4.2.5  **Sulfur and Low Temperature SiN\textsubscript{x} Passivation of InGaAs/InP Heterostructure Bipolar Transistors**

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**Introduction**

Driad et al. [1] used (NH\textsubscript{4})\textsubscript{2}S\textsubscript{x} solution in the passivation of InGaAs/InP HBTs. InGaAs surface after sulfur treatment was found to be oxide-free. The current gain was improved remarkably. However, the treated surface is unstable. Silicon nitride (SiN\textsubscript{x}) passivation suffers from some limitations: such as degradation of current gain. To maintain the sulfur passivation effects, the passivated surface is typically covered with SiN\textsubscript{x} (or SiO\textsubscript{2}) [2, 3]. In this paper we investigate the combination of sulfur and SiN\textsubscript{x} passivations of self-aligned InGaAs/InP HBT with compositionally graded base structure. Our study showed that the current gain increased after the combination of S and SiN\textsubscript{x} passivation. The current gain can be further improved by annealing.

**Experiment**

The heterostructure was grown by LP-MOVPE on (001) semi-insulating (001) InP (Fe) substrates in the following sequence: 300 nm Si-doped (2×10\textsuperscript{19} cm\textsuperscript{-3}) In\textsubscript{0.53}Ga\textsubscript{0.47}As, 140 nm Si-doped (3×10\textsuperscript{17} cm\textsuperscript{-3}) InP, 70 nm C-doped (1.5×10\textsuperscript{19} cm\textsuperscript{-3}) In\textsubscript{x}Ga\textsubscript{1-x}As (0.49≤x≤0.60), 300 nm unintentionally doped In\textsubscript{0.53}Ga\textsubscript{0.47}As, and 300 nm Si-doped (2×10\textsuperscript{19} cm\textsuperscript{-3}) In\textsubscript{0.53}Ga\textsubscript{0.47}As. The HBTs were fabricated by conventional wet chemical etching and optical contact lithography. The (NH\textsubscript{4})\textsubscript{2}S\textsubscript{x} solution was prepared from commercial (NH\textsubscript{4})\textsubscript{2}S solution (20 %) with excess pure sulfur. The concentration of (NH\textsubscript{4})\textsubscript{2}S\textsubscript{x} is about 3 %. The HBTs were soaked in this solution for 10 minutes at 40 °C. The samples were cleaned by propanal and acetone solvents. After the cleaning process, the sample was blown dry by nitrogen. Then the samples were transferred into an ECR-plasma enhanced CVD chamber. The HBTs were then covered with 100-nm-thick SiN\textsubscript{x}. For the SiN deposition, a PlasmaLab System 90 ECR-PECVD from Oxford Instruments was used. To check the thermal effects, we annealed HBTs at 300 °C for 5 minutes in a N ambient after SiN\textsubscript{x} deposition. The DC characteristics of the fabricated HBTs were measured by an HP 4515B semiconductor parameter analyzer.

**Results and Discussion**

Fig.1(a) shows the common-emitter I-V characteristics of the HBTs before and after S/SiN passivation. The characteristics of the HBT annealed after passivation is also shown in this figure. Before the passivation, the current gain larger than 100 was derived. Figure 1(b) shows that the offset voltage is 0.17 V. The S/SiN\textsubscript{x} passivation results in the increase of the collector current by 15 % at the same base current, indicating that the current gain increases by about 15 %. The offset voltage decreases to 0.15 V, which is smaller than that before passivation. The annealing causes the further collector current increases by 5 % compared with passivated HBT. As shown in Fig. 1(b), the offset voltage increases to 0.17 V, which is the same as that before passivation.
Fig. 1  The common-emitter I-V characteristics of HBTs studied (a) and the I-V characteristics of HBT near the offset voltage (b). The emitter area is $3 \times 10^2 \mu m^2$.

Fig. 2  The Gummel plots (a) and corresponding current gain (b) of HBT. The HBT structure and the treatment are the same as those in Fig. 1.

Fig. 2 shows the Gummel plots and corresponding current gains of the HBTs before and after passivation. Before S/SiN passivation, the collector current increases much faster than the base current and they cross at base-emitter bias $V_{BE}=0.3$ V, as shown in Fig. 2(a). After S/SiNx passivation, the base current decreases in the whole range of $V_{BE}$ compared with that before passivation. This indicates that the surface recombination is suppressed by the passivation. In contrast, the passivation results in the increase of collector current. Especially, at small applied voltage, the collector current is much larger than that before passivation. A similar phenomenon was also found in SiNx passivation of InP/InGaAs/InP double HBT and this is attributed to the leakage current of base-collector junction [4]. But the increase of the collector current at the small applied voltage is accompanied by the large increase of the base current. The increase of the base current is due to the increase of the leakage at the surface of the base-emitter junction. While in our case, the base current is smaller than that before passivation in the whole measured voltage. This indicates that the S/SiNx passivation affects the emitter-base diode and base-collector diode differently. The decrease of the base current indicates that the surface recombination is suppressed by the S/SiNx passivation. The S passivation typically decreases drastically the base current in InGaAs/InP HBTs by removing the native oxide layer and forming the In-S-In and Ga-S-Ga bonds [5]. The native oxide acts as non-radiative recombination center. But this surface is sensitive to the plasma conditions. Our results show that the room-temperature deposited SiNx is suitable for the over passivation of the S-treated surface. The annealing causes further decrease of base current, as shown in Fig. 2(a). It also causes the decrease of collector current. The collector current is even less than that before passivation. This indicates that the annealing process can effectively suppress the base-collector leakage current caused during S/SiNx passivation. The current gain increases after the passivation and annealing, as shown in Fig. 2(b). However, the behaviors of their increases are different. For S/SiNx passivated HBT without annealing, the current gain decreases with the decrease of the collector current at first, it increases after it passes its minimal value. The current gain has a valley at $I_C=10^{-8}$ A. If we check the Gummel plots, we find that the collector current is
larger than that before passivation in this region. This is due to the leakage current of base-collector junction. The current gain of the HBT after annealing increases monotonously with the increase of the collector current. The current gain is much larger than that before passivation in the whole measured range. It is larger than that before annealing when $I_c > 10^{-8}$ A, indicating that the annealing can further improve the current gain. This is consistent with the results of the common-emitter I-V characteristics, as shown in Fig. 1. It is notable that the peak of the current gain at the low collector current disappears, indicating the leakage current is suppressed by the annealing process.

Fig. 3 shows the I-V characteristics of base-collector junctions. The passivation and annealing do not affect the forward characteristics. While the reverse current increases drastically after the passivation, the annealing results in two-order decrease of the reverse current.

![Fig. 3](image)

*The I-V characteristics of base-collector diodes in HBTs before and after passivation.*

References: