Current Gain Dependence on Subcollector and Etch-Stop Doping in InGaP/GaAs HBTs

Theodore Chung, Seth R. Bank, John Epple, and Kuang-Chien Hsieh

***Abstract*—The dc current gain dependence of InGaP/GaAs heterojunction bipolar transistors (HBTs) on subcollector and etch-stop doping is examined. Samples of InGaP/GaAs HBTs having various combinations of subcollector doping and etch-stop doping are grown, and large area (60 μm × 60 (μ) HBTs are then fabricated for dc characterization. It is found that the dc current gain has a strong dependence on the doping concentration in the subcollector and the subcollector etch-stop. Maximum gain is achieved when the subcollector is doped at 6 $\sim$ 7 × 10^{18} cm^{-3} while the subcollector etch-stop is doped either above 6 × 10^{18} cm^{-3} (current gain/sheet resistance ratio, $\beta/R_b = 0.435$ at $I_c = 1$ mA) or below 3.5 × 10^{17} cm^{-3} ($\beta/R_b = 0.426 \sim 0.438$ at $I_c = 1$ mA). The data show that it is not necessary to heavily dope the subcollector etch-stop to reduce the conduction barrier and to obtain high current gain. The high current gain obtained with the low InGaP etch-stop doping concentration is attributed to the reduction of the effective energy barrier thickness due to band bending at the heterojunction between the InGaP etch-stop and the GaAs subcollector. These results show that the β/R_b of InGaP/GaAs HBTs can improve as much as 69% with the optimized doping concentration in subcollector and subcollector etch-stop.**

***Index Terms*—Current gain, gallium arsenide, heterojunction bipolar transistor, indium gallium phosphide, subcollector concentration.**

I. Introduction

In recent years, InGaP/GaAs HBTs look increasingly promising as replacements for the more widely used AlGaAs/GaAs HBTs due to a number of advantages. These advantages include low surface recombination velocity, large valence band offset between InGaP and GaAs, high etch selectivity, having no DX center problem (which occurs in aluminum containing compounds such as $Al_xGa_{1-x}As$), and superior long-term reliability [1]–[4]. High dc current gain in HBT devices is extremely attractive because of the increased current drive capability and lower noise figure. In this work, we investigate the dc current gain dependence on the doping concentration in both subcollector and InGaP etch-stop layers. An InGaP etch-stop between the lightly doped collector and the heavily doped subcollector enables a more robust processing. It ensures a flatter surface for the collector metal to be deposited than a conventional structure without an etch-stop. This study uses dc current gain to investigate the current flow in the presence of the collector etch-stop heterojunction. The experiment is composed of two parts. The first portion studies the gain dependence on the subcollector concentration, while the second part focuses on the current gain dependence on the etch-stop concentration.

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II. Material and Fabrication

The material for this work was grown using an Emcore DS-125 vertical flow MOCVD reactor. The chamber pressure was kept at 76 torr. TMGa, TEGa, and TMIn were used as group III precursors, and AsH_3 and PH_3 were used as group V precursors. Silicon was used as n-type dopant, while carbon was used as the p-type dopant. The HBT epitaxial structure consists of a 5000 Å GaAs subcollector, a 157 Å InGaP subcollector etch-stop, a 5000 Å GaAs collector ($n = 3 \times 10^{16}$ cm^{-3}), a 700 Å C-doped GaAs base ($p = 4 \times 10^{19}$ cm^{-3}), a 700 Å InGaP emitter ($n = 5 \times 10^{17}$ cm^{-3}), a 1300 Å heavily doped GaAs emitter cap, a 300 Å graded layer from GaAs to $In_{0.5}Ga_{0.5}As$, and a 300 Å heavily doped $In_{0.5}Ga_{0.5}As$ contacting layer. An InGaP etch-stop thickness of 157 Å is designed to provide a reliable etch-stop layer for subcollector metal deposition. The HBT structure with the InGaP etch-stop is the same as that in [5]–[7]. Different combinations of doping concentration in the subcollector and the subcollector etch-stop were experimented in this work. The substrates used in the experiment were semi-insulating GaAs, 2° misoriented off (100) toward the (110) direction. The samples were cleaved into 1 cm × 1 cm squares for dc large area HBT processing. The devices tested in this study have 60 μm × 60 μm emitter area. Nonalloyed TiPtAu was used for emitter, base, and collector contacts. For the current gain measurement, the base and the collector voltages were kept the same, so that the base-collector junction remained at equilibrium (unbiased) during testing. The dc current gain of all the samples in this work were done at $I_c = 1$ mA, and the base sheet resistance R_b of the samples were ~250 $\Omega/\square$.

III. Results and Discussion

Fig. 1 shows the gain over the base sheet resistance (β/R_b) as a function of subcollector doping concentration with the InGaP etch-stop concentration at 6 × 10^{18} cm^{-3} (solid line) and at 4 × 10^{18} cm^{-3} (dotted line). For the sample with the etch-stop concentration at 6 × 10^{18} cm^{-3}, a maximum β/R_b of 0.438 is estimated from the figure to be at subcollector doping concentration of 6 × 10^{18} cm^{-3}. As the subcollector doping concentration moves away from 6 × 10^{18} cm^{-3}, β/R_b decreases. This current gain dependence on subcollector doping concentration is attributed to the conduction spike at the interface between the InGaP etch-stop and the GaAs subcollector. For the sample with the etch-stop concentration of 4 × 10^{18} cm^{-3}, a maximum β/R_b

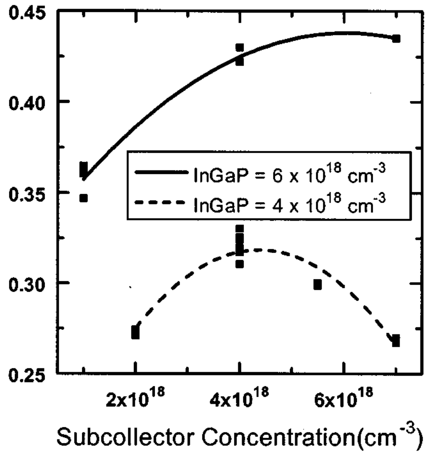

Fig. 1. Current gain over base resistance ratio (β/R_b) as a function of subcollector doping concentration of large-area InGaP/GaAs HBTs with the etch-stop doping concentration at 6 $\times$ 10^{18} cm^{-3} and 4 $\times$ 10^{18} cm^{-3}.

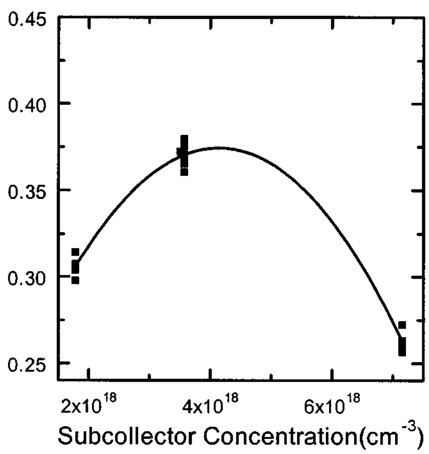

Fig. 2. Current gain over base resistance ratio (β/R_b) as a function of subcollector doping concentration of large-area InGaP/GaAs HBTs with the etch-stop doping concentration at 1.8 $\times$ 10^{18} cm^{-3}.

of 0.317 is obtained at the subcollector concentration of 4 $\times$ 10^{18} cm^{-3}. The reason that β/R_b for the sample with the etch-stop concentration of 4 $\times$ 10^{18} cm^{-3} is lower than the sample with the etch-stop concentration of 6 $\times$ 10^{18} cm^{-3} in the entire range of subcollector concentration in Fig. 1 is due to the rising of the etch-stop conduction band with the lower doping concentration. When the doping concentration InGaP etch-stop of the samples decreases, the Fermi level alignment produces a higher energy barrier in the conduction band, which reduces the electron flow from the base into the subcollector. The change in the conduction band offset between the GaAs collector and the InGaP is calculated to be 10.5 meV as the InGaP etch-stop doping concentration decreases from 6 $\times$ 10^{18} cm^{-3} to 4 $\times$ 10^{18} cm^{-3}. Fig. 2 shows the β/R_b as a function of subcollector doping concentration with the subcollector InGaP etch-stop concentration at 1.8 $\times$ 10^{18} cm^{-3}. The profiles for the sample with the etch-stop concentration of 4 $\times$ 10^{18} cm^{-3} in Fig. 1 and the sample in Fig. 2 are identical except for the fact that the sample in Fig. 2 has a higher maximum β/R_b peak ($\beta/R_b = 0.374$). Both figures have a maximum β/R_b at subcollector doping concentration of 4 $\times$ 10^{18} cm^{-3}. The decrease in β/R_b of the two samples as the subcollector concentration moves from 4 $\times$ 10^{18} cm^{-3} to 1 $\times$ 10^{18} $cm^{-3}$is due to the increase in barrier height of the conduction spike at the heterojunction between the InGaP etch-stop and the GaAs subcollector, while the reason it decreases as the subcollector concentration increases from 4 $\times$ 10^{18} cm^{-3} to 7 $\times$ 10^{18} cm^{-3} remains unknown.

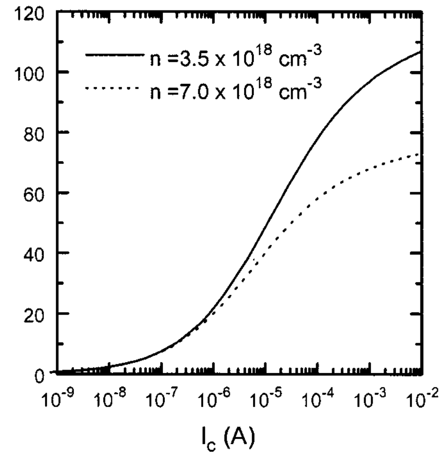

Fig. 3. DC current gain of the annealed HBTs as a function of collector current. The samples have the etch-stop doping of 1.8 $\times$ 10^{18} cm^{-3} and the subcollector doping of 3.5 $\times$ 10^{18} cm^{-3} and 7 $\times$ 10^{18} cm^{-3}.

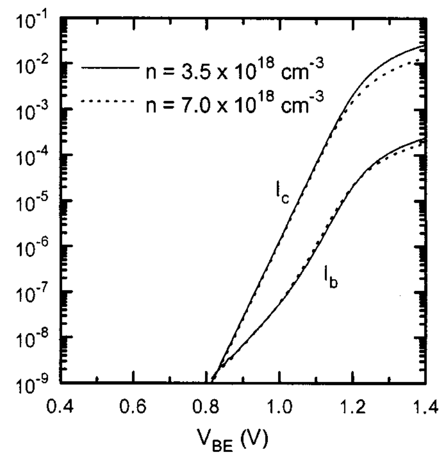

Fig. 4. Gummel plots of InGaP/GaAs HBTs with the etch-stop doping of 1.8 $\times$ 10^{18} cm^{-3} and the subcollector doping of 3.5 $\times$ 10^{18} cm^{-3} and 7 $\times$ 10^{18} cm^{-3}.

Fig. 3 shows the dc current gain as a function collector current up to 10^{-2} A for two devices from Fig. 2. Both have their InGaP etch-stop doped at 1.8 $\times$ 10^{18} cm^{-3}. One of them has the subcollector concentration of 3.5 $\times$ 10^{18} cm^{-3} and the other with the subcollector concentration of 7 $\times$ 10^{18} cm^{-3}. For collector current I_c less than 10^{-6} A, the dc current gains of the devices overlap on top of each other. For collector current I_c larger than 10^{-6} A, the dc current gain β of the device with lower subcollector concentration ($n = 3.5\times 10^{18}$ cm^{-3}) shows a much higher gain, and the difference in current gain diverges increasingly with the collector current I_c. A Gummel plot of the large-area devices in Fig. 3 is shown in Fig. 4. In the figure, the base currents lie almost on top of one another; therefore, the base recombination remains the same in both devices. Although the collector currents are almost identical at low applied voltage ($V_{BE} < 1.2$ V), the device with a lower subcollector doping (n= $3.5\times$ 10^{18}

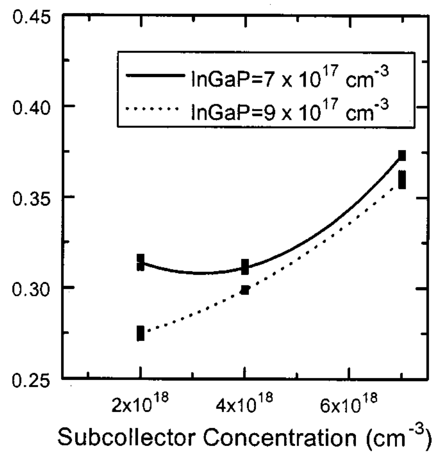

Fig. 5. Current gain over base resistance ratio (β/R_b) as a function of subcollector doping concentration of large-area InGaP/GaAs HBTs with the etch-stop doping concentration at 9 × 10^{17} cm^{-3} and 7 × 10^{17} cm^{-3}.

cm^{-3}) concentration shows a larger collector current at high-applied base-emitter voltage ($V_{BE} > 1.2$ V). These results from Figs. 2–4 support that the current gain dependence on the subcollector doping concentration is caused by the change in conduction spike height between the InGaP etch-stop and the GaAs subcollector. The fact that a change in subcollector doping concentration only impacts the collector current but not the base current indicates that the cause cannot be due to the degradation of the material quality or decrease in minority carrier lifetime in the base layer. Figs. 3 and 4 show clearly that a change in subcollector doping concentration does not degrade the material quality of the base layer of an InGaP/GaAs HBT. The only possible explanation must be a change in heterojunction barrier in the conduction band with different subcollector doping concentration.

Plots of β/R_b as a function of subcollector doping concentration of large-area InGaP/GaAs HBTs with the etch-stop doping concentration at 9 × 10^{17} cm^{-3} and 7 × 10^{17} cm^{-3} are shown in Fig. 5. It is important to note that the maximum β/R_b in both figures are at the subcollector doping of 7 × 10^{18} cm^{-3} ($\beta/R_b = 0.360$ for the sample with the etch-stop concentration of 9 × 10^{17} cm^{-3} and $\beta/R_b = 0.373$ for the sample with the etch-stop concentration of 7 × 10^{17} cm^{-3}). Fig. 6 illustrates the schematic energy band diagram of the base-collector junction of InGaP/GaAs HBT with the etch-stop and the subcollector heavily doped (∼6 × 10^{18} cm^{-3}). The depletion width of the base-collector junction at equilibrium (unbiased) is calculated to be 2625 Å, which is smaller than the width of the collector thickness. Consequently, the InGaP etch-stop remains undepleted at equilibrium. The 5000 Å lightly doped GaAs collector is designed to have a high breakdown voltage (>15 V) between the base-collector junction. It can be seen from the figure that there exist two conduction spikes: one between the GaAs collector and the InGaP etch-stop and the other between the InGaP etch-stop and the GaAs subcollector. The height of the conduction band spike at the heterojunction between the InGaP etch-stop and the GaAs subcollector varies with the subcollector doping concentration. Consequently, electrons going from the collector to the subcollector experience different conduction spike height with different subcollector concentration. This explains the current gain dependence of the HBTs on the subcollector doping concentration.

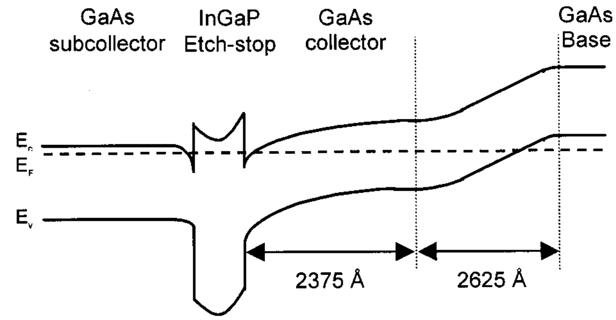

Fig. 6. Energy band diagram of the base-collector junction of InGaP/GaAs HBT. There is one conduction spike between the GaAs collector and the InGaP etch-stop and one between the InGaP etch-stop and the GaAs subcollector. The InGaP etch-stop doping concentration is at 6 × 10^{18} cm^{-3} and the GaAs subcollector concentration is at 7 × 10^{18} cm^{-3}.

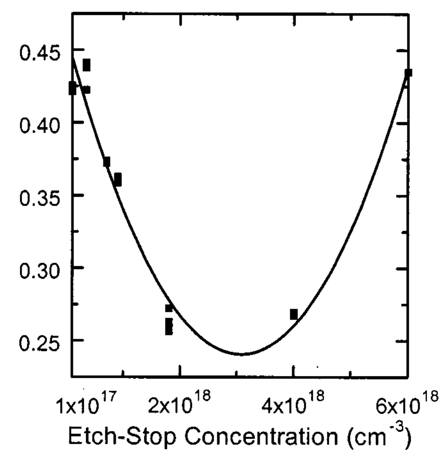

Fig. 7. Current gain over base resistance ratio (β/R_b) as a function of etch- stop doping concentration of large-area InGaP/GaAs HBTs with the subcollector doping at 7 × 10^{18} cm^{-3}.

In the second part of the experiment, we have studied the effect of gain dependence on the etch-stop concentration with a constant subcollector concentration. In order to obtain good high-frequency performance of HBTs, the subcollector concentration is desired to be as high as possible to reduce the collector resistance. For this reason, the subcollector concentration is fixed at 7 × 10^{18} cm^{-3} (the highest concentration possible for n-type GaAs) while the etch-stop concentration is varied from 1 × 10^{17} cm^{-3} to 6 × 10^{18} cm^{-3}. Fig. 7 shows β/R_b as a function of the etch-stop doping of HBT samples. β/R_b appears to be a "U" shape and reaches a minimum of 0.25 at the etch-stop concentration of 3 × 10^{18} cm^{-3}. The value of β/R_b increases when the etch-stop doping concentration move away from 3 × 10^{18} cm^{-3}. It approaches to a maximum value of ∼0.44 when the etch-stop doping is at 6 × 10^{18} cm^{-3} or at 3.5 × 10^{17} cm^{-3}. When the InGaP etch-stop is heavily doped at 6 × 10^{18} cm^{-3}, the conduction band energy barrier between the GaAs collector and the InGaP etch-stop is the lowest. It is understandable that the one of the maximum β/R_b is at this etch-stop concentration. The conduction spike and the band gap offset determine the amount of electrons going from the collector to the subcollector. As the etch-stop doping decreases, the conduction band energy barrier from the GaAs collector to

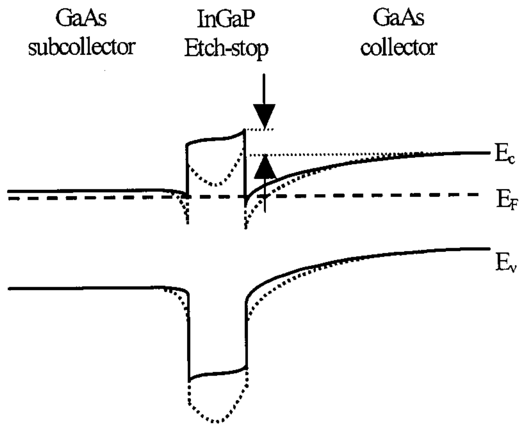

Fig. 8. Energy band diagram of the collector-subcollector portion of the InGaP/GaAs HBT with a medium doped InGaP etch-stop. The dotted line shows the energy band diagram of a heavily doped InGaP etch-stop while the solid line shows the energy band diagram of a medium doped etch-stop. The arrows show the increase in energy barrier height that electrons have to over come going from the collector to the subcollector.

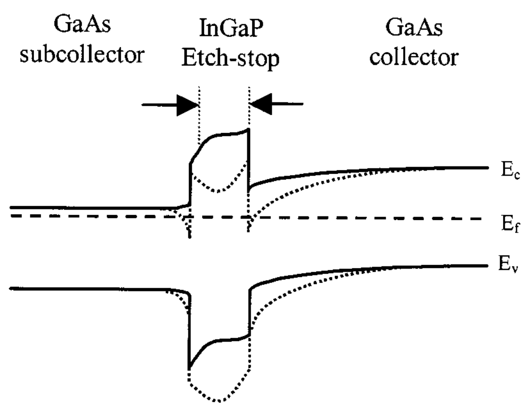

Fig. 9. Energy band diagram of the collector-subcollector portion of the InGaP/GaAs HBT with a lightly doped InGaP etch-stop. The dotted line shows the energy band diagram of a heavily doped InGaP etch-stop (6×10^{18} cm^{-3}) while the solid line shows the energy band diagram of a lightly doped etch-stop (1×10^{17} cm^{-3}). For the lightly doped etch-stop, there is only one conduction spike between the GaAs collector and the InGaP etch-stop. The other side of the InGaP etch-stop is bent downwards. The arrows show the reduced effective energy barrier of the InGaP etch-stop.

the InGaP etch-stop becomes increasingly larger and β/R_b decreases accordingly (see Fig. 8), although the conduction spike at the heterojunction between the InGaP etch-stop and the GaAs subcollector is reduced at the same time. This explains the decrease in β/R_b as the InGaP etch-stop concentration drops from 6×10^{18} cm^{-3} to 3×10^{18} cm^{-3}. When the InGaP etch-stop doping concentration reaches a low enough value, the conduction spike is totally eliminated and the InGaP etch-stop starts to bend downward at the heterojunction. As a result, the effective thickness of the InGaP etch-stop energy barrier decreases as band bending increases with decreasing etch-stop doping concentration. The effective energy barrier thickness due to the InGaP etch-stop blocking electrons going from the collector to the subcollector becomes smaller, and the total current reaching the subcollector increases. Fig. 9 illustrates the energy band diagram of the base-collector junction of InGaP/Gas HBT with a lightly doped InGaP etch-stop ($n < 3.5 \times 10^{17}$ cm^{-3}). The figure shows that the overall electrons reaching the subcollector across the InGaP etch-stop increases with decreasing InGaP etch-stop concentration although the band gap offset between the GaAs collector and the InGaP etch-stop becomes larger.

IV. Conclusions

The dc current gain of InGaP/GaAs heterojunction bipolar transistors shows a strong dependence on the concentration of the subcollector and the subcollector etch-stop. This gain dependence on the concentration of the subcollector and the subcollector etch-stop is attributed to two reasons: the change in conduction band barrier height between the GaAs collector and the InGaP etch-stop and the change in conduction spike barrier height between the InGaP etch-stop and the GaAs subcollector. The current gain dependence on the subcollector doping concentration plays an important role in the entire range of InGaP etch-stop doping levels due the fact that the height of the conduction spike at the InGaP-GaAs heterojunction depends on the subcollector doping concentration. At high InGaP etch-stop concentration ($n > 3 \times 10^{18}$ cm^{-3}), the current gain increases with increasing InGaP etch-stop doping concentration because the energy barrier at the heterojunction is reduced. At low InGaP etch-stop concentration ($n < 3 \times 10^{18}$), the current gain increases with decreasing InGaP etch-stop doping concentration because of the reduction in effective barrier thickness due to band bending. The current gain dependence on the etch-stop doping concentration is determined by the conduction band profile at the heterojunction between the GaAs collector and the InGaP etch-stop as well as between the InGaP etch-stop and the GaAs subcollector. It is found that the dc current gain is maximized when the etch-stop doping concentration is either at 6 $\times 10^{18}$ cm^{-3} or below 3.5 $\times 10^{17}$ cm^{-3} with the subcollector heavily doped at 7 $\times 10^{18}$ cm^{-3}. The optimized devices show a current gain β over 100 at $I_c = 1$ mA with the base sheet resistance $R_b \sim 250\Omega/\Box$. The data show that InGaP etch-stop concentration has a dramatic impact on the current gain of the InGaP/GaAs HBT's with as much as 69% change in β/R_b. In addition, the results show that it is not necessary to heavily dope the InGaP etch-stop in order to achieve high dc current gain.

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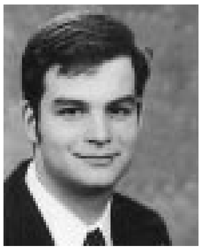

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