Influence of InGaP and AlGaAs Schottky Layers on ESD Robustness in GaAs pHEMTs

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***Abstract*—GaAs high-electron-mobility transistors (HEMTs) have been widely used for radio-frequency (RF) applications due to the excellent material properties. One of the essential elements of the HEMTs is the gate Schottky barrier layer. InGaP has been proposed and proven as a better Schottky barrier material for the RF performance of the GaAs HEMTs. This letter investigates the influence of the GaAs HEMTs with two different Schottky layers, which are InGaP and AlGaAs on device transient characteristics under electrostatic discharge (ESD) stress. Although InGaP presents significant advantages on improving RF performance of GaAs HEMTs, it shows inferiority in ESD robustness.**

***Index Terms*—Electrostatic discharge (ESD), GaAs pseudomorphic high-electron-mobility transistor (pHEMT), InGaP Schottky layer, transmission-line pulsing (TLP) systems.**

I. Introduction

THE III–V compound semiconductors have been widely known for several material advantages, such as high electron mobility and high quantum efficiency, which are beneficial in the applications of wireless communication and photo-detecting and photo-emission elements. For radio-frequency (RF) integrated circuits, the GaAs pseudomorphic high-electron mobility transistors (pHEMTs) also have been used in low-noise amplifier and power amplifier circuits. In order to further improve the device performance of GaAs pHEMTs, recently, the aluminum-free InGaP has been used as a Schottky barrier layer due to high etching selectivity, low surface-recombination velocity, and oxidation reaction, and even no presence of deep-level defects (DX center) [1]–[3]. Many prior publications have presented the significant enhancement of RF performance with the InGaP or the AlGaAs Schottky layer on GaAs pHEMTs. Some have disclosed high electrostatic discharge (ESD) sensitivity in III–V compound semiconductor devices [4], for instance, light-emitting diodes [5], laser diodes [6], and HEMTs [7], [8]. However, none has investigated the influence of the different Schottky layers on the ESD characteristics of the HEMTs.

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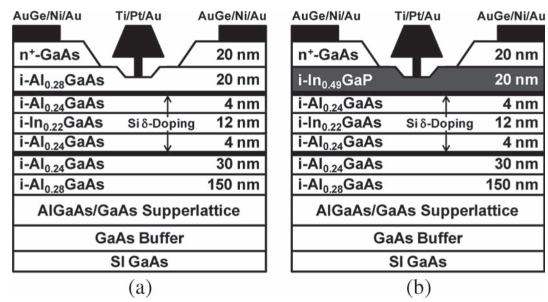

Fig. 1. Schematic cross-sectional views (not to scale) of the investigated InGaAs/GaAs pHEMTs with different Schottky barrier layers of (a) AlGaAs and (b) InGaP, respectively.

In this letter, the ESD robustness of two GaAs pHEMTs with different Schottky layers, which are AlGaAs and InGaP, is compared. The ESD characteristics of these two metal–semiconductor Schottky barrier contacts are analyzed by transmission-line pulse (TLP) and very fast TLP (vfTLP) I–V curves, which have been always used to emulate ESD events.

II. Devices and Experiments

Two different GaAs pHMET devices with different Schottky layers, which are AlGaAs and InGaP, respectively, have been fabricated, and schematic cross sections are shown in Fig. 1(a) and (b). Besides, the different Schottky layers, both pHEMTs have the same AlGaAs/GaAs supperlattice, AlGaAs spacer with dual delta (δ) doping, and InGaAs 2-D electron gas channel. These two pHEMTs were processed by five major steps, including the definition of the active region by mesa etch, ohmic metal (AuGe/Ni/Au) deposition and annealing at 340 °C for 30 s, wet chemical recess, gate formation (Ti/Pt/Au) by electron beam lithography and the liftoff process, and final gold plating of air bridges for the interconnects. The gate lengths (L) for these two pHEMTs are 0.25 μm, and the total widths (W) range from 160 to 500 μm. There is a symmetric gate-to-source and gate-to-drain layout style in these two pHEMTs. The gate-to-drain distance (D_{GD}) is $\sim 2 \mu$m.

