Changes of Electrical Characteristics for AlGaN/GaN HEMTs Under Uniaxial Tensile Strain

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***Abstract*—This letter investigates the characteristics of unpassivated AlGaN/GaN high-electron mobility transistors (HEMTs) under uniaxial tensile strain. Mechanical stress can produce additional charges that change the HEMT channel current. This phenomenon is dependent upon gate orientation and may be the result of the piezoelectric effect and changes in electron mobility due to the applied uniaxial stress. In addition, results show that tensile strain reduces the transient current, which is likely due to the additional donorlike surface states created through the piezoelectric effect.**

***Index Terms*—AlGaN/GaN, gate orientations, high-electron mobility transistors (HEMTs), transient current, uniaxial tensile strain.**

I. INTRODUCTION

DUE TO THEIR potential in high-frequency and high-power applications, AlGaN/GaN high-electron mobility transistors (HEMTs) have been widely studied in recent years, with many excellent results [1], [2]. One of the issues encountered in the early stages of investigating this material is its significant RF current dispersion. This dispersion is due to the sensitive surface of AlGaN and may be related to its piezoelectric nature [3]. One approach to solving this problem is to apply a silicon nitride (SiN_x) passivation layer on the ungated region. This technique improves the dc and RF performances. Eliminating the surface-state density reduces the surface-related RF dispersion [4], [5]. Furthermore, the increase in dc current can be explained by additional charges induced by piezoelectric polarization resulting from tensile strain in the SiN_x film [6]. However, previous studies have not examined the effect of purely tensile strain on AlGaN/GaN HEMTs or the impact of this strain on the surface states.

This letter presents a three-point bending test fixture that simulates the tensile strain on the c-axis induced by SiN_x passivation. This letter describes the characteristics of unpassivated AlGaN/GaN HEMTs under mechanical uniaxial tensile strain and the effect of this strain on dc forward and transient characteristics of devices with gates oriented along the [10–10] and [11–20] directions.

II. EXPERIMENTS

An undoped AlGaN/GaN HEMT heterostructure was grown on a 2-in (0001) sapphire substrate using metal-organic chemical vapor deposition. The epitaxial structure consisted of a 2-μm-thick GaN buffer layer, followed by a 30-nm-thick $\mathrm{Al}_{0.25}\mathrm{GaN}_{0.75}\mathrm{N}$ barrier layer. The room temperature Hall mobility and sheet electron concentration of the sample were $1100\ \mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$ and $1\times10^{13}\ \mathrm{cm}^{-2}$, respectively.

The wafer was cut into test die (25 mm × 15 mm) with the edges along the [10–10] and [11–20] directions, as shown in Fig. 1(a). The devices were then fabricated using a conventional process with 7-μm drain–source spacing and gates oriented along the [10–10] and [11–20] directions. The gate length and width were 1 μm and 2×50 μm, respectively. Devices were left unpassivated to avoid the stress effects caused by SiN_x passivation.

This letter used a bending test fixture consisting of three stainless steel cylindrical bars used to apply the stresses, as shown in Fig. 1(b). The tensile strain was calculated as

$$\varepsilon_{\mathrm{yy}} = 3hJ_0/L^2\ [7]$$

where h is the thickness of the test die, J_0 is the deformation at the center, and L is the length of the test die. Devices were probed through the region between the two cylindrical bars on the top. The dc characterizations of the devices were performed by Agilent E5270B semiconductor analyzer. An Accent DiVA D225 measured the pulsed I–V characteristics with a pulsewidth of 100 ns, 1-ms separation between each pulse signal, and pulsed from the bias point of $V_{\mathrm{GS}} = V_{\mathrm{pinch-off}}$ and $V_D = 0$ V.

III. RESULTS AND DISCUSSION

Fig. 2 shows the saturation current density (I_{DSS}) shift of the devices with two gate orientations under different uniaxial

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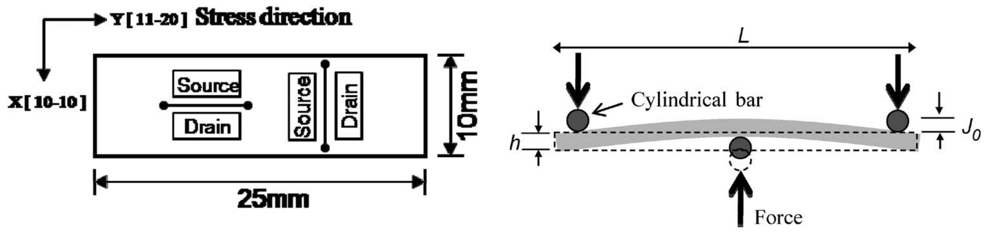


(a) (b)

Fig. 1. (a) Top view of the test die and gate orientations under uniaxial stress along [11–20] and [10–10]. (b) Schematic configurations of the three-point bending test fixture for the tensile stress.

