Available online at www.sciencedirect.com
ScienceDirect
Applied Surface Science 252 (2006) 7664–7670
applied surface science
www.elsevier.com/locate/apsusc

Passivation of InP-based HBTs

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Available online 11 May 2006

Abstract

The surface effects, the $(NH_4)_2S$ and low-temperature-deposited SiN_x passivations of InP-based heterostructure bipolar transistors (HBTs) have been investigated. The surface recombination current of InP-based HBTs is related to the base structures. The $(NH_4)_2S$ treatment for InGaAs and InP removes the natural oxide layer and results in sulfur-bonded surfaces. This can create surface-recombination-free InP-based HBTs. Degradation is found when the HBTs were exposed to air for 10 days. The low-temperature-deposited SiN_x passivation of InGaAs/InP HBTs causes a drastic decrease in the base current and a significant increase in the current gain. The improvement in the HBT performance is attributed to the low deposition temperature and the effect of N_2 plasma treatment in the initial deposition process. The SiN_x passivation is found to be stable. S/SiN_x passivation of InGaAs/InP HBTs results in a decrease in the base current and an increase in the current gain. The annealing process can cause the base current to decrease further and the current gain increase.

PACS: 73.20.At; 73.40.Kp; 73.50.Gr; 73.61.Ey; 81.65.Rv; 85.30.Pq

Keywords: InP; Heterostructure bipolar transistor; Passivation; Sulfur; Silicon nitride

1. Introduction

The applications in high-speed communications and radar drive the research on wide bandwidth heterojunction bipolar transistors (HBTs). Compared to the counterpart Si-base material, III–V semiconductor materials have their advantages, such as the lower sheet resistance, higher saturation velocity, and so on. InP-based HBTs are attractive for optoelectronic integrated circuits because they are compatible with the growth and processing of optoelectronic devices that operate at the 1.3 and 1.55 μm communication wavelengths.

In a three-mesa InP-based HBT, the surface recombination occurred at the extrinsic base region can cause an increase in the base current and a decrease in the current gain. Thus, the passivation process is necessary. The HBT passivation consists of the chemical passivation [1–4], dielectric passivation [5–8], and ledge passivation [9]. The ledge passivation normally uses a larger band gap material (typically the emitter) to cover the base region. The ledge is required to be fully depleted, but this makes the passivation of self-aligned HBTs difficult. Here, we concentrate on the chemical and dielectric passivations.

Since the Na_2S solution was used to passivate AlGaAs/GaAs HBT and a marked increase in current gain was observed [1], many kinds of sulfur-containing solutions have been widely investigated. Among them, $(NH_4)_2S_x$ solution yields significant results. Recently, Driad et al. [2] used this solution in the passivation of InGaAs/InP HBTs. The InGaAs surface after sulfur treatment was found to be oxide-free. The current gain was improved remarkably. We further proved that $(NH_4)_2S$ can suppress the effect of surface recombination completely [3,4]. However, the treated surface is unstable [3]. The HBTs would degrade again with time.

Silicon nitride (SiN_x) or silicon dioxide (SiO_2) dielectric films deposited by plasma-based technology have been intensively investigated for HBT passivation in recent years [5–8]. However, this technology suffers from some limitations, such as degradation of the current gain. This may be caused by the thermal damage and nonstoichiometric surface. Recently, we developed a room-temperature-deposited SiN_x passivation [7]. This passivation is a low-damage method and results in an

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0169-4332/$ – see front matter
doi:10.1016/j.apsusc.2006.03.050

increase in the current gain. The perimeter-to-area ratio dependence was also found to be suppressed.

To maintain the sulfur passivation effects, the passivated surface is typically covered with SiN_x (or SiO_2) [10–12]. The sulfur-treated surface is extremely sensitive to the fabrication processes of the insulator overlayer [10]. Among the many candidates for deposition, which are widely used in semiconductor fabrications, electron cyclotron resonance chemical vapor deposition (ECR-CVD) appears to be a promising system for the deposition for over-passivation of sulfur-treated surfaces because of its low-energy deposition [10]. Recently, the $(NH_4)_2S$ treatment and SiN_x over-passivation was successfully used in InGaAs/InP HBTs [12]. An increase in the current gain was obtained.

In this paper, both the $(NH_4)_2S$ and SiN_x passivation of InP-based HBTs and a combination of them were investigated.