Since the only difference in these two pHEMTs is the AlGaAs and InGaP Schottky layers, as shown in Fig. 1, the ESD characteristics will focus on the metal–semiconductor Schottky barrier contacts. The TLP (or vfTLP) stress with a pulsewidth of 100 ns (or 5 ns) and rise time of 2 ns (or 200 ps) was applied at the Schottky gate with a grounding ohmic drain and floating ohmic source configuration. More specific, it is a Schottky barrier diode between the gate and the drain. After each (vf)TLP stress, the dc I–V characteristic is measured to detect device failure. The device failure was defined as a 2× increase in the dc leakage current at a −3-V Schottky gate voltage.

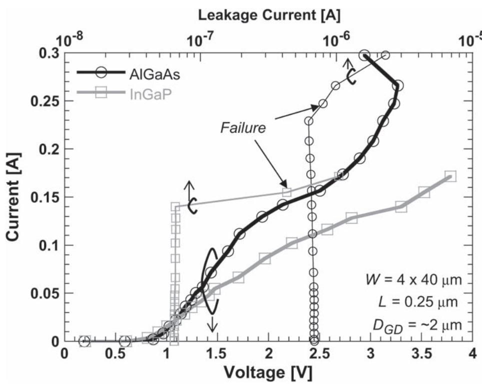

Fig. 2. TLP I–V characteristics (with corresponding leakage curves) of the AlGaAs and InGaP Schottky diodes under forward mode.

III. Results and Discussion

According to the previous study [9], the InGaP Schottky layer can significantly enhance the RF performance of the GaAs pHEMT, such as very low noise figure, low third-order distortion, and low dc power consumption, comparing with the AlGaAs Schottky layer. It also presents a very low dc gate leakage current due to the better material features of InGaP. Here, we evaluate the ESD robustness of these two pHMETs through TLP and vfTLP I–V characteristics under forward and reverse modes of the Schottky gate diodes.

A. Forward Mode of Schottky Gate Diode

Fig. 2 shows TLP measured results of the two different Schottky diodes with AlGaAs and InGaP Schottky layers. These two diodes have similar cut-in voltages (around 0.7–0.8 V), but they have significant differences of on resistance (Ron) and failure current level $(It2)$. The one with the AlGaAs Schottky layer has lower Ron and higher $It2$, comparing with that with the InGaP Schottky layer. The lower Ron and higher $It2$ are beneficial for ESD protection. Generally, the Human Body Model (HBM) ESD robustness can be estimated by the corresponding TLP $It2$ value; for example, the $It2$ values of the AlGaAs and InGaP Schottky diodes are 0.23 and 0.14 A, respectively. It can be interpreted that the latter one would have a lower HBM ESD robustness.

