is called as ac measurements) of the fabricated devices were performed using Sony Tektronix 370A high-resolution programable curve tracer. The ac characteristic of AlGaN/GaN HEMTs were carried out at different drain sweep-voltages (V_{DS}) of 0–4, 0–8, 0–12, 0–15, and 0–20 V. To obtain thermally activated deep traps, dc I_{DS}–V_{DS} characteristics were measured at different temperatures (25–500 °C in a step of 50 °C).[12] To confirm the trapping effect, I_{DS}–V_{DS} characteristics were carried out on AlGaN/GaN HEMTs under both dark and white-light illumination.

Figures 1(a) and 1(b) show the dc and ac I_{DS}–V_{DS} characteristics of AlGaN/GaN HEMTs on sapphire and SiC substrates, respectively. Though the drain-current collapse has been observed on a reproducible basis in both the HEMTs fabricated on sapphire and SiC substrates, the drain current collapse in HEMTs on SiC was very small compared with the HEMTs on sapphire substrates. The current collapse reaches high for the sweep voltage of 15 V, low thermal conductivity of sapphire substrate may partly involve in the current collapse mechanism. About 3.5% and 9.3% of dc drain current reduction due to the device temperature effect has been observed at $V_g = +1.5$ V on the SiC-based HEMTs and sapphire-based HEMTs, respectively.[10]

Figure 2 shows the maximum drain current density (I_{Dmax}) as a function of drain sweep-voltage for different gate voltages of HEMTs on sapphire and SiC substrates. It is clear that, the drain-current collapse is severe for sapphire grown AlGaN/GaN HEMTs when compared with the HEMTs on SiC substrates. The current collapse behavior of both sapphire and SiC grown HEMTs is due to the existence of deep traps associated with the material defects/ dislocations. To observe the trapping effects, the drain-leakage-current (I_{DLeak}) of HEMTs was measured at different temperatures.[12] An activation energy plot of I_{DLeak} measured at the gate voltage of -5 V with the drain voltage of 10 V is shown in Fig. 3. Two deep trap activation energies of $\Delta E = 1.05$ and 0.040 eV were observed on the SiC-based

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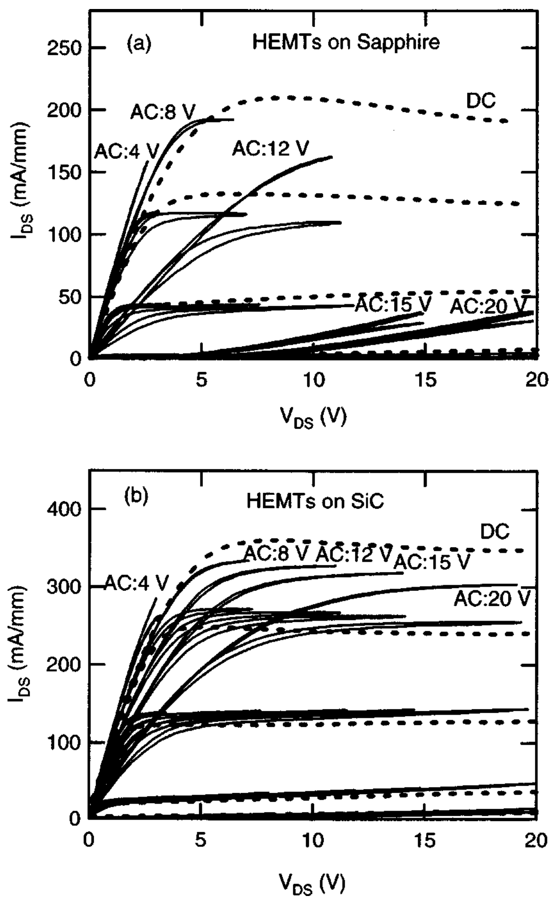

FIG. 1. Measured dc and ac I_{DS}–V_{DS} characteristics (for different drain sweep voltages $V_{DS}=4$, 8, 12, 15, and 20 V) of AlGaN/GaN HEMTs on (a) sapphire and (b) SI–SiC substrates. Top trace was at $V_{GS}=+1.5$ V step voltage was -1.0 V.

HEMTs.[7] However, three deep trap activation energies of $\Delta E=1.23$, 0.61, and 0.046 eV were observed on the sapphire-based HEMTs. These deep trap activation energies are related with the material defects/dislocations. Low defect density has been realized on GaN epilayers grown on SiC substrates (2×10^{8} cm^{-2}) when compared with the GaN epilayers on sapphire substrates (6×10^{8} cm^{-2}). The low dislocation density of GaN on SiC is related to its small lattice mismatch and thermal expansion coefficient with GaN. Moreover, low radiative recombination centers have also been observed on the SiC grown GaN using electron beam induced current (EBIC) measurements.[13] The product of Hall mobility and sheet carrier density ($\mu_H\cdot n_s$) values were also high for AlGaN/GaN heterostructures on SiC substrate.[10–12] Figure 4 shows the dc I_{DS}–V_{DS} characteristics of HEMTs measured at $V_g=0$ V under dark and white-light illumination. The increase in percentage of drain current under white light illumination was high for sapphire-based HEMTs (33%) when compared with the SiC-based HEMTs (5%). The white-light illuminated I_{DS}–V_{DS} characteristics support the existence of more number of traps in the sapphire-based HEMTs. The ac I_{DS}–V_{DS} curve of sapphire grown HEMTs shows [see Fig. 1(a)] large hysteresis width ($\leqslant 910$ mV) when compared with the HEMTs on SiC substrates ($\leqslant 310$ mV). Large values of hysteresis width confirm the presence of more deep traps located adjacent to the channel, which increases the device capacitance. Both the low thermal conductivity of sapphire and an additional activation energy deep trap ($\Delta E=0.61$ eV) level located nearer to the valence band severely degraded the drain current of sapphire-based HEMTs [see Figs. 1(a) and 3]. These results are in good agreement with the low dislocation density, high value of $\mu_H\cdot n_s$ and small number of radiative recombination centers of GaN on SiC substrates, which was measured by atomic force microscopy, Hall effect, and EBIC published elsewhere.[10–13]

