Mechanism of Current Gain increase of Heterostructure Bipolar Transistors Passivated by Low-Temperature Deposited SiN_x

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Abstract — **The graded base InGaAs/InP heterostructure bipolar transistors (HBTs) were passivated by the low-temperature plasma deposited SiN_x. The current gain was found to increase after the passivation. The study of the Gummel plots shows that the passivation results in the reduction of both the collector current and base current, while the decrease of the base current is more significant. This causes the increase of the current gain. Nitrogen plasma treatment results in the increase of the current gain, while Silane plasma treatment results in a small reduction of the current gain. The influence of the plasmas of the two sources on the HBTs' performance are investigated. *In-situ* ellipsometer study showed that at the initial state of SiN_x deposition, the SiN_x deposition rate was zero, and nitrogen plasma has strong effects on the passivation of HBTs and results in the increase of the current gain.**

I. INTRODUCTION

SiN_x (or SiO_2) passivation of InP-based HBT was intensively investigated in recent years. But the passivation typically suffers from the degradation of current gain. In SiN_x passivation, NH_4 and SiH_4 are typically used as sources. These two gases generate hydrogen radicals during SiN_x deposition. For the SiN_x passivation of InP-based HBTs, the hydrogen radicals in the plasma result in the preferential loss of group-V elements and in an group-III element rich surface [1]. This nonstoichiometric surface typically serves as a leakage channel and results in enhanced surface recombination, these cause the increase of the base current and the decrease of current gain. The degradation of the current gain is also related to the high deposition temperature of SiN_x. For example, the degradation of the current gain in HBTs was suppressed to a certain degree when SiN_x was deposited at low temperature. But the current gain after passivation is always smaller than that before passivation. When the semiconductor surface is exposed to the plasma, the reaction between the surface and plasma becomes stronger with increasing temperature. The higher deposition temperature causes the even more severe nonstoichiometric problem, while the surface nonstoichiometry can be suppressed by the addition of nitrogen gas in plasma [2]. Here we report on SiN_x passivation of graded-base InGaAs/InP HBTs. N_2 gas was used as source instead of NH_3 in conventional PE-CVD in order to decrease hydrogen radicals. SiN_x was deposited at room temperature in order to decrease the thermal damages. An increase of current gain is obtained by the SiN_x passivation. The mechanism is investigated.

II. EXPERIMENT

The HBT layers were grown by LP-MOVPE on semi-insulating (001) InP (Fe) substrates. The layer structure is shown in Table I. The HBTs were

Layer		Thickness (nm)	Doping (/cm^3)	In concentration	Growth temperature
Cap	n^+-InGaAs	135	1.5×10^{19}	0.53	620 °C
Emitter	n-InP	65	5×10^{17}	-	600 °C
Base	p^+-InGaAs	70	1.5×10^{19}	0.49→0.60	500 °C
Collector	i-InGaAs	300	-	0.53	620 °C
	n^+-InGaAs	300	2×10^{19}	0.53	620 °C
InP substrate		S. I.-InP	-	-	

TABLE I
MOVPE GROWN LAYER STRUCTURE USED FOR HBT FABRICATION.

fabricated by conventional wet etching and metal deposition. The HBTs were nonself-aligned. The layout is single emitter and double base contacts. The space between the emitter and base contact is 1 µm. For SiN_x deposition, a PlasmaLab System 90 ECR-PECVD from Oxford Instruments was used. Details about the facility were given in Ref. [3]. The temperature of the sample holder was maintained at 20 °C during the deposition. The HBTs were covered with 100-nm-thick SiN_x without any pre-treatment. The microwave power was set to 180 W. 90 sccm silane (SiH_4) diluted in helium (5%/95%) and 5 sccm nitrogen gases were used as sources. The chamber pressure was kept at 5 mTorr during the deposition process. The refractive index of the SiN_x is about 1.9 in this deposition condition. DC characteristics was measured by HP 4515B semiconductor analyzer.

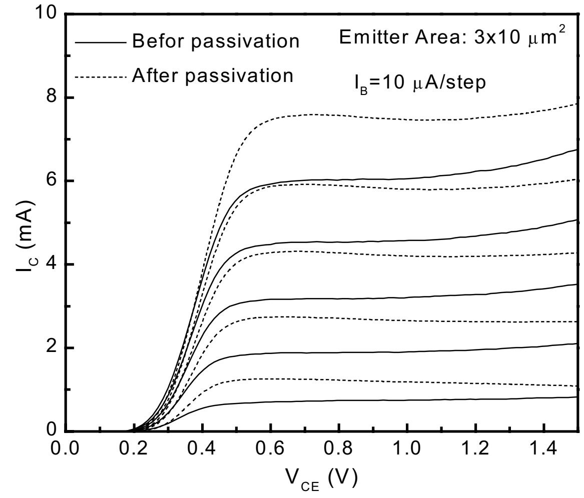

Fig. 1. The common-emitter I-V characteristics of HBTs before and after passivation.

