Chapter 3

New Cu/Mo/Ge/Pd Ohmic Contacts on Highly-Doped n-GaAs for InGaP/GaAs Heterojunction Bipolar Transistors

In this chapter, the feasibility of using novel Cu/Mo/Ge/Pd ohmic contacts on n^+-GaAs for InGaP/GaAs heterojunction bipolar transistor (HBT) is investigated. The electrical and material characteristics of the Cu/Mo/Ge/Pd/n^+-GaAs structure were studied by judging from the data of sheet resistance, X-ray diffraction, Auger electron spectroscopy, and transmission electron microscopy.

3.1 Introduction

An ohmic contact is a low resistance junction formed between metal and semiconductor to allow current to flow into the semiconductor device. Low-resistance ohmic contacts which are thermally stable are very essential for the GaAs-based microwave and millimeter-wave circuits.[1] Ever since IBM first engaged in the copper interconnection technology,[2-4] copper metallization has drawn great attention in the silicon IC industry. Conventionally, gold is used as the contact and interconnect metal for the GaAs microwave devices and circuits. Using copper in place of gold as the metallization metal for the GaAs devices has the advantages of lower resistivity, higher thermal conductivity and lower cost. Copper diffuses very fast into silicon if without any diffusion barrier. Similarly, copper is known to diffuse rapidly into GaAs via a kick-out mechanism if without any diffusion barrier [5] and creates deep traps that degrade the device characteristics. Even though copper metallization has played an important role in the Silicon IC industry, the literatures related to the copper metallization for GaAs devices are quite few.[6-8]

The AuGeNi alloyed ohmic contact is commonly used as the ohmic contact to n-GaAs in the past. In this study, the feasibility of using novel Pd/Ge-based copper ohmic contacts on highly-doped n-GaAs for heterojunction bipolar transistor (HBT) is investigated. In comparison with the AuGeNi ohmic system, the PdGe-based ohmic contact has the following advantages: (1) a better surface morphology, (2) a better contact edge definition due to the solid phase regrowth.[9] In this study, Cu/Mo/Ge/Pd was used as the ohmic metals. In this structure, Ge/Pd was used to reduce the contact resistance. The refractory metal molybdenum was used as the diffusion barrier between Cu and underlying materials due to its high melting point and low solubility in copper even at high temperatures. Some refractory metals and refractory metal nitrides are usually used as the diffusion barriers for Si-based device applications. These barriers include Ta, TaN, Ta_2N, TiW, TiN, and WN_x. The thick Cu metal on the top was used to reduce the sheet resistance of the metal layers. Finally, the Cu/Mo/Ge/Pd ohmic structure was used to fabricate the InGaP/GaAs HBTs. The properties of the InGaP/GaAs HBTs fabricated with the new n-type ohmic metals (Cu/Mo/Ge/Pd) were compared with the devices fabricated using the traditional n-type ohmic contacts (Au/Ni/Ge/Au). After thermally annealing at 250℃ for 24 hours and a high current-accelerated stress test at the current density of 120kA/cm^2 at a V_{CE} of 1.5V for 24 hours, the InGaP/GaAs HBTs with the Cu/Mo/Ge/Pd ohmic contacts exhibit excellent electrical characteristics and thermal stability.

3.2 Experimental

The ohmic contact structure of Cr/Cu/Mo/Ge/Pd/n$^+$-GaAs was prepared for electrical and material characterizations. The substrates were semi-insulating (100) GaAs wafers with Si-doped layers (~ 5×10^{18} cm^{-3}, 0.2 μm) grown by metal-organic chemical vapor deposition (MOCVD). After ohmic contact pattern was defined by photolithography, the ohmic metals were deposited by electron beam evaporation. A palladium film of 50nm thickness was evaporated onto the n$^+$-GaAs substrate first, then a 125nm germanium was evaporated onto the Pd film. The thin Mo (40nm) barrier was then deposited by sputtering (in Ar gas) before copper deposition. Note that for the test samples, a top Cr (15nm) layer was deposited on the surface of Cu to prevent the copper layer from oxidation for material study. After metal deposition, the samples were annealed in nitrogen ambient and followed by a series of material analyses. X-ray diffraction (XRD), Auger electron spectroscopy (AES), transmission electron microscopy (TEM) and sheet resistance measurements were used to identify the phases and the interfacial reactions of the contact materials.

An InGaP/GaAs HBT structure was fabricated using the proposed ohmic structure, as shown in Table 3.1. The HBT was grown by MOCVD method and the layer structure includes an n^+-GaAs subcollector (600nm, $5\times10^{18}cm^{-3}$), an n^--GaAs collector (650nm, $4\times10^{16}cm^{-3}$), a p^+-GaAs base (120nm, $2\times10^{19}cm^{-3}$), an n-InGaP emitter (85nm, $2\times10^{17}cm^{-3}$), and an n^+-GaAs cap (100nm, $5\times10^{18}cm^{-3}$). The Cu/Mo/Ge/Pd ohmic metals were used as the emitter and collector ohmic contacts for the proposed InGaP/GaAs HBT. Non-alloyed Au/Pt/Ti/Pt was used as the base contact metals and Au/Ti as the interconnect metals. A traditional HBT which uses Au/Ni/Ge/Au and Au/Pt/Ti/Pt as n-type and p-type ohmic metals and Au/Ti as the interconnect metals was prepared for comparison. The typical GaAs-based HBT device fabrications are described as follows. The HBTs were fabricated using a standard triple mesa process, as shown in Figs. 3.1.1-3.1.3. The GaAs and InGaP layers were etched by $H_3PO_4/H_2O_2/H_2O$ and H_3PO_4/HCl, respectively. During the isolation etch, the GaAs subcollector was etched to the extent of undercut to separate each device and reduce the leakage current. After the ohmic metals were deposited, as shown in Figs. 3.1.4-3.1.5, a liftoff process was used to remove the unwanted metals. PECVD silicon nitride was used for device passivation and contact via etch, as shown in Figs. 3.1.6-3.1.7. The passivation can protect the active area of the exposed wafer surface from chemicals, gases, particles. Then, the metal lines (Au/Ti) were used to interconnect three electrodes with metal pads, as shown in Fig 3.1.8. The electrical characteristics of the fabricated HBTs were measured and compared with the characteristics of the devices fabricated using the conventional n-type Au/Ni/Ge/Au ohmic contacts. The thermal stability of the copper metallization HBTs was evaluated by annealing these devices at 250℃ for 24 hours in nitrogen ambient. More, the reliability of the HBTs with the Cu/Mo/Ge/Pd ohmic contacts were carried out by using a high current-accelerated stress test at the current density of 120kA/cm^2 at a V_{CE} of 1.5V for 24 hours.

3.3 Discussion

3.3.1 Thermal Stability of the Cr/Cu/Mo/Ge/Pd/n$^+$-GaAs Contact

The specific contact resistances of the Cr/Cu/Mo/Ge/Pd/n$^+$-GaAs ohmic contacts were obtained by transmission line method (TLM). The lowest specific contact resistance was achieved after 350℃ annealing for 10 minutes. At this annealing temperature, the specific contact resistance of the Cr/Cu/Mo/Ge/Pd/n$^+$-GaAs contact was measured to be $2.8\times10^{-7}\Omega cm^2$. Figure 3.2 shows the sheet resistances of the Cr/Cu/Mo/Ge/Pd thin film stacks on the n$^+$-GaAs (~ 5×10^{18} cm^{-3}, 0.2 μm) after annealing at 300℃, 350℃ and 400℃ for 30 minutes. The sheet resistance of this thin film structure initially descends a little after 350℃ annealing, which may be due to grain growth and a decrease in defect density in these ohmic metal films. The lowest sheet resistance was also achieved after the sample was annealed at 350℃. The sheet resistance of the ohmic contact increases significantly after annealing at 400℃, suggesting that the atomic diffusion and the interfacial reactions between Cu layer and the underneath films have occurred. X-ray diffraction (XRD) was used to identify the interfacial reactions between the ohmic metals and n$^+$-GaAs. Figure 3.3 shows the X-ray diffraction patterns of the Cr/Cu/Mo/Ge/Pd/n$^+$-GaAs as deposited and after annealing at 350℃ and 400℃. The XRD data show no significant phase changes after annealing up to 350℃, suggesting that the contact was quite stable up to 350℃. When the annealing temperature was increased to 400℃, the inter-diffusion of the ohmic metals and the substrate material occurred. Extra compounds such as $MoGe_2$, Cu_3Ga and Ge_3Cu had formed after 400℃ annealing as indicated in the X-ray diffraction data. It is apparent that the Mo diffusion barrier failed to block the Cu atoms from penetrating into the Pd/Ge layers and the Cu atoms diffused through Mo and reacted with the Pd/Ge metals and GaAs at this temperature. This is consistent with the drastic increase of the sheet resistance after annealing at 400°C as shown in Figure 3.2. Additional evidences showing the stability of the contact after 350°C annealing can be seen from the AES depth profiles as shown in Figure 3.4. As can be seen from this figure, the Auger depth profiles clearly indicate that the Mo layer was very stable and there was no Cu diffusion into the Pd/Ge layers after 350°C annealing. To further investigate the reactions at the interfaces after thermal annealing at 350℃, cross-sectional TEM analysis was performed on the annealed samples. Figure 3.5 shows the cross-sectional TEM micrograph of this ohmic contact after 10 minutes, 350℃ annealing. In Figure 3.5, the TEM image shows that the interface between Cu and Mo is quite sharp. It shows no evidence of intermixing between Cu and Mo, indicating that Mo is a reliable diffusion barrier for Cu. Judging from the data of XRD, AES and TEM stated above, it can be concluded that Mo is a reliable diffusion barrier for Cu ohmic contacts on n^+-GaAs. To test the feasibility of using this novel Cu/Mo/Ge/Pd for device application, an HBT device with the proposed novel ohmic contacts was fabricated and evaluated.

3.3.2 Device Electrical Characteristics

The HBTs using the traditional n-type ohmic metal (Au/Ni/Ge/Au) and the new n-type ohmic metal (Cu/Mo/Ge/Pd) were both fabricated and characterized. The electrical performances of these two kinds of HBTs were compared. Figure 3.6 shows the plot of the common emitter I-V characteristics of the InGaP/GaAs HBTs fabricated with these two kinds of ohmic contacts, the emitter area of these devices was $4\times20\mu m^2$. Both devices show similar values of knee voltage and offset voltage. Besides, the common emitter current gains of the Cu- and Au-based ohmic contact HBTs were 95 and 93, respectively. Figure 3.7 shows the comparison of the Gummel plot of the HBTs with the Cu ohmic contacts and the traditional Au-based contacts. The electrical characteristics of these two HBTs are comparable. The thermal stability of the HBTs with the Cu/Mo/Ge/Pd contacts was also examined. Figure 3.8 shows the common emitter I-V curves of the HBT with Cu/Mo/Ge/Pd ohmic contact before and after annealing at 250℃ for 24 hours. As shown in Figure 7, there was no obvious degradation of the knee voltage after the thermal annealing. Figure 3.9 shows the measured current gain (β) of the Cu/Mo/Ge/Pd HBT after being stressed at the current density of 120kA/cm^2 at a V_{CE} of 1.5V for 24 hours. It can be seen from Figure 3.9 that the current gain was still higher than 120 after 24 hours current-accelerated stress and the deviation of the current gain was around 3.9%. The results of the electric characterizations and the material analyses in this study suggest that the Cu/Mo/Ge/Pd structure can be used as the ohmic contacts for the fabrication of the InGaP/GaAs HBTs.

3.4. Conclusions

A novel Cu/Mo/Ge/Pd ohmic contact was characterized and applied to the n^+-GaAs for HBT applications. The Cu/Mo/Ge/Pd ohmic contact structure reached the lowest contact resistance and was measured to be $2.8\times10^{-7}\Omega cm^2$ when annealed at 350℃. However, the contact structures deteriorated due to the interfacial reactions between Cu and the underneath films when annealed at 400℃. The sheet resistance, XRD, AES and TEM analysis data also indicate that Mo is a reliable diffusion barrier for the Cu-based ohmic contacts to n^+-GaAs up to 350℃ annealing. The InGaP/GaAs HBTs with the Cu/Mo/Ge/Pd ohmic contact was also fabricated and studied. From the device characterizations, the HBTs fabricated using the traditional n-type ohmic metal (Au/Ge/Ni/Au) and the HBTs fabricated using the proposed Cu/Mo/Ge/Pd n-type ohmic metal showed comparable electrical characteristics. The devices with the Cu/Mo/Ge/Pd ohmic contacts were also thermally annealed at 250℃ for 24 hours for thermal stability study and showed no obvious electrical degradation after the thermal test. Under the high current density of $120kA/cm^2$ at a V_{CE} of 1.5V for 24 hours, the HBTs with the novel Cu/Mo/Ge/Pd ohmic contacts show little change in electrical characteristics. The experimental results in this study suggest that Cu/Mo/Ge/Pd is an effective copper based ohmic contact structure and can be used for future copper metallization of the GaAs based electronic devices.

3.5 References

1) Asbeck P. M.: High-Speed Semiconductor Devices (1990)

2) K. Holloway and P. M. Fryer: Appl. Phys. Lett. **57** (1990) 1736

3) K. Holloway, P. M. Fryer, C. Cabral, Jr., J. M. E. Harper, P. J. Bailey and K. H. Kelleher: J. Appl. Phys. **71** (1992) 5433

4) D. Gupta: Mater. Chem. Phys. **41** (1995) 199

5) F. C. Frank and D. Turnball: Phys. Rev. **104** (1956) 617

6) C. Y. Chen, E. Y. Chang, L. Chang, S. H. Chen and D. F. Chang: Appl. Phys. Lett. **77** (2000) 3367

7) C. Y. Chen, E. Y. Chang, L. Chang, and S. H. Chen: Electron. Lett. **36** (2000) 1318

8) C. Y. Chen, E. Y. Chang, L. Chang, and S. H. Chen: IEEE Trans. Electron Devices **48** (2001) 1033

9) L. S. Yu, L. C. Wang, E.D. Marshall, S. S. Lau and T. F. Kuech: J. Appl. Phys. **65** (1989) 1621

Layer	Material	Type	Doping	Thickness (nm)
Emitter cap	GaAs	n+	5×10^{18} cm^{-3}	100
Emitter	InGaP	n	2×10^{17} cm^{-3}	85
Base	GaAs	p+	2×10^{19} cm^{-3}	120
Collector	GaAs	n-	4×10^{16} cm^{-3}	650
Subcollector	GaAs	n+	5×10^{18} cm^{-3}	600
Substrate	GaAs			

Table 3.1 The proposed epitaxial structure of the InGaP/GaAs HBT

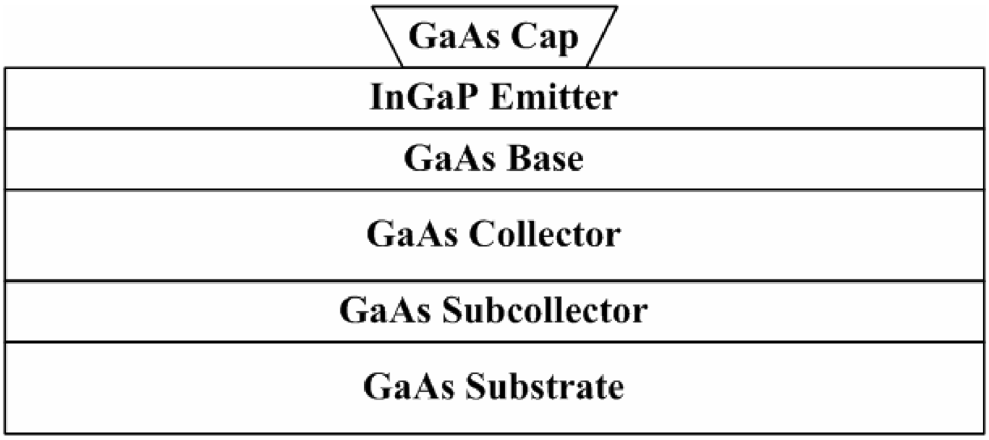

Fig 3.1.1 Emitter mesa etch

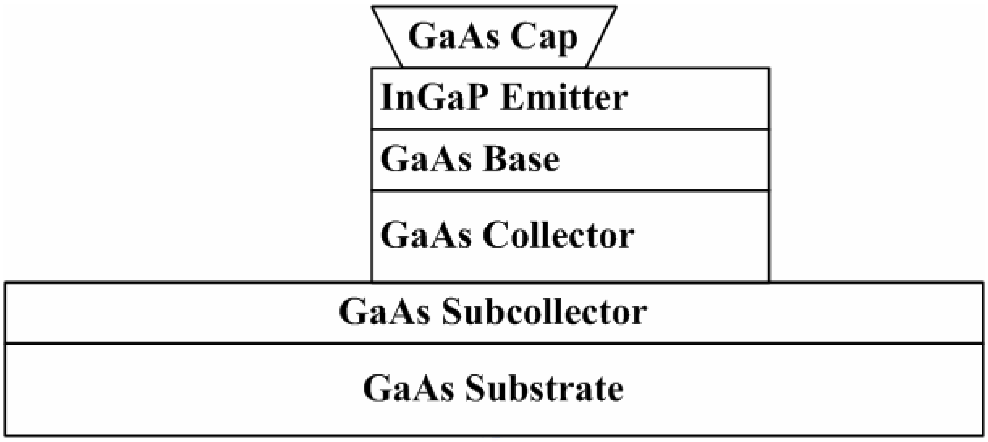

Fig 3.1.2 Base and collector mesa etch

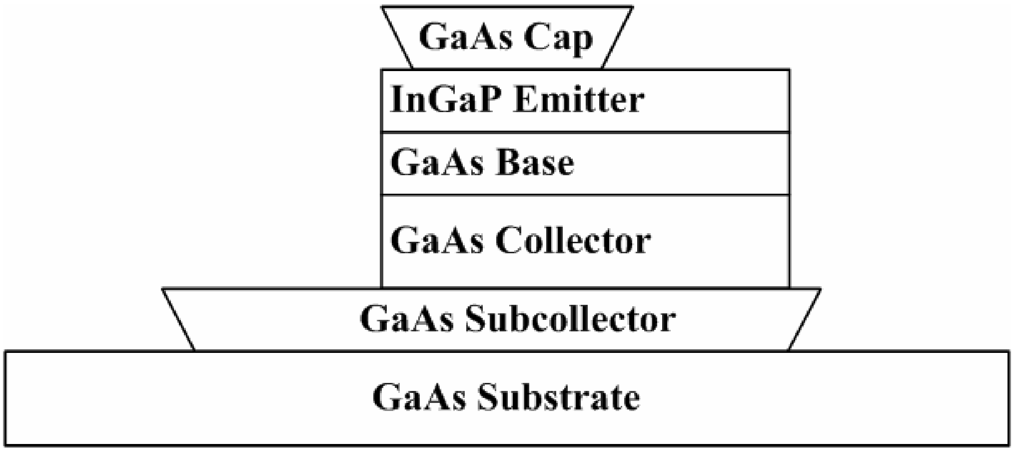

Fig 3.1.3 Mesa isolation

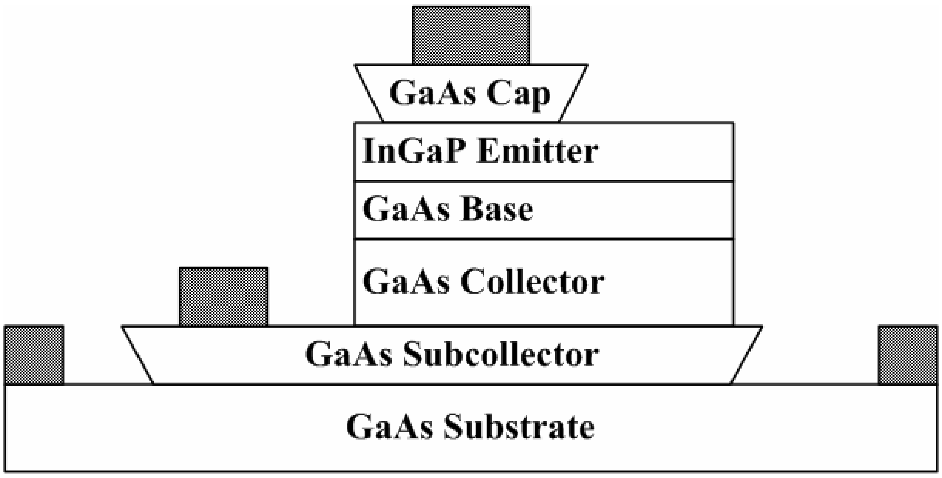