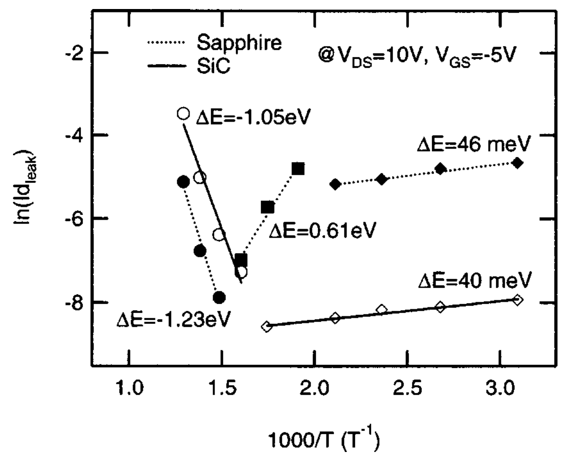

FIG. 3. Activation energy plot of drain leakage current (I_{DLeak}) measured at the gate voltage of $V_g=-5$ V and drain voltage of $V_{DS}=10$ V.

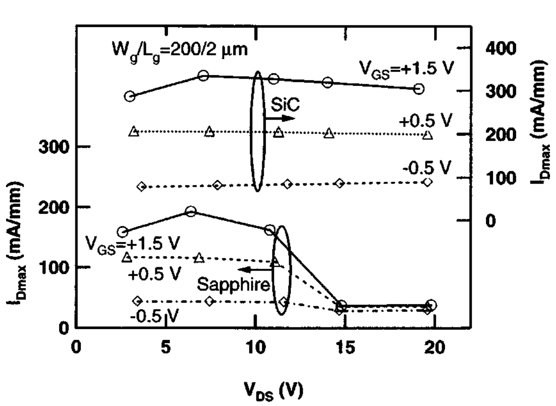

FIG. 2. Maximum drain current (I_{Dmax}) of AlGaN/GaN HEMTs on sapphire and SI–SiC substrates as a function of ac drain sweep voltages for different gate voltages (+1.5, +0.5, and −0.5 V).

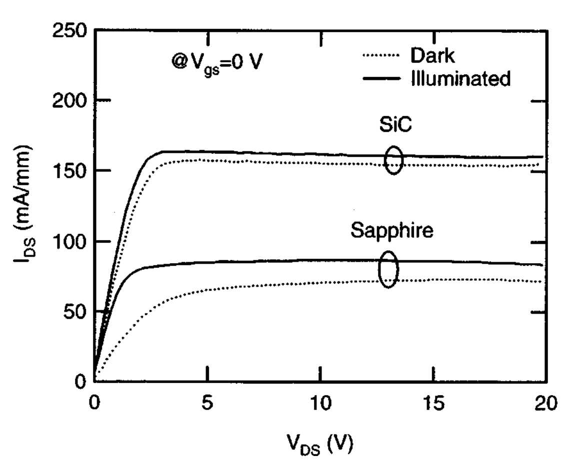

FIG. 4. dc I_{DS}–V_{DS} characteristics of AlGaN/GaN HEMTs on sapphire and SiC substrates measured under dark and white-light illumination.

More number of deep traps captured almost all of the channel carriers when high drain voltages ($\geqslant$15 V) were applied. This trapped charge depletes the two-dimensional electron gas from beneath the active channel and results in the reduction of drain current and, hence, the output power.[2,6] For example, the dc characteristics of AlGaN/GaN HEMTs on SI–SiC[11] with a maximum saturation current about $I_{DS} = 850$ mA/mm and the knee voltage of $V_{KN} = 4.5$ V at a moderate $V_{DS} = 30$ V, would deliver an output power of $P_{OUT} \approx (I_{DS}/2) \times (V_{DS} - V_{KN})/2 \approx 5.4$ W/mm. Small knee voltage (V_{KN}) shift (2.31 V for drain sweep voltage of 12 V) with small current reduction has been observed for SiC-based HEMTs. However, drastic V_{KN} shift with severe current collapse was observed for sapphire-based HEMTs [see Figs. 1(a) and 2]. The current collapse may be suppressed by low dislocation density GaN epilayer growth and passivation processes.[2,9,14–16] Further studies are required to understand the properties of existing deep traps in the device structure. From these results, it is clear that the HEMTs on SiC substrates show better dc and ac characteristics when compared with the HEMTs on sapphire substrates.

In conclusion, small frequency (120 Hz) sinusoidal wave superimposed dc I_{DS}–V_{DS} characteristics were performed on sapphire and SI–SiC grown AlGaN/GaN HEMTs. The percentage of current collapse in SiC grown HEMTs was negligibly small compared with the HEMTs on sapphire substrates. Low drain-current collapses in AlGaN/GaN HEMTs on semi-insulating SiC substrate is due to the existence of small number of deep traps associated with the material defects/dislocations. The existence of an additional deep trap ($\Delta E = 0.61$ eV) could be associated with the material defects responsible for the severe drain current collapse in sapphire-based HEMTs. The deep trapping effects were confirmed using illuminated dc I_{DS}–V_{DS} characteristics of HEMTs. Hence, SiC-based HEMTs are suitable for fast switch operating circuits when compared with the sapphire-based HEMTs.

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