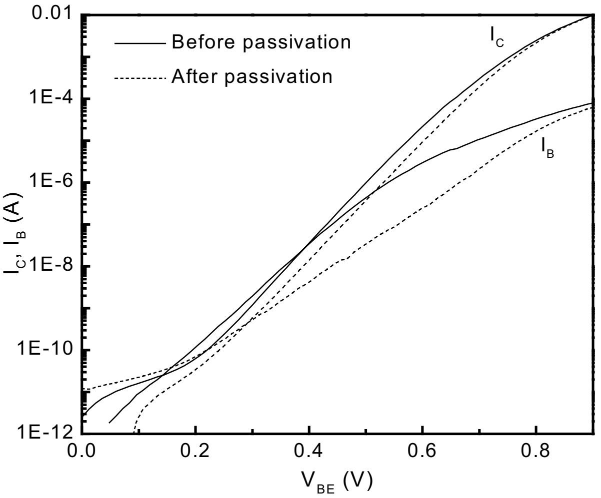

Fig. 2. The Gummel plots of HBTs before and after passivation.

III. RESULTS AND DISCUSSION

Figure 1 shows the common-emitter I-V characteristics of the HBT before and after SiN_x passivation. Before the SiN_x passivation, the current gain of more than 100 can be derived from this figure. The collector current, I_C, increases by more than 20% at the same base current after the passivation, indicating the increase of the current gain. Although we found the reverse current of the base-collector diode increased from 6×10^{-10} to 3×10^{-7} A at V_{BC}=1.5 V after passivation, I_{CEO} (the collector current at I_B=0 in the common emitter configuration) was not affected, as shown in Fig. 1.

Figure 2 shows the Gummel plots of the HBT before and after SiN_x passivation. Both the collector current and base current, I_B, decrease after

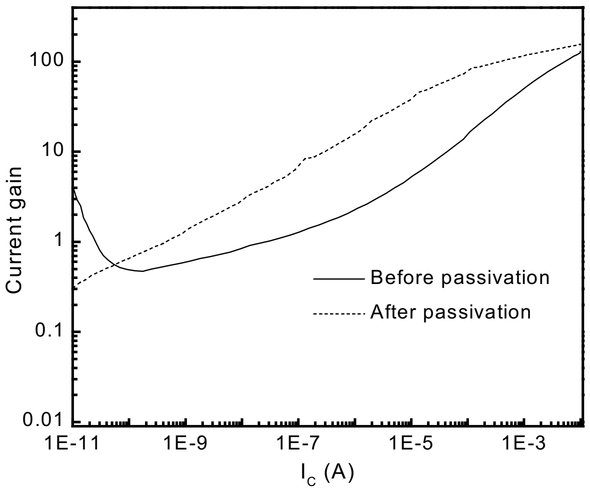

Fig. 3 The current gains as function of the collector current for the HBTs before and after passivation.

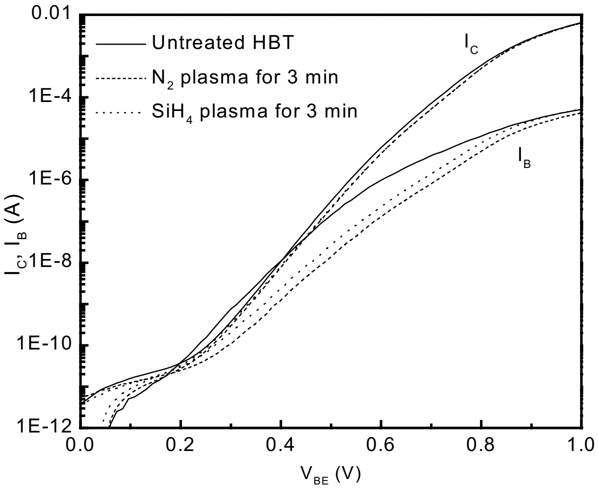

Fig. 4 The Gummel plots of HBTs before treatment, after N_2 and SiN_4 plasmas treatments.

passivation. The decrease of the base current is much larger than that of the collector current. The base current is composed of the following four components: the space charge recombination, the bulk recombination in the neutral base region, the surface recombination current at the space between the emitter and base contact, and the interface recombination under the base contact. For a nonself-aligned HBT, the space between the emitter and base contact is large, thus the excess carrier concentration under the base contact is very small and the interface recombination current can be neglected. While the space charge recombination and the bulk recombination components are mainly generated in the intrinsic base region. Thus the decrease of the base current is due to the decrease of the surface recombination. The decrease of the base current is also found in $(NH_4)_2S$ passivation of InGaAs/InP HBT. But for SiN_x passivation the base current typically increases drastically. The study of Kikawa et al. [4] showed that the SiN_x passivation causes the shift of the Fermi level position. A surface leakage channel was formed and results in the increase of the base current. In our case, the decrease of the base current indicates that no such surface channel was formed.

Figure 3 shows the current gains which are derived from Fig. 2. As shown in this figure, the current gain increases after the passivation. the increase of the current gain is due to the significant decrease of the base current, as shown in Fig. 2. The large current gain before the passivation at very small collector current level is due to the leakage current of the base and collector junction [5]. To our knowledge, there is first report that the current gain can be improved by just SiN_x passivation.

