

Drain Current DLTS of AlGaIn–GaIn MIS-HEMTs

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Abstract—The transient behavior of AlGaIn–GaIn MIS-HEMTs were studied by drain current deep level transient spectroscopy. Two electron traps were observed, one of which had similar activation energy to that of defect that was commonly observed in epitaxial GaIn. We compared the results with those of AlGaIn–GaIn HEMTs. The hole-trap-like positive peaks in the DLTS, which were observed in the HEMTs, were not observed in the MIS-HEMTs. It has been pointed out that the positive peaks did not originate from change in hole trap population in the channel but reflected the change in the electron population in the surface states of the HEMT access regions. The gate insulator was effective to suppress not only the gate leakage current but also the surface-state-related signals.

Index Terms—AlGaIn–GaIn MIS-HEMTs, current DLTS, hole-trap-like, surface states.

I. INTRODUCTION

AlGaIn–GaIn HEMTs have received much attention for a high-power and high-frequency applications because of a high breakdown field in the wide-bandgap semiconductor. In order to fully develop the potential of the device, it is important to solve problems such as large gate leakage current [1], [2] and drain current collapse [3]–[5], because they limit the RF performance of the device. We have recently reported that the gate leakage current and current collapse were suppressed in AlGaIn–GaIn MIS-HEMTs with a SiN_x gate insulator [6]. It is important to understand the transient behavior of the devices to apply them to the systems. Deep level transient spectroscopy (DLTS) is one of the most powerful techniques to study the transient behavior caused by deep levels. Capacitance DLTS of the Schottky diode is often used to characterize the crystal quality. However, it is important to directly study the transient behavior of the device to understand the effects of the deep levels on the device performance. We have recently studied the transient behavior of AlGaIn–GaIn HEMTs by the drain current DLTS, where surface-state-related levels were observed in the DLTS signal [7]. In this letter, we studied the transient behavior of AlGaIn–GaIn MIS-HEMTs by the current DLTS.

II. EXPERIMENTS

The AlGaIn–GaIn MIS-HEMTs with SiN_x gate insulator were fabricated on metal–organic chemical vapor deposition (MOCVD) grown epitaxial layer. The layer structure is

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TABLE I
DEVICE CHARACTERISTICS OF MIS-HEMT AND HEMT

	AlGaIn/GaIn MIS-HEMTs	AlGaIn/GaIn HEMTs
I_{DSS} (mA/mm) (@ $V_{GS}=3$ V, $V_{DS}=10$ V)	470	465
g_{mmax} (mS/mm)	90	140
I_{Gleak} (A/mm)	6.9×10^{-9}	8.9×10^{-6}
V_{th} (V)	-7	-4

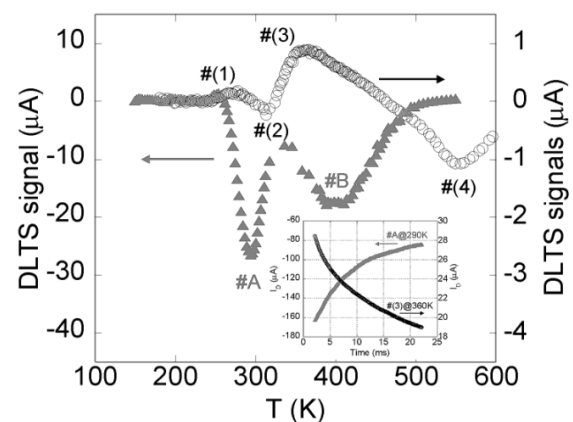


Fig. 1. Typical drain current DLTS spectrum measured on 1.5- μ m gate AlGaIn–GaIn MIS-HEMTs (solid triangles) and AlGaIn–GaIn HEMTs (open circle) at $V_{DS} = 8$ V. The inset is a typical drain current transients for the peaks #A at 290 K and #B at 360 K.

i-AlGaIn (3 nm)/n-AlGaIn (7 nm, 6×10^{18} cm⁻³)/i-AlGaIn (3 nm)/i-GaIn (3 μ m)/i-AlN (40 nm). The AlN mole fraction of the AlGaIn layers is 0.3. SiN_x gate insulator (10 nm) was deposited by ECR sputtering after the ohmic contact formation. SiN_x serves simultaneously as a gate insulator and a surface passivation film. The gate length (L_G) was 1.5 μ m. Reference device without SiN_x gate insulator was also fabricated. The device characteristics of both HEMTs are summarized in Table I. I_{Gleak} of the MIS-HEMT was three orders magnitude smaller than that of the HEMT. DC current–voltage (I – V) curve was about 90% lower than pulsed I – V curve in the MIS-HEMT. In the drain current DLTS, a voltage pulse with a peak value of 1 V and a pulse width of 10 ms was applied to the gate of the device biased at $V_{DS} = 8$ V, and the drain current transient after switching the gate voltage to negative direction was measured by DLTS technique. The negative value of the gate voltage pulse was about 1 V higher than the threshold voltage.