The maximum tolerable power $(P_{\max})$ of AlGaAs Schottky diodes is 0.69 W, which is higher than 0.49 W of the InGaP Schottky diode. The lower $P_{\max}$ of the InGaP Schottky diode further indicates the disadvantage under ESD conditions. The $It2$ values of these two Schottky diodes are linearly increased by increasing W. This illustrates that the TLP current can be uniformly discharged in these two diodes. Therefore, the lower $It2$ and lower $P_{\max}$ of the InGaP Schottky diodes are not strongly connected to a nonuniform behavior. Rather, they seem to be attributed to the essential material properties of the Ti/InGaP Schottky barrier contact or the InGaP barrier layer. Although the reaction energy between Ti and AlGaAs is lower than that between Ti and InGaP [10], Ti penetrating into AlGaAs forms a TiAs phase, which does not destroy the Schottky barrier and even slightly increases the barrier height (ϕ_b) [11], [12]. A locally increasing ϕ_b by forming a TiAs phase can further help in spreading out the current to prevent a localized hot spot inducing failure. In addition, a narrower band gap (Eg) and a higher thermal conductivity of AlGaAs can also have a positive influence on ESD robustness. These can be possible explanations on the difference of the TLP $It2$ between the AlGaAs and InGaP diodes. With a much shorter pulsewidth (only 5 ns) and much faster rise time (∼200 ps), vfTLP has been used for analyzing the device turn-on speed and initial transient characteristics. Fig. 3 demonstrates the comparisons between the TLP and vfTLP measurement results of the AlGaAs and InGaP Schottky diodes. The AlGaAs diodes have similar TLP and vfTLP I–V curves below 0.2 A (which approaches to the $It2$ of TLP); however, the InGaP diodes only have similar curves below 0.06 A, and the Ron of vfTLP is higher than that of TLP. In Fig. 4, the TLP transient voltage (V) waveforms show the InGaP diodes need over 15 ns for fully clamping the V at a lower voltage level, particularly for a higher current level, whereas the AlGaAs diodes only need ∼5 ns. This difference indicates that carriers spend longer time to transit through the Schottky barriers between Ti and InGaP. It is probably due to the higher ϕ_b and the wider Eg of InGaP. The deficient transient behavior of the InGaP diodes also induces the higher Ron under vfTLP stress.

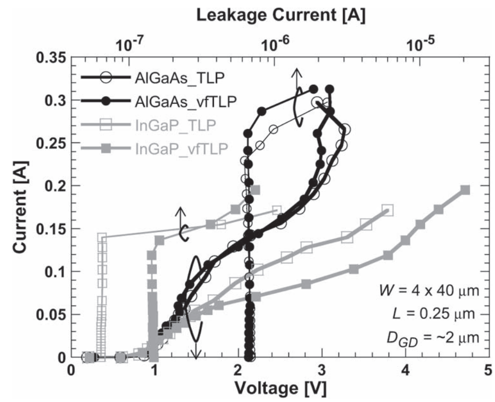

Fig. 3. TLP and vfTLP I–V characteristics (with corresponding leakage curves) of the AlGaAs and InGaP Schottky diodes under forward mode.

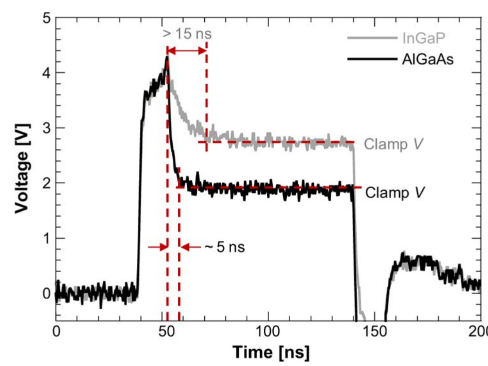

Fig. 4. TLP transient voltage waveforms of the AlGaAs and InGaP Schottky diodes under forward mode.

In addition, the vfTLP $It2$ of both diodes are not significantly higher than their TLP $It2$. This does imply that the failure mechanism of these Schottky barriers between Ti and AlGaAs (or InGaP) is not dominantly related to thermal energy. The diodes were a failure at certain current values, which are ∼0.23 A and ∼0.14 A in the AlGaAs and InGaP diodes, respectively. Recently, similar observations have been also reported for GaN Schottky gate diodes [13]. It seems to be associated with the huge TLP current, which causes high current density

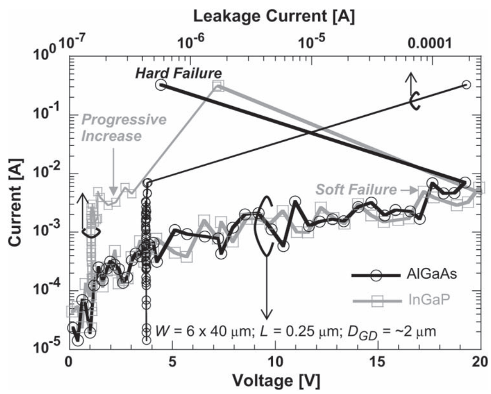

Fig. 5. TLP I–V characteristics (with corresponding leakage curves) of the AlGaAs and InGaP Schottky diodes under reverse mode.