We now discuss the mechanism of the increase of the current gain in our case. There are two gases in our SiN_x deposition: N_2 and SiH_4. We investigate the effects of the two kinds of plasma treatments on the HBT performance. Here, the HBTs were treated by N_2 and SiH_4 plasmas at room temperature, subsequently. Figure 4 shows the Gummel plots of the HBT before and after treatment by the N_2 and SiH_4 plasmas. The mirowave power was 60 W and the pressure was 5 mTorr during the treatments. The collector current decreases slightly after N_2-plasma treatment. In contrast, the base current decreases drastically when treated by the N_2-plasma. The behavior is much like that of the HBT passivated by SiN_x. The nitrogen plasma can partly remove the oxide on the surface. While the oxide typically acts as non-recombination centers. Thus the nitrogen plasma treatment causes the decrease of the surface recombination and the decrease of the base current. When the same sample was subsequently treated by the SiH_4 plasma, the collector current is the same as that treated by N_2-plasma, but the base current increases. The reason may be that the stoichiometric surface is broken down by the hydrogen radicals in the SiH_4 plasma. This results in the increase of the surface recombination current and in the increase in the base current. Another possibility is that the stress between the InGaAs and the deposited Si attributed to the leakage current.

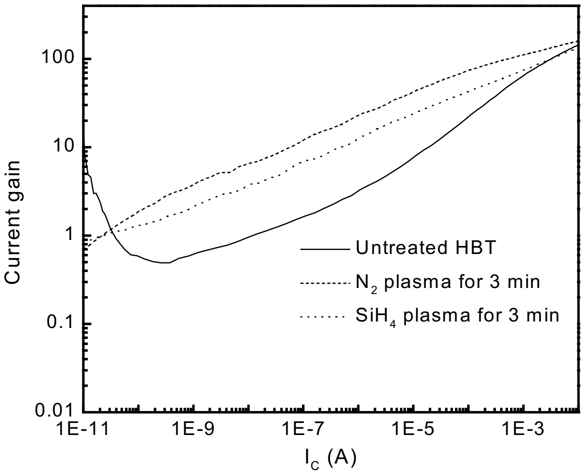

Fig. 5 The current gains of HBTs before treatment, after N_2 and SiN_4 plasmas treatments.

Figure 5 shows the current gain derived from Fig. 4. The derived current gain shows that the current gain of HBT was improved by the N_2-plasma treatment and the current gain of HBT was decreased a little by SiH_4-plasma, as shown in Fig. 5. But the current gain is still much larger than that before treatment.

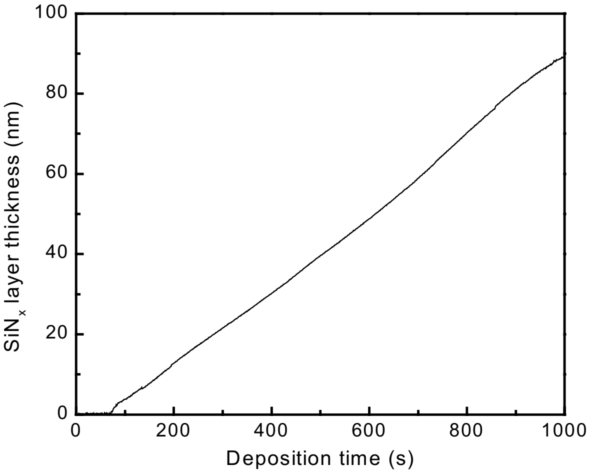

Fig. 6 SiN_x layer thickness as function of deposition time. This is measured by the *in-situ* ellipsometry.

It is very helpful to understand the mechnsm of the SiN_x passivation through the investigation of the deposition process. Figure 6 shows the SiN_x layer thickness as a function of deposition time measured by the *in-situ* ellipsometry. The deposition rate is 0 at the beginning 70 s. In our system, the plasma is generated by the N_2 gas, while the SiH_4 gas does not flow through the ECR chamber [3]. Thus in the initial stage of the deposition, the sample surface was treated by the N_2 plasma (note that the deposition rate is 0). We believe that the N_2 plasma can passivate the defects near the surface which is related to the surface recombination centers. This results in the decrease of the surface recombination and in the decrease of the base current, as shown in Figs. 4 and 5. Furthermore, the surface stoichiometry was maintained by the plasma treatment. Even the SiH_4 plasma treatment did not damage the N_2 plasma treated surface. This can be seen from the higher current gain and lower base current, shown in Figs. 4 and 5.

IV. CONCLUSION

We developed a new SiN_x passivation process. The graded based InGaAs/InP HBTs were successfully passivated. After the passivation, both the collector and base currents in Gummel plots were found to decrease, but the base current decreased more significantly. This resulted in the increase of the current gain. When InGaAs/InP HBT is treated by one of the sources, the nitrogen plasma only, the current gain was also found to increase, while Silane treatment resulted in a little decrease of the current gain. The in-situ ellipsometry study showed that the increase of current gain is related to the effect of N_2 plasma treatment at the initial deposition process.

ACKNOWLEDGEMENT

The authors would like to thank Ms. A. Osinski for her technology support.

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