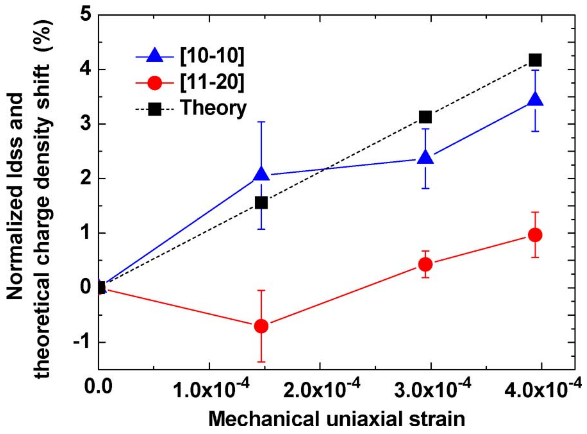


Fig. 2. Normalized I_{DSS} of the devices with gates oriented along [10–10] and [11–20] directions, and theoretical charge density shift as a function of mechanical uniaxial strain.

tensile strains. Devices with gates oriented along the [10–10] direction exhibited an increase in I_{DSS} when the uniaxial tensile strain increased. The saturation current increased by approximately 3.42% under a uniaxial tensile strain of 3.94×10^{-4}. For devices with gates oriented along the [11–20] direction, I_{DSS} declined by about 0.73% at a strain level of 1.47×10^{-4} and then increased to approximately 0.96% at a strain level of 3.94×10^{-4}.

The additional polarization charge induced by the mechanical uniaxial strain P_{un} is theoretically calculated by

$$P_{\mathrm{un}} = \left(e_{31} - e_{33}\frac{C_{12}}{C_{13}}\right)\varepsilon_{\mathrm{yy}} \; [8]$$

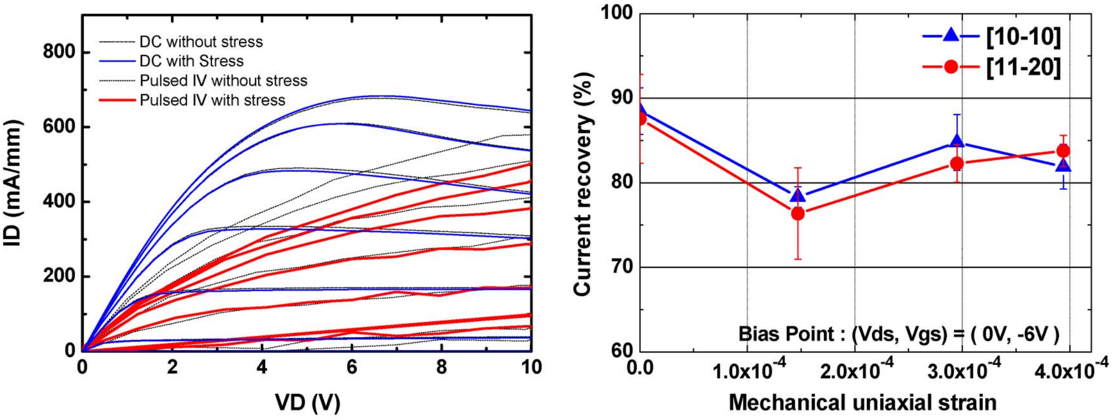
where e is the piezoelectric constant and C is the elastic constant of the Wurzite lattice [9]. Fig. 2 shows the results normalized to the original electron sheet concentration from the Hall measurement as a function of uniaxial tensile strain. These results agree with those for devices with gate orientations of [10–10]. However, for devices with a gate orientation of [11–20], this deviation is likely due to the modulation of electron mobility by the uniaxial strain. The decrease of the electron mobility in the current flow direction of [10–10] dominates the current density behaviors at lower strain states. The increase in the charge density then dominates as the strain becomes greater. Previous research reports that hole mobility of p-type GaN material under the uniaxial strain depends upon direction [10], but such an effect on the electron mobility of AlGaN/GaN requires further investigation.