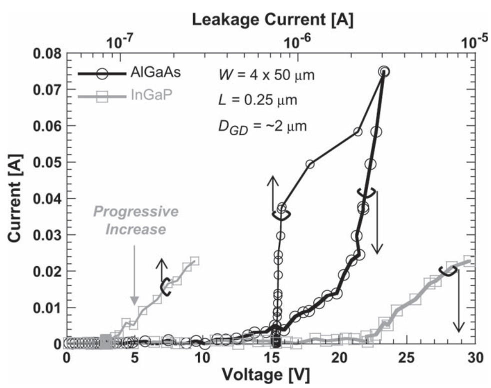

Fig. 6. vfTLP I–V characteristics (with corresponding leakage curves) of the AlGaAs and InGaP Schottky diodes under reverse mode.

and, thus, induces the electromigration between Ti and AlGaAs (or InGaP). Unfortunately, the firm root cause has not yet been well found; therefore, further study on III–V Schottky diodes is required to solve this puzzle.

B. Reverse Mode of Schottky Gate Diode

The TLP measured results of both Schottky diodes under the reverse mode are presented in Fig. 5. These two different Schottky diodes had an almost zero $It2$, and both failed below 20 V of the corresponding TLP voltage.

In Fig. 5, once the diodes failed, the TLP currents suddenly jumped up to $\sim$0.3 A. Simultaneously, the reverse dc leakage currents also drastically increased to indicate the device failure. Although the InGaP diode shows a higher failure voltage (close to 20 V), its dc leakage current has progressively increased before the catastrophic failure, which is defined as a hard failure. The progressive increase in the dc leakage current starts at $\sim$17 V, and it suggests that the Ti/InGaP Schottky barrier contact had already a soft failure before the hard failure. However, for the AlGaAs diode, there is no progressive increase in the dc leakage current (or soft failure) before the hard failure at $\sim$19 V. These reverse-mode TLP measured results still infer that the InGaP Schottky diodes are more susceptive to ESD events.

Fig. 6 exhibits the reverse mode vfTLP results of both types of Schottky diodes. The InGaP diode had an almost zero $It2$ under reverse vfTLP stress as well as its $It2$ under reverse TLP stress. Although the vfTLP current of the InGaP diode started to increase after 22 V, its dc leakage current also started to progressively increase. This means that a progressive soft failure has been induced once this reverse diode started conducting current. However, the AlGaAs diode did not fail until the vfTLP current exceeded 0.04 A. It indeed started conducting current after 10 V, as shown in Fig. 6, and the conducting current was greatly increased after 20 V. The current conduction relieved the voltage stress across the Schottky barrier contact. The AlGaAs diode did not show a catastrophic hard failure under reverse-mode vfTLP stress. This can be attributed that only one-twentieth reverse stress time was applied to it during the 5-ns vfTLP stress. The failure voltages of the AlGaAs diodes are $\sim$19 and 21 V under the TLP and vfTLP stresses, respectively.

IV. Conclusion

In this letter, we studied the ESD robustness of the InGaAs/GaAs pHEMTs with two different Schottky barriers, which are AlGaAs and InGaP. The InGaP Schottky layer is more sensitive to ESD events, although it has been proven to have better RF performance. Under the Schottky barrier forward-mode TLP stress, the InGaP Schottky diodes show lower $It2$, higher Ron, and lower $P_{\max}$, comparing with the AlGaAs Schottky diodes. In addition, the InGaP Schottky diodes also have the early progressive soft failure under the reverse-mode TLP stress.

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