Heterojunction Bipolar Transistors with Emitter Barrier Lowered by δ-Doping

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Abstract— **An Npn heterojunction bipolar transistor with a Si-δ-doped layer at the emitter-base hetero-interface is demonstrated. The Si δ-doped layer reduces the potential spike at the emitter junction. This design reserves the abruptness of the heterojunction, reduces electron barrier and increases the hole barrier simultaneously. Experimental results show that the HBT's turn-on characteristics are greatly improved while the current gain remains high. The offset voltages as low as 44 mV have been obtained. Very high current gains at very low collector current densities are obtained.**

IT is of great interest to reduce the potential spike at the emitter-base (EB) junction of heterojunction bipolar transistors (HBT's). Normally, the potential spike is smoothed out by grading the A1 composition in the depletion region of the EB junction [1]. But either the linear or parabolic grading of the A1 composition is difficult to be precisely controlled and this technique is not applicable to InP/InGaAs HBT's. Several methods, such as heterostructure-emitter bipolar transistors (HEBT) [2]–[6] and HBT's with thick spacers [7]–[8] have been utilized to eliminate this spike. But both methods result in charge storage because thick narrow band gap n-emitter or i-spacer are used. This decreases current gain, especially at low current densities.

In this letter, we demonstrate a new method which can effectively reduce the potential spike and at the same time maintain a high current gain. By using the Si δ-doping at the EB junction, the electron barrier is lowered while the hole barrier is increased. This technique was also applied to double heterojunction bipolar transistors [9]. To ensure full depletion of the charge sheet, a δ-doped layer is used instead of a highly-doped thin layer. The barrier lowering can be tuned by the position and concentration of the δ-doped layer. In this study, the δ-doped layer is put at the hetero-interface because the effect of barrier lowering increases as it is moved toward the hetero-interface [10].

HBT's with different δ-doping concentration were studied. The films were grown by molecular beam epitaxy (MBE) in a Varian Gen II system on (100) oriented n^+-GaAs substrate. The layers, beginning from the substrate, consisted of an n^+-GaAs buffer layer (2000 Å, 4×10^{18} cm^{-3}), n^--GaAs collector (5000 Å, 5×10^{16} cm^{-3}), p^+-GaAs base (1000 Å, 5×10^{18}cm^{-3}), i-GaAs spacer (50 Å), N-$Al_{0.3}Ga_{0.7}As$ emitter (2000 Å, 5×10^{17}cm^{-3}), and n^+-GaAs cap layer (2000 Å, 4×10^{18}cm^{-3}). The δ-doping was introduced at the spacer-to-emitter interface. The δ-doping concentration can be easily controlled by setting the time for impurity deposition while the growth is interrupted. Three samples with δ-doping of 2.5×10^{11}, 5×10^{11}, and 1×10^{12}cm^{-2} were made. After the growth, HBT's were fabricated with an emitter size of 100×100 μm^2 and a collector-to-emitter area ratio of 4.7.

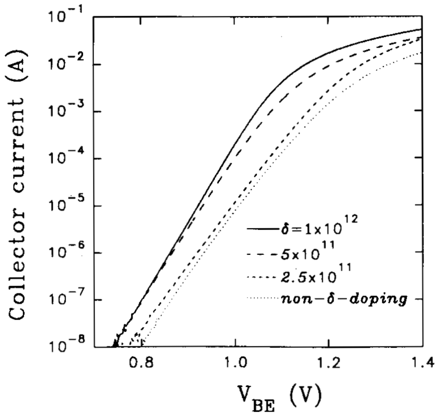

Fig. 1. The collector transfer characteristics for HBT's with different δ-doping concentrations at $V_{BC} = 0$. The δ-doping reduces the turn-on voltage and the ideality factor, and increases the collector current for a given base-emitter bias.