III. RESULTS AND DISCUSSION

DLTS signals of the AlGaIn–GaIn MIS-HEMT are shown in Fig. 1 by solid triangles. There are two negative peaks (#A and #B) corresponding to the electron traps in the epitaxial layer.

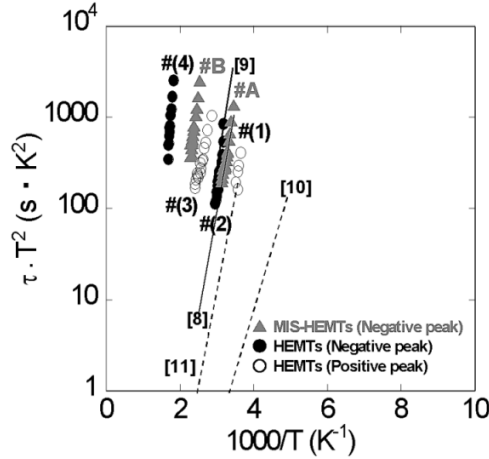


Fig. 2. Arrhenius plots of $T^2\tau$ for MIS-HEMTs (triangles) and HEMTs (circles). Solid symbols are for the negative peaks and open symbols are for the positive peaks, respectively. Solid lines are the results reported by Hacke *et al.* and Lee *et al.* Broken lines are the results obtained by low-frequency noise and frequency dispersion in AlGaIn–GaIn HEMTs.

AlGaIn–GaIn HEMTs without SiN_x gate insulator fabricated on the same wafer were also measured for comparison. The results are shown in Fig. 1 by open circles. There are four peaks; #1)–#4). In addition to the two negative peaks, #2) and #4), which correspond to the electron traps, the hole-trap-like positive peaks, #1) and #3), were also observed. The typical drain current transients for the peaks #A at 290 K and #3) at 360 K are shown in the inset. The positive peaks do not correspond to the changes in hole trap population in the bulk, because the hole traps in the bulk are usually occupied by electrons and do not contribute to the drain current transient. Moreover, no hole generation in the bulk is possible under present bias condition. The hole-trap-like positive peaks can be explained by the change in the population of surface states. Details will be discussed later.

The Arrhenius plots of $T^2\tau$ for these peaks are shown in Fig. 2. Solid triangles are for the negative peaks (#A and #B) in the AlGaIn–GaIn MIS-HEMTs. Solid circles are for the negative peaks, #2) and #4), and open circles are for the positive peaks, #1) and #3), in the AlGaIn–GaIn HEMTs. Solid lines are the commonly observed point-defect-related deep levels obtained by capacitance DLTS of MOCVD grown n-GaN [8], [9]. Broken lines are the results obtained by low-frequency noise and frequency dispersion in AlGaIn–GaIn HEMTs [10], [11]. The data which correspond to the negative peaks, #A and #2), are plotted at almost the same position as the solid lines. This suggests that the levels #A and #2) are probably due to the commonly observed electron trap originating from the point defects or their complex in GaN. The activation energies and capture cross sections, which are summarized in Table II, were 0.49 eV and $8.5 \times 10^{-17} \text{ cm}^{-2}$ for #A and 0.58 eV and $1.1 \times 10^{-15} \text{ cm}^{-2}$ for #2), respectively. These are comparable with the results in [8] (0.59 eV and $2.9 \times 10^{-15} \text{ cm}^{-2}$) and [9] (0.49 eV and $4.9 \times 10^{-17} \text{ cm}^{-2}$). A relatively large scatter of the capture cross sections is probably due to that the small error in the activation energy caused a large deviation in the capture cross section. Even though the origin of electron trap, #B and #4), is not clear at present, a new peak, #B, might be due to the damage during SiN_x deposition.

TABLE II
ACTIVATION ENERGIES AND CAPTURE CROSS SECTIONS OF MIS-HEMT AND HEMT

	AlGaIn/GaN MIS-HEMTs		AlGaIn/GaN HEMTs			
	#A	#B	#(1)	#(2)	#(3)	#(4)
Activation energy E_a (eV)	0.49	0.62	0.68	0.58	0.34	1.1
Capture cross section σ (cm^2)	8.5×10^{-17}	8.8×10^{-18}	2.5×10^{-12}	1.1×10^{-15}	2.2×10^{-20}	5.8×10^{-16}

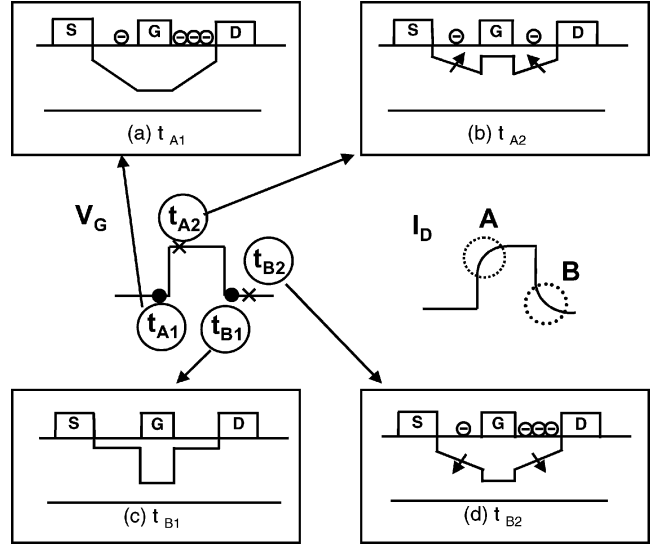


Fig. 3. Schematic illustration of response of the depletion layers: (a)–(d) represent the response of the depletion layer at the timing of t_{A1} , t_{A2} , t_{B1} , and t_{B2} on the gate bias pulse, respectively.

The hole-trap-like positive peaks can be explained by electron capture/emission at the surface states, which were proposed to explain the drain current collapse in the HEMTs [12]. In this model, electrons are injected from the gate to the gate-drain access region and captured by the surface states, resulting in a decrease in two-dimensional electron gas density due to the charge neutrality. Fig. 3 represents the response of the depletion layer at the timing of (a) t_{A1} , (b) t_{A2} , (c) t_{B1} , and (d) t_{B2} on the gate bias pulse, respectively. Just before the application of the positive pulse at $t = t_{A1}$, electrons injected from the gate electrode are captured at the surface states and depletion layer in the access region extends to the steady state position, as shown in Fig. 3(a). When the gate voltage is switched to positive value, gate depletion layer shrink instantaneously. However, the depletion layer in the access region does not respond to the gate voltage immediately because it takes long time to emit electrons from the surface states. This causes slow response of the depletion layer of the access regions [Fig. 3(b)], resulting in a gradual increase in the drain current, as shown in broken circle A on the drain current transient. The time constant is dominated by the emission rate of electrons from the surface states and nonzero surface conductivity in the access region of the device.

When the gate voltage is switched from positive to negative values at $t = t_{B1}$, depletion layer thickness under the

gate increases instantaneously, as shown in Fig. 3(c). The response of the depletion layer in the access region, on the other hand, does not respond to the gate voltage change due to the following phenomena: 1) electron injection from the gate, 2) the electron transport on the surface, and 3) electron capture at the surface states. Even though the electron capture is generally faster than emission, electron transport on the surface is not instantaneous. Then the depletion layer in the access regions can not respond to the rapid change in the gate voltage [Fig. 3(d)]. This causes a gradual decrease in the drain current, as shown in broken circle B on the drain current transient, resulting in a positive peak of DLTS. These explanation are consistent with surface-state-related current collapse model [12]. The electron transport is dominated by a low surface conductivity probably due to electron hopping between surface states. The activation energies obtained for the positive peaks, 0.68 eV for #1 and 0.34 eV for #3, are thought to be related with the depth of surface states from conduction band.

If the hole-trap-like positive peaks are caused by electron capture/emission at the surface states, the positive peaks are expected to change when the device surface is passivated with dielectric film. It is notable that the surface-state-related positive peak was not observed in the MIS-HEMTs, as shown in Fig. 1. This indicates that the SiN_x gate insulator is effective to suppress not only gate leakage current but also the surface-state-related DLTS signals.

IV. CONCLUSION

Current DLTS was applied to the AlGaIn–GaIn MIS-HEMTs to study the transient behavior of the device. Two electron traps, one of which was attributed to commonly observed point-defect-related deep level in GaN, were observed in the DLTS spectrum. Hole-trap-like positive peaks were attributed to the changes in the electron population in the surface states of

the HEMTs access region. In the AlGaIn–GaIn MIS-HEMTs, the surface-state-related positive peaks were suppressed.

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