Fig 3.1.4 Emitter and collector ohmic contact metal formation

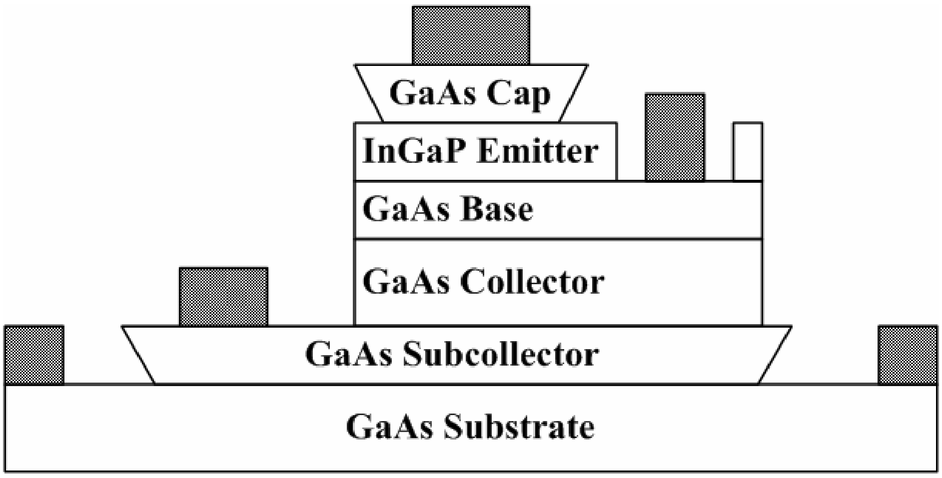

Fig 3.1.5 Base ohmic contact metal formation

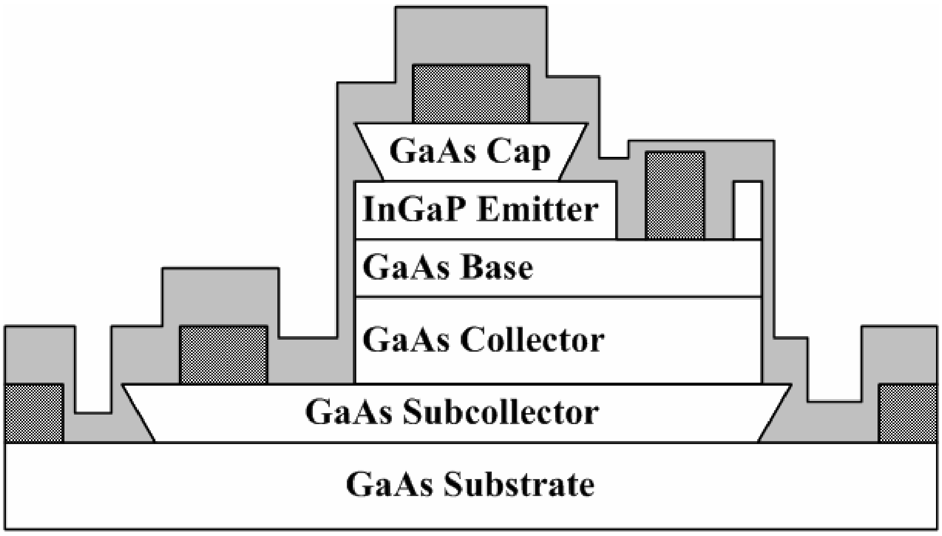

Fig 3.1.6 Silicon nitride passivation

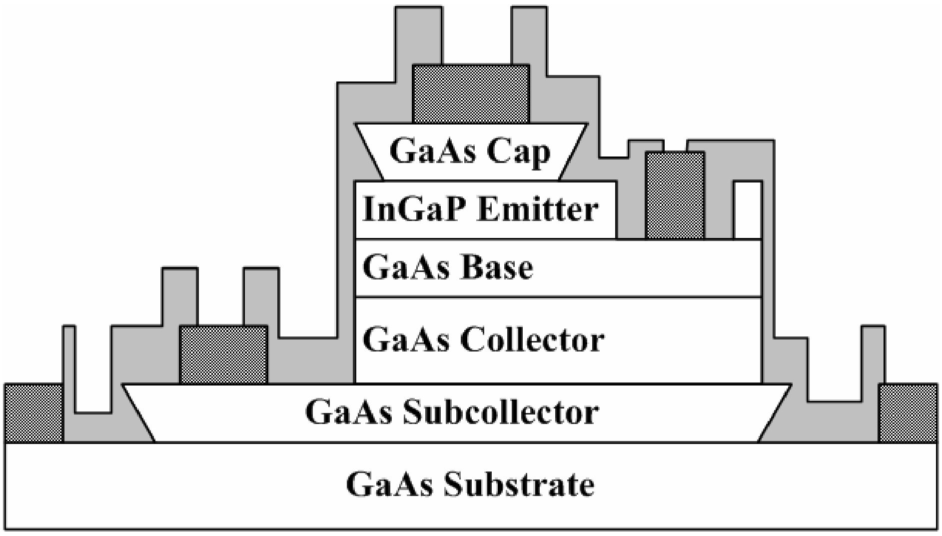

Fig 3.1.7 Contact via etch

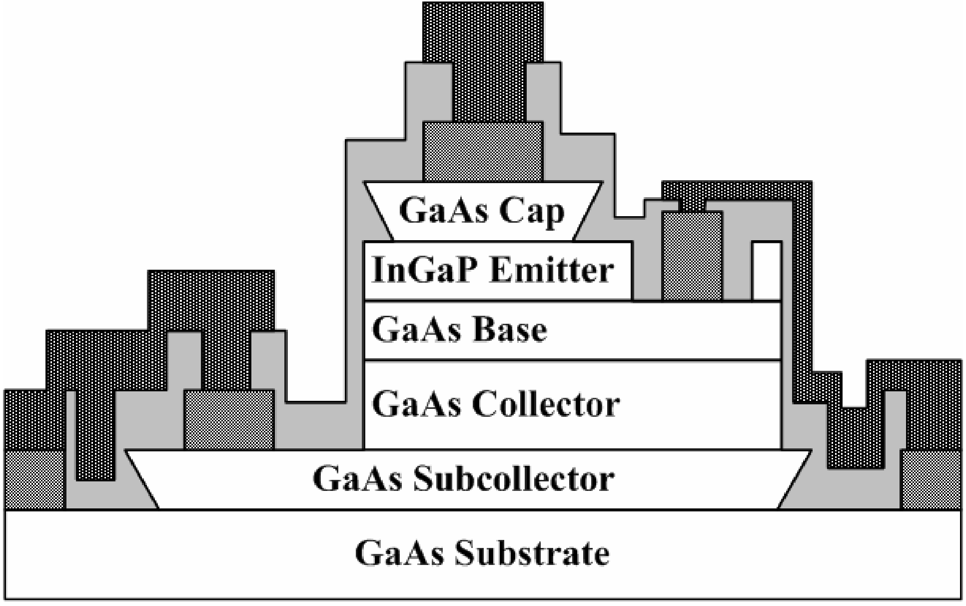