Fig. 1 shows the collector transfer characteristics for different δ-doping concentration at $V_{BC} = 0$. An HBT without δ-doping but with other layers identical to the δ-doped HBT's was also measured for comparison. As can be seen, the δ-doping improves the collector turn-on characteristics. The ideality factors for collector current of HBT's with δ-doping of 1×10^{12}cm^{-2} and without δ-doping is 1 and 1.2, respectively. The turn-on voltage decreases and the collector current increases with the amount of δ-doping. These confirm that the potential spike at EB junction decreases with the δ-doping concentration. The collector to emitter offset voltage also decreases with the amount of δ-doping. For a δ-doping concentration of 1×10^{12}cm^{-2}, the offset voltage distributes between 44-60 mV and the average offset voltage is 53 mV.

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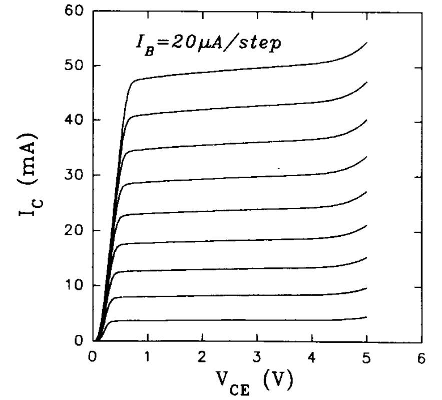


Fig. 2. The common-emitter characteristics of δ-doped HBT with $1 \times 10^{12} \mathrm{cm}^{-2}$ concentration. The offset voltage is 44 mV and the current gain is 350.

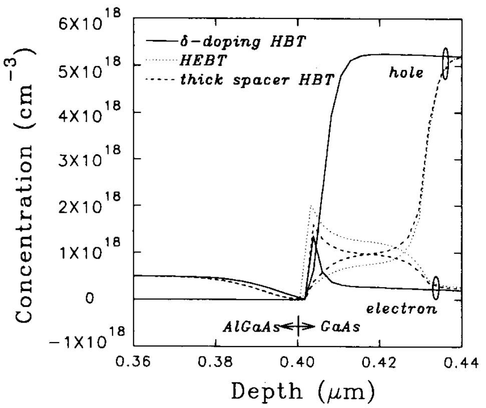
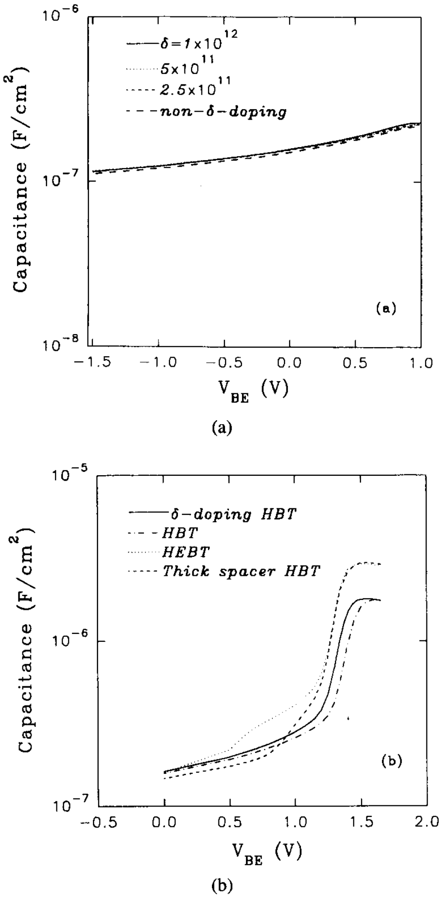


Fig. 3. The calculated charge distribution of δ-doped HBT (solid), thick spacer HBT (dashed) and HEBT (dot). Severe charge storage is observed for the thick spacer HBT and the HEBT, while the case is effectively improved in the δ-doped HBT.



(a)

(b)

Fig. 4. (a) The measured C_{EB} as a function of V_{BE} of δ-doped HBT with different doping concentration. Only 4/ increase in C_{EB} is observed for δ-doping of $1 \times 10^{12} \mathrm{cm}^{-2}$ at $V_{BE} = 0$. (b) The calculated C_{EB} at V_{BE} forward biased. A δ-doped HBT, a non-δ-doping-HBT with a 50 Å spacer, an HEBT with a 300 Å n-GaAs emitter, and a thick spacer HBT with a 300 Å spacer were calculated. Although the thick spacer HBT has the lowest C_{EB} at low biases, it increases at higher biases.

The average offset voltage of HBT without δ-doping is 190 mV. Another sample with a very high δ-doping concentration of $5 \times 10^{12} \mathrm{cm}^{-2}$ was also tested. No further improvement in the characteristics is observed.

During the deposition of the Si atoms for the δ-doped layer, the growth was stopped. In order to see whether the growth interruption may cause changes in the device characteristics, we have grown an HBT with a 360 second growth interruption at the E-B junction but without Si deposition. No detectable difference in characteristics was found as compared to the HBT's without growth stop. For the δ-doped samples, only 72 seconds growth interruption is needed for a concentration of $1 \times 10^{12} \mathrm{cm}^{-2}$, so the difference in device characteristics for devices with and without δ-doping is not from growth interruption.

The common-emitter characteristics of an HBT with a $1 \times 10^{12} \mathrm{cm}^{-2}$ δ-doping concentration are shown in Fig. 2. Very low offset voltage of 44 mV and very high current gain of 350 are observed. Some devices exhibit current gains over 700 with offset voltages less than 60 mV. These devices also exhibit current gains over 100 at very low collector densities of 5.5×10^{-2} A/cm^2. As compared to the abrupt HBT's, the graded HBT exhibit lower current gain because of the increase of surface recombination due to the removal of the potential spike [11]. This also happens to the δ-doped HBT's. The δ-doped HBT's exhibit current gain a little lower than those of the abrupt HBT's without δ-doping because of the removal of the potential spike. But as compared to the graded HBT's, thick spacer HBT's and HEBT's, simulation results indicate that δ-doped HBT's exhibit much higher current gains, especially at lower collector currents. The higher current gain of the δ-doped HBT's can be attributed to the increase of the hole barrier result from the δ-doping and the reduction of charge storage because of a thin spacer. Fig. 3 shows the calculated charge distribution of a δ-doped HBT, a thick spacer HBT and an HEBT. The δ-doped HBT has a 1×10^{12} cm^{-2} δ-doped layer and a 50 Å spacer. Thick spacer HBT and

HEBT has a 300 Å i-GaAs and n-GaAs spacer, respectively. Severe charge storage at the spacer is observed for the thick spacer HBT and the HEBT, while it is greatly improved in the δ-doped HBT.

One concern about the δ-doped HBT's is the possible increase in the emitter-base capacitance, C_{EB}. The measured C_{EB} as a function of V_{BE} is shown in Fig. 4(a). Note that only 4% increase in C_{EB} is observed for the δ-doped HBT with $1 \times 10^{12}\mathrm{cm}^{-2}$ δ-doping at $V_{BE} = 0$ V. So for the δ-doping concentration range considered here the influence of δ-doping on C_{EB} is negligible. The EB capacitance is controlled by the spacer length and the doping concentration in the emitter. Fig. 4(b) shows the calculated C_{EB}. Similar to the measured data in Fig. 4(a), the C_{EB} of δ-doped HBT is only 2.6% higher than that of non-δ-doped HBT at $V_{BE} = 0$ V. From calculation, the use of δ-doped layer also increases the total depleted charge. So, as compared to HBT's without δ-doping, the reduction of the depletion region due to the use of δ-doping is not significant and the discrepancy in capacitance is also small. At a high bias of 1.6 V, C_{EB} tends to saturate and these two devices have the same C_{EB}. Note that although the thick spacer HBT has the lowest C_{EB} at low biases, it increases to a value the same as that of the HEBT at higher biases because of charge storage. At $V_{BE} = 1.6$ V, the C_{EB} of HEBT and thick spacer HBT is about 65% larger than that of δ-doped HBT. So, taking into account the effect of C_{EB}, δ-doped HBT's are also superior to HEBT's and thick spacer HBT's.

In conclusion, an HBT with a δ-doped EB hetero-interface is demonstrated. The potential spike can be easily reduced without junction grading. High current gain and low offset voltage can be obtained at the same time.

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