Fig. 3(a) compares the pulsed I–V and dc I–V characteristics. Devices under a uniaxial tensile strain of 1.47×10^{-4} exhibited a significant reduction in transient drain current. Fig. 3(b) shows the current recovery (I_T/I_{DC}) (i.e., transient drain current at $V_{\mathrm{GS}} = 0$ V and $V_{\mathrm{DS}} = 10$ V, I_T normalized to dc values at the same bias point) as a function of different uniaxial tensile strains. No significant difference in current recovery appears in devices with these two gate orientations, and there is an approximately 10% reduction in current recovery at a strain level of 1.47×10^{-4}. When the strain exceeds 1.47×10^{-4}, there is still an approximately 5% reduction in current recovery at a strain level of 3.94×10^{-4}. This implies that the existence of additional donorlike surface states, which provide the electrons for the 2DEG through the additional piezoelectric polarization, results in the increased gate lag. This finding agrees with the source for electrons in AlGaN/GaN heterostructure reported by Ibbetson, *et al.* [3]. The slight upward trend in current recovery beyond a strain level of 1.47×10^{-4} implies that there could be other sources for the electrons [11].

To confirm the role of the SiN_x-induced tensile strain in drain current transient behavior, another wafer was fabricated using the same process flow mentioned earlier and then passivated with a sequence of SiN_x films using the standard PECVD process, as shown in Fig. 4(a). The first SiN_x layer helped avoid the contribution due to interface reactions between AlGaN and SiN_x. The second SiN_x layer induced a tensile stress of 2.32×10^{-4} to the devices, as determined by the lattice deformation on the AlGaN c-axis using high-resolution X-ray diffraction (not shown here). Fig. 4(b) compares the transient characteristics of the device before and after the second nitride layer passivation. The transient drain current decreases after the tensile stress SiN_x passivation, and this phenomenon is independent of gate orientation.

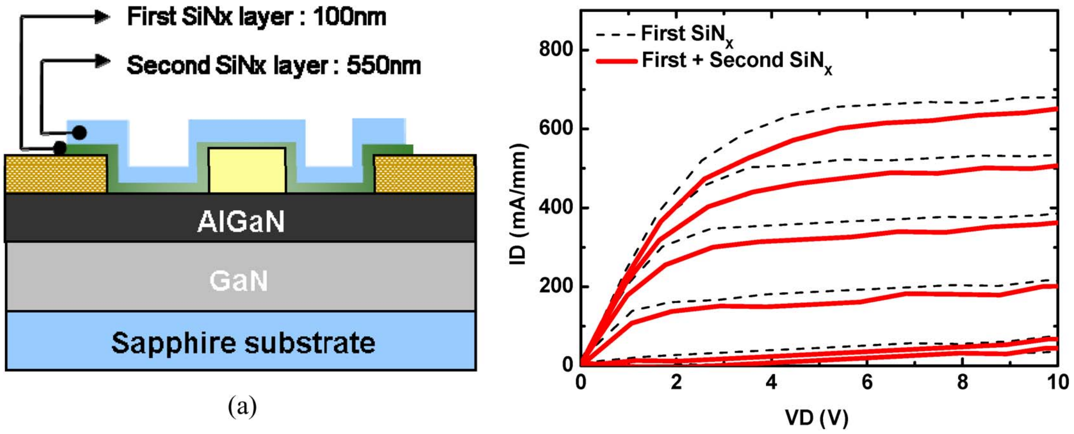
IV. CONCLUSION

The channel current density of AlGaN/GaN HEMTs can be modulated by applying a uniaxial tensile strain. The magnitude of the change in current density depends on the gate orientation. Although this strain can enhance dc characteristics, it also severely degrades current recovery. Similar results from a SiN_x passivation test suggest that tensile strain degrades the device transient performance. This could be attributed to the additional donorlike surface states induced by the additional piezoelectric



(a) (b)

Fig. 3. (a) Transient characteristics ($V_{\rm GS} = V_{\rm pinch-off}$ to 0 V, 1 V/step) of unpassivated AlGaN/GaN HEMTs under the strain of zero and 1.47×10^{-4} in comparison with the dc characteristics. (b) Current recovery of the unpassivated AlGaN/GaN HEMTs as a function of mechanical uniaxial strain.



(a) (b)

Fig. 4. (a) Cross section of the HEMT device with a sequence of SiN$_x$ passivation, including the first 100-nm-thick SiN$_x$ layer and the second 550-nm-thick SiN$_x$ layer. (b) Transient characteristics ($V_{\rm GS} = V_{\rm pinch-off}$ to 0 V, 1 V/step) of the device before and after second layer passivation.

polarization that the tensile strain produces. These findings could be useful for the optimization of SiN$_x$ passivation on AlGaN/GaN HEMTs.

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