Fig 3.1.8 Interconnect line

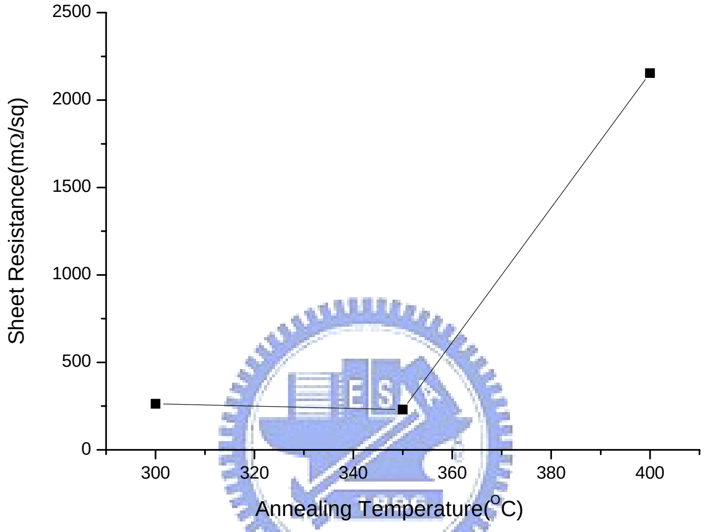

Fig.3.2. Sheet resistances of Cr/Cu/Mo/Ge/Pd/n^+-GaAs after annealing at 300, 350 and 400℃ for 30 min.

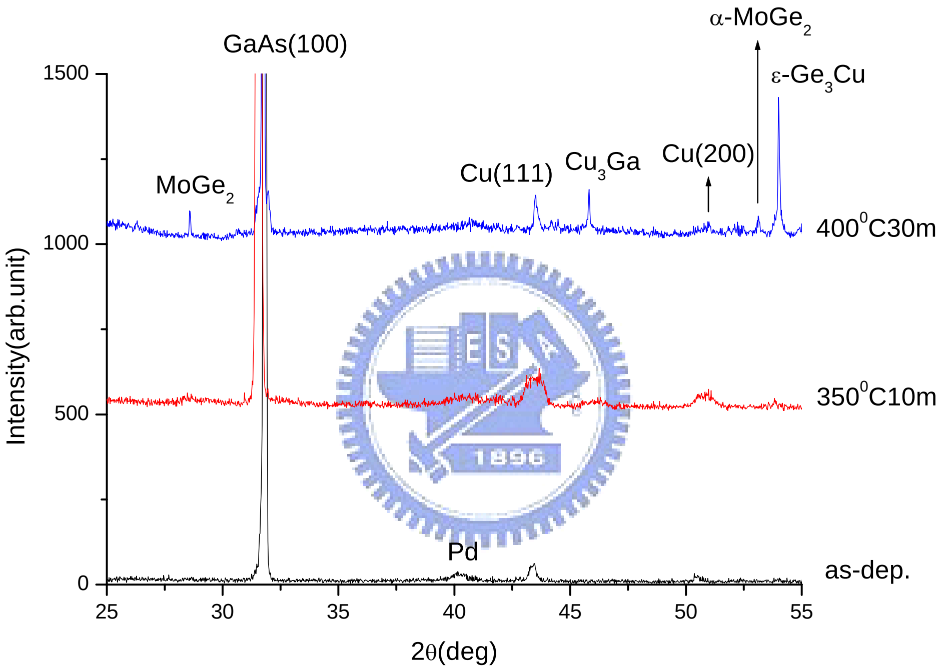

Fig.3.3 XRD results of Cr/Cu/Mo/Ge/Pd/n^+-GaAs as-deposited and after annealing at various temperatures.

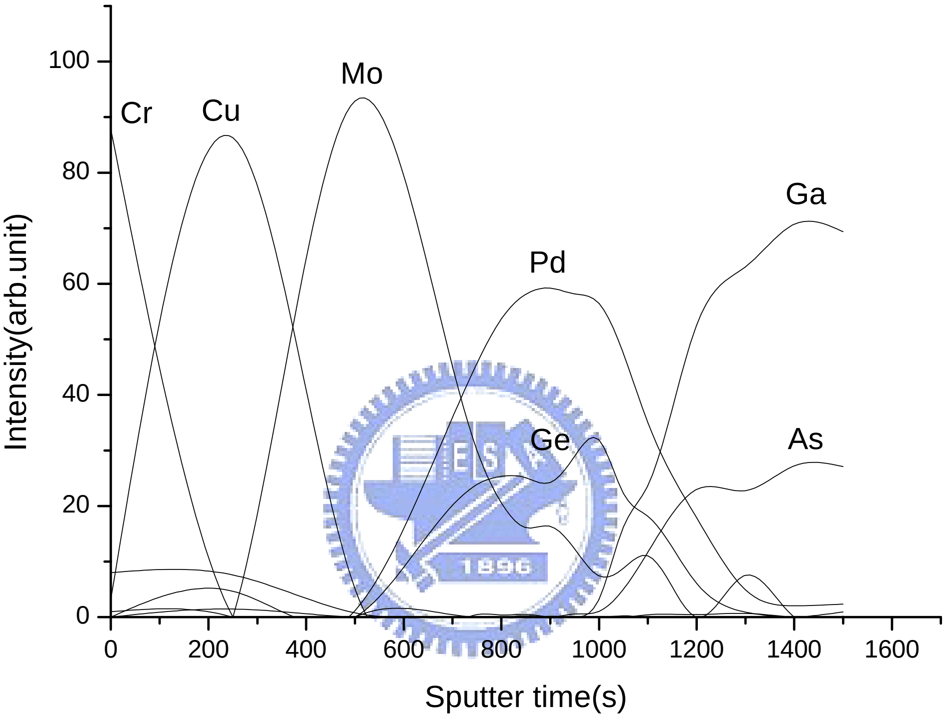

Fig.3.4. AES depth profiles of Cr/Cu/Mo/Ge/Pd/n$^+$-GaAs after annealing at 350℃ for 10 min.

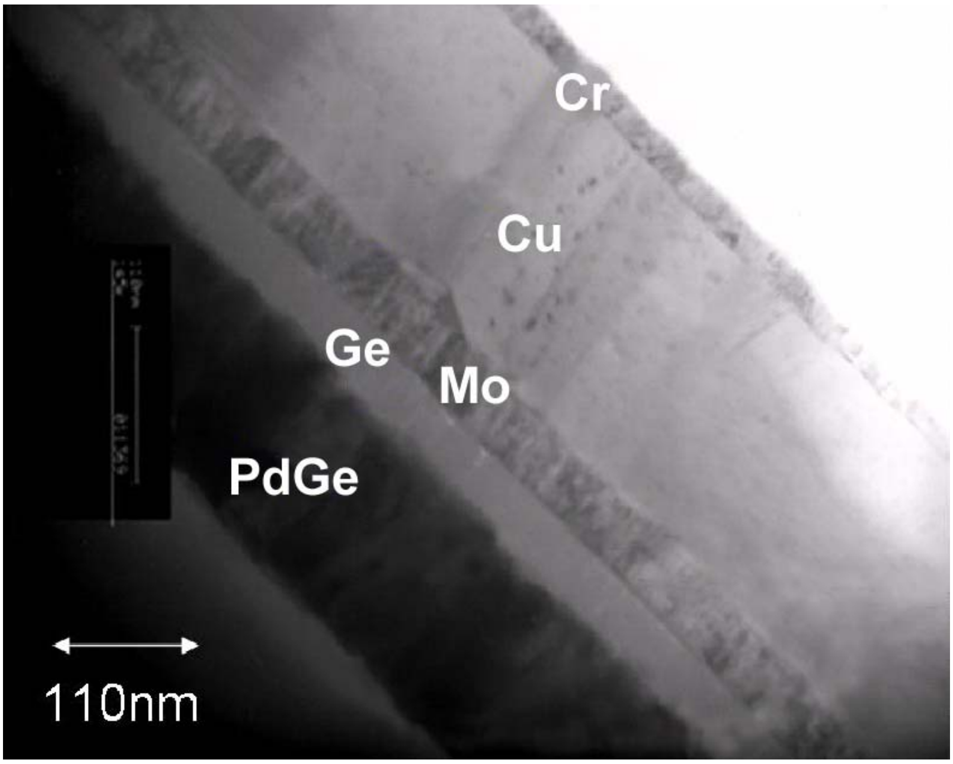

Fig.3.5. Cross-sectional TEM micrograph of Cr/Cu/Mo/Ge/Pd/n^+-GaAs after annealing at 350℃ for 10 min.

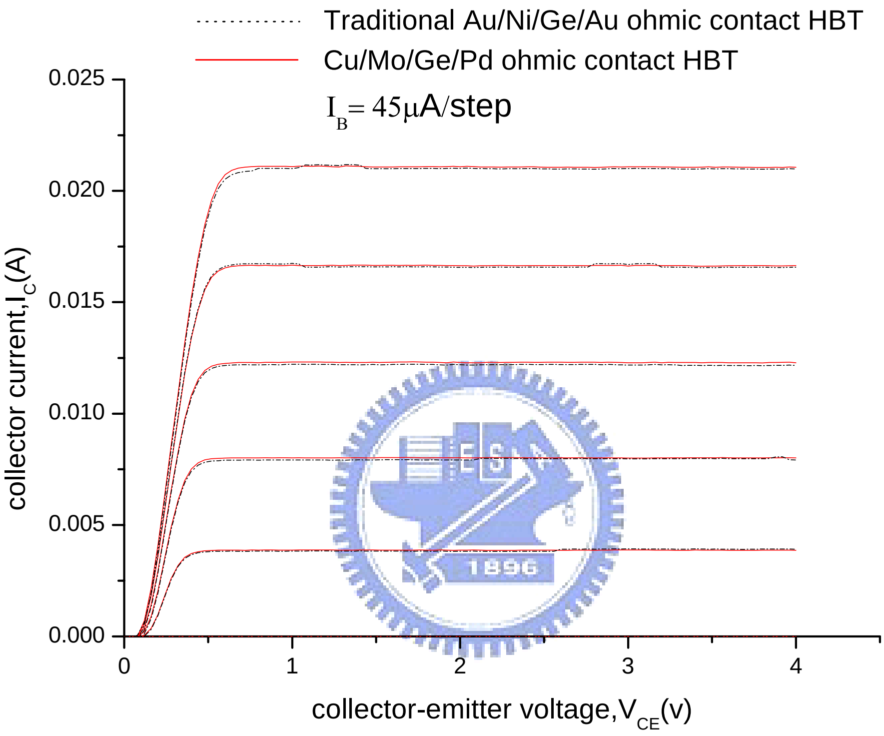

Fig.3.6. Comparison of common-emitter I-V characteristics of InGaP/GaAs HBTs with Au/Ni/Ge/Au and Cu/Mo/Ge/Pd ohmic contacts.

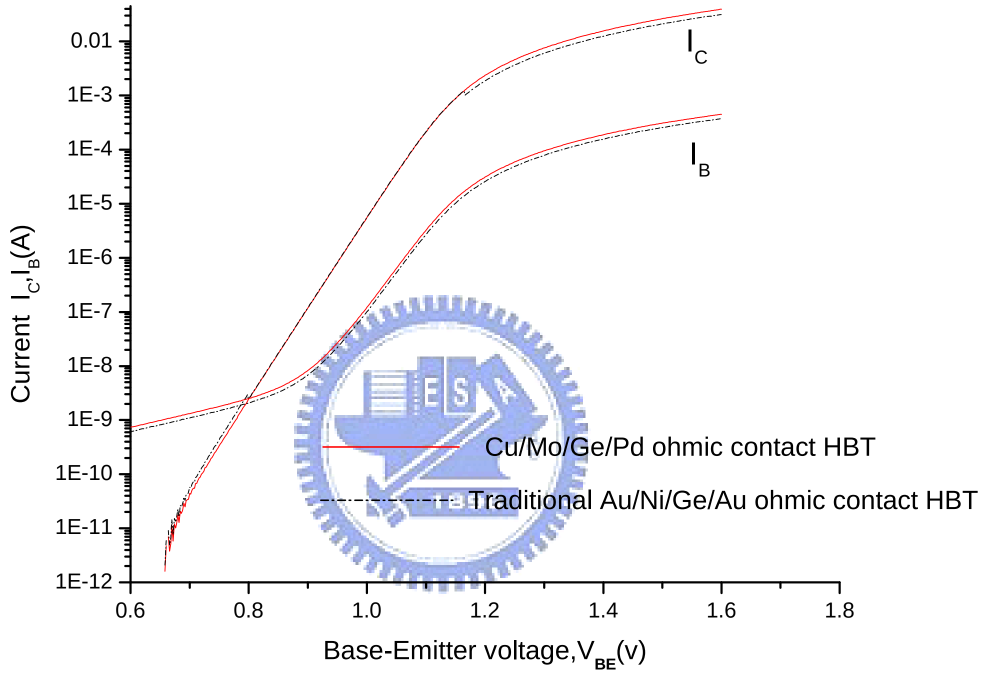

Fig.3.7. Comparison of Gummel plots of InGaP/GaAs HBTs with Au/Ni/Ge/Au and Cu/Mo/Ge/Pd ohmic contacts.