2. Experimental

Both InP-based single HBTs (SHBTs) and double HBTs (DHBTs) were studied in this paper. The HBT structures were grown by low pressure metallorganic vapor-phase epitaxy (LP-MOVPE) (AIXTRON 200) on a (0 0 1) $\pm$ 0.5 oriented semi-insulating (0 0 1) InP (Fe) substrate. The details of the growth of the DHBT can be found in our previous paper [13]. Sample A was a graded-base SHBT. The layer structure has the following sequence from the bottom to the top: 300-nm Si-doped (2×10^{19} cm^{-3}) $In_{0.53}Ga_{0.47}As$ as the subcollector, 300-nm unintentionally doped $In_{0.53}Ga_{0.47}As$ as the collector, 70-nm C-doped (1.5×10^{19} cm^{-3}) $In_xGa_{1-x}As$ ($0.49 \le x \le 0.60$) as the base, 140-nm Si-doped (3×10^{17} cm^{-3}) InP as the emitter, and 150-nm Si-doped (2×10^{19} cm^{-3}) $In_{0.53}Ga_{0.47}As$ as the emitter cap layer. The layer structures of samples B and C are DHBTs. Sample B is an abrupt-base DHBT, which consists of a 270-nm $In_{0.53}Ga_{0.67}As$ subcollecter (Si: 2×10^{19} cm^{-3}), a 200-nm InP collector (unintentionally doped), unintentionally doped 20-nm $In_{0.73}Ga_{0.27}As_{0.58}P_{0.42}$, 10-nm $In_{0.64}Ga_{0.36}As_{0.77}P_{0.23}$ and 20-nm $In_{0.53}Ga_{0.67}As$ layers to eliminate the blocking effect, a 70-nm InGaAs base layer (C: 1.5×10^{19} cm^{-3}), a 65-nm InP emitter (Si: 3×10^{17} cm^{-3}), and a 135-nm $In_{0.53}Ga_{0.47}As$ cap layer (Si: 2×10^{19} cm^{-3}). Sample C is a graded-base DHBT, which has the same structures as those of sample B, except that the base is graded with the In concentration changing from 0.49 to 0.61. The HBTs were fabricated by conventional wet etching and metal deposition with a three-mesa design.

For $(NH_4)_2S$ treatment, a commercial $(NH_4)_2S$ solution was used for the passivation. The samples were soaked in the solution for 2 min at room temperature. The samples were cleaned with propanol (or ethanol) and acetone solvents. They were finally blown dry by nitrogen gas. The surfaces were very clean after the treatment; no residual substances were found. To characterize the surface chemical changes, X-ray photoelectron spectroscopy (XPS) was used. Both InGaAs and InP were carried out.

For SiN_x deposition, a PlasmaLab System 90 ECR-PECVD from Oxford Instruments was used. Details about the facility are given in our previous paper [14]. The temperature of the sample holder was maintained at 20 °C during the deposition. The samples were covered with 100-nm-thick SiN_x without any pretreatment. The microwave power was set to 180 W. Ninety-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 SiN_x is about 1.9 under this deposition condition. dc characteristics were measured by an HP 4515B semiconductor analyzer.

3. Results and discussion

3.1. Surface recombination in InP-based DHBTs

In an HBT, the base current originates from the recombinations between the holes in the base and the electrons injected from the emitter. According to the places where the holes recombine, the base current can be classified into five components [7]: the back-injected current (I_{Bp}), the space charge recombination current ($I_{B,scr}$), the bulk recombination current ($I_{B,bulk}$), the surface recombination current ($I_{B,surf}$) and the contact recombination current ($I_{B,cont}$). At a different bias, the importance of each component is different [15]. At a small bias, the base current is dominated by the space charge and surface recombination currents. At a large bias, the increasing importance of the bulk recombination component will occur. In a Gummel plot, in which the base–emitter junction is forward-biased and the base–collector junction is zero-biased, most of the electrons injected from the emitter go through the base region and are collected by the built-in field of the base–collector junction; only a small part of the electrons recombine with the holes in the base. Thus, the base current is very sensitive to each of recombination components.

We now examine the Gummel plots of samples B and C to understand the base current components. Fig. 1 shows the forward Gummel plots. Samples B and C have almost the same collector current. The ideality factors of them are near unity, indicating the current transport is limited by the base layer [16]. Their base currents are different, however. The base current of sample B is smaller than that of sample C at a small V_{BE}, while at a large base–emitter bias, the base current of sample B is

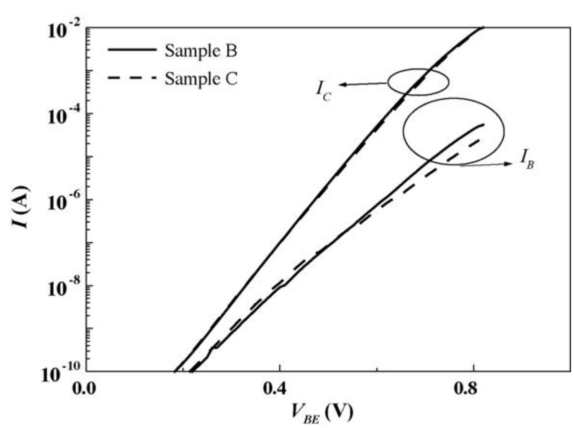

Fig. 1. The Gummel plots of the graded- and abrupt-base DHBTs.