氫效應在異直接面電晶體所引起的穩定性及可靠性問題

H Effect in MOCVD Grown Heterojunction Bipolar Transistors

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一、中文摘要

本計畫的目的在研究在 MOCVD 所成長的 HBT 內的氫所引起的暫態效應. 氫與炭在base內形成complex, 而它們所放出的氫離子成為複合中心. 而這些複合中心的數目因著捕捉電子而隨時間降低. 從而造成 base 電流的下降及電流增益的上升. 本計畫對複合中心濃度對時間的變化作了仔細的模擬, 得到與實驗吻合的結果. 我們並研究了 HBT 的溫度的效應, 並提出了模型於以解釋.

INTRODUCTION

Heterostructure Bipolar Transistor is the key component for many high-speed systems such as power amplifiers for cellular phones and encoding and decoding circuits for fiber communication systems. To achieve high device performance, the base is usually very heavily doped. To avoid diffusion of p type dopants and the reliability problem, carbon is the most commonly used p-type dopant due to its low diffusivity and its ability to achieve high doping levels. However, during the metalorganic chemical phase deposition (MOCVD) growth, a popular choice for production, hydrogen is also incorporated into GaAs at a concentration comparable to the carbon doping. Such a high concentration of hydrogen has been found to passivate carbon acceptors and effectively reduce the doping concentration. Not only that, a fast initial rise in current gain (β), followed by a gradual decrease and possibly defect generation in the base, is often observed. Unless the wafers are carefully annealed to drive the hydrogen atoms right after growth, this effect is not avoidable. A detailed understanding of the short-term hydrogen effects is, however, lacking. This effect causes stability problem for the HBTs and affects the yield of the circuits. The purpose of this program is to investigate this H related effect. Devices with various dimensions with different driving current densities were characterized. The transient behavior as a function of annealing time is studied. A comprehensive model is proposed.

Besides the hydrogen effect, in this program, we have also studied the temperature dependence of HBTs' characteristics. The temperature dependent behavior depends on various kinds of base recombination mechanisms and the device structure. We have successfully modeled this behavior our calculated results agree with the experimentally measured results.

EXPERIEMENTAL

The C-doped AlGaAs/GaAs and InGaP/GaAs HBTs used for this study were fabricated with wafers grown by commercial sources with the MOCVD method. The base layer was 70 nm thick and doped with C to 4 x10^{19} cm^{-3}. The hydrogen content in the base layer was around 10 to 30% of the carbon doping. The initial rise in current gain was found in all devices. A typical example is shown in Fig.1, where two sets of Gummel plots of a 75x75μm^2 device were shown. The solid lines were the initial Gummel plot obtained by the first scan and the dashed lines were the steady state curves. It is clearly shown that the current gain increases by about two times. Since Ic and Ib are related to Vbe in the following way.

$$Ic = I_s \exp(qV_{be}/kT)$$

$$I_b = I_1 \exp(qV_{be}/kT) + I_2 \exp(qV_{be}/2kT)$$

So the current gain is

$$\beta^{-1} = \frac{I_b}{I_c} = \frac{I_1}{I_s} + \frac{I_2}{\sqrt{I_s}}(I_c)^{-\frac{1}{2}}$$

By plotting out β^{1} vs. $I_c^{-1/2}$, we should obtain a straight line with the slope proportional to the 2kT component of the base current and the intersection to the vertical axis proportional to the 1kT component of the base current. Fig.2 shows such curves for an initial scan and the steady state curve for an AlGaAs HBT and an InGaP HBT. We can see clearly that the slopes of the two curves for the first scan and the steady state scan are nearly the same but the y-axis intersection is quite different. So the increase in current gain is mainly due to the increase of the 1kT part of the base current. This confirms that the transient effect that we see here is caused by the neutral base recombination due to the presence of H. This effect is present for both GaAlAs/GaAs and InGaP/GaAs HBTs as long as they are MOCVD grown with C-doped base.

RESULTS AND DISCUSSION

The initial transient effect is quite different for small size transistors as compared with large transistors described above. Fig.3a and 3b show the β^{1} vs. $I_c^{-1/2}$ plots for a group of 2x6 transistors. As can be seen that the transient effect is much smaller than that in the large transistors. .

When the base layer is grown, C and H form complexes which suppress the carbon doping. But the C-H complexes can release H ions, which serve as recombination centers in the base via the following processes

$[C - H] \Leftrightarrow C- + H^+$

$H^+ + e- \Leftrightarrow H^0$ K_1

$H^0 + e- \Leftrightarrow H-$ K_2

$H^+ + 2\ e- \Leftrightarrow H-$ K_3

$H^0 + H^+ = A \exp(-t/\tau_1) + B \exp(-t/\tau_2)$

where K's are the equilibrium reaction constants and $\tau_1^{-1} = K_2[e-]$ and

$$\tau_2^{-1} = K_1[e-] + K_3[e-]^2$$

These equations are governed by the thermal equilibrium processes. Once H^+ ions are formed, they and the intermediate product, H^0, become recombination centers. But these recombination centers are consumed by capturing electrons when there is current flowing through the device. As the number of recombination centers decreases, the current gain increases and slowly reaches a steady state. Another possibility for the decrease of the recombination centers is the outdiffusion of the hydrogen atoms once they are free from the C-H complexes. The outdiffusion depends on the device geometry with a faster diffusion rate for smaller emitter fingers and slower diffusion rate for the larger fingers. The diffusion process is controlled by the diffusion equation

$$\frac{\partial n(r,t)}{\partial t} = D\nabla^2 n(r,t)$$

We have modeled the time dependence of the current gain change and the base current change using the above two models. It was found that better fitted results are obtained with both models are considered. The calculated results along with the measured results for devices with dimensions of 50x50, 75x75 and 100x100 are shown in Fig.4. Very good agreement between the model and the measured results was obtained.

Besides the effect of hydrogen on the transient behavior of HBTs, we have also modeled the temperature dependence of HBTs. It is known that HBTs' characteristics are temperature dependent, but there has never been comprehensive study on this effect.

The collector current and the base current of an HBT can be expressed by

$$I_c = I_o \exp(-E/kT + qV/kT)$$
$$I_b = A \exp(-E/kT + qV/kT) + I_1 \exp[-(E + \Delta E_1)/kT + qV/kT] + I_2 \exp[-(E + \Delta E_2)/2kT + qV/2kT]$$

Here V stands for the base-emitter voltage. E is the barrier energy for the electrons to overcome when entering the base. For a well graded junction, E is approximately the base bandgap energy. For the base current, I separate it into three terms. The first one is the neutral base recombination which is proportional to the collector current. The second term is the back injection hole current. Because of the heterojunction, the holes need to overcome a higher barrier with an additional energy barrier ΔE_1. For an abrupt junction, ΔE_1 is the valence band offset. For a well graded junction, it should be the bandgap energy difference between the emitter and the base. The third term accounts for the 2kT part of the base recombination, which largely consists of the space charge recombination in the emitter and the recombination in the depleted ledge. Since it happens in the emitter, the holes also need to overcome an additional barrier ΔE_2.

From Ic and Ib, we get

$$\beta^{-1} = Ib/Ic = A/Io + (I_1/I_o)\ exp(-\Delta E_1/kT) + I_2\ I_c^{-0.5} exp(-\Delta E_2/2kT)\ I_c^{-0.5}$$

This equation is similar to what we have described earlier. It is a straight line relationship. The slope is proportional to the 2kT base current and the intersect with the y axis is proportional to the 1kT base current. This relationship is temperature sensitive and the temperature sensitivity depends on the two activation energies ΔE_1 and ΔE_2. The nice thing about this equation is that it does not depends on the emitter resistance and the bandgap energy.

We used the above equations and fitted the experimentally measured results. Fig.5 shows the measured and the calculated beta vs. Ic curves for a AlGaAs HBT at 25C, 75C, 125C and 175C. Excellent agreement was achieved. Similar calculation was performed for InGaP HBTs. The InGaP HBTs were found to be much less temperature sensitive, and it is because of a higher ΔE_1 and ΔE_2.

CONCLUSION

In conclusion, in this year's program, we have investigated the H induced I_b and current gain transient in MOCVD grown HBTs. This transient is caused by the H+ recombination centers released by the [C – H] complexes in the base. It affects only the 1kT base current and a severe effect on the current gain. Annealing experiment for reduction of this effect was performed. It was found that after 650C annealing for 300sec, the devices are free from the H effect. The transient effect is recoverable after the devices reaches steady state by a short time heat treatment at low temperatures. The mechanism including the annihilation of the recombination centers was proposed to explain the time dependence of transient effect. Very good agreement was obtained between the modeled results and the experimental results.

The temperature dependence of the HBTs' characteristics has also been modeled by taking into consideration of the structure parameters and the band alignment. Excellent agreement between the calculated results and the measured results was achieved.

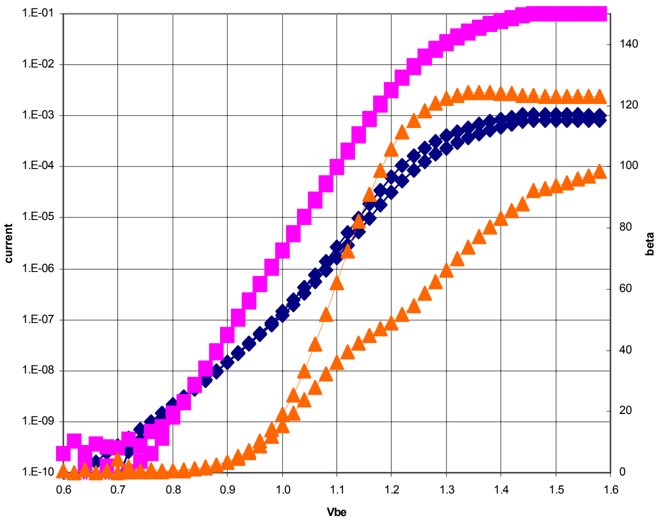

Fig.1

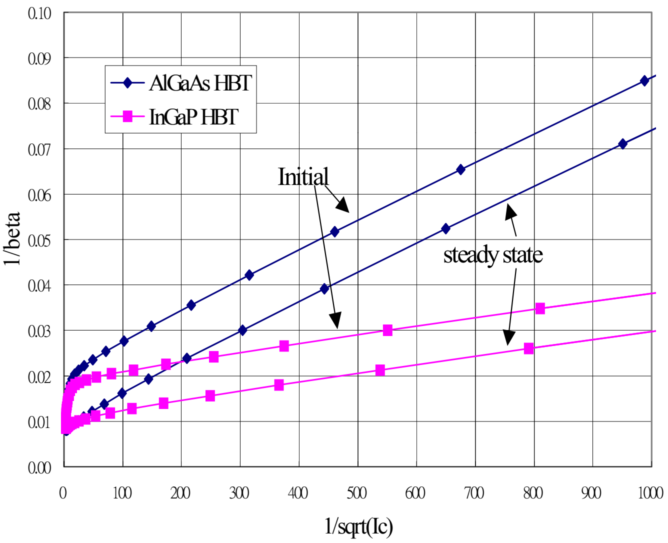

Fig.2

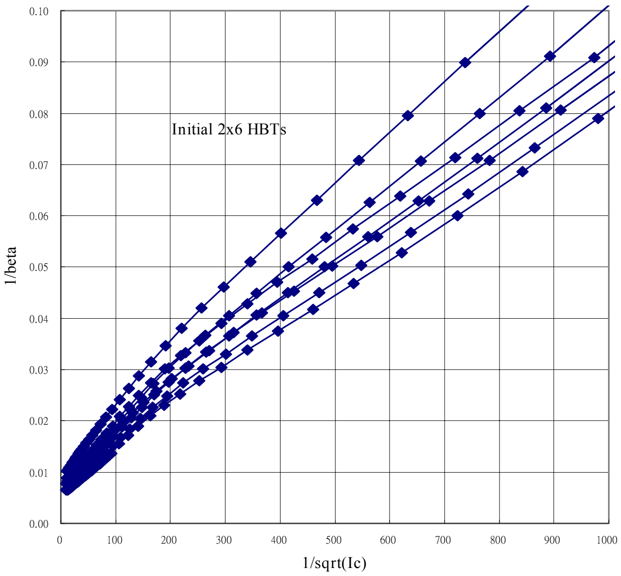

Fig.3a

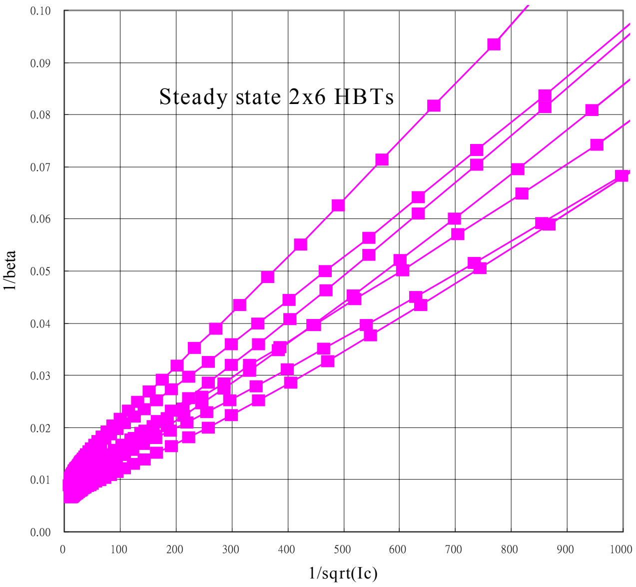

Fig.3b

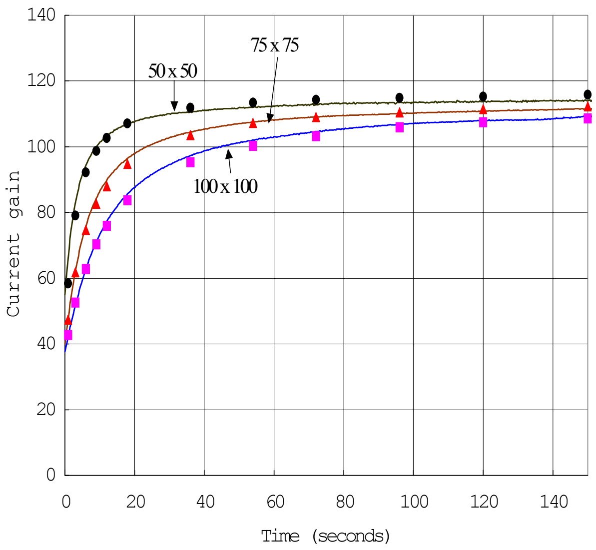

Fig.4

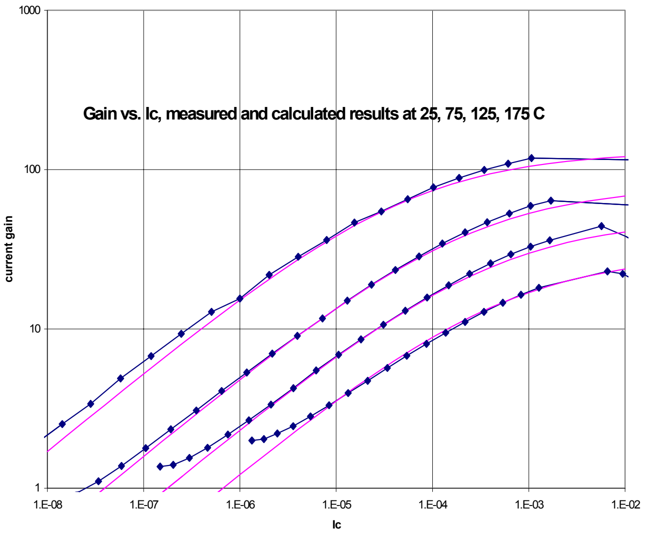

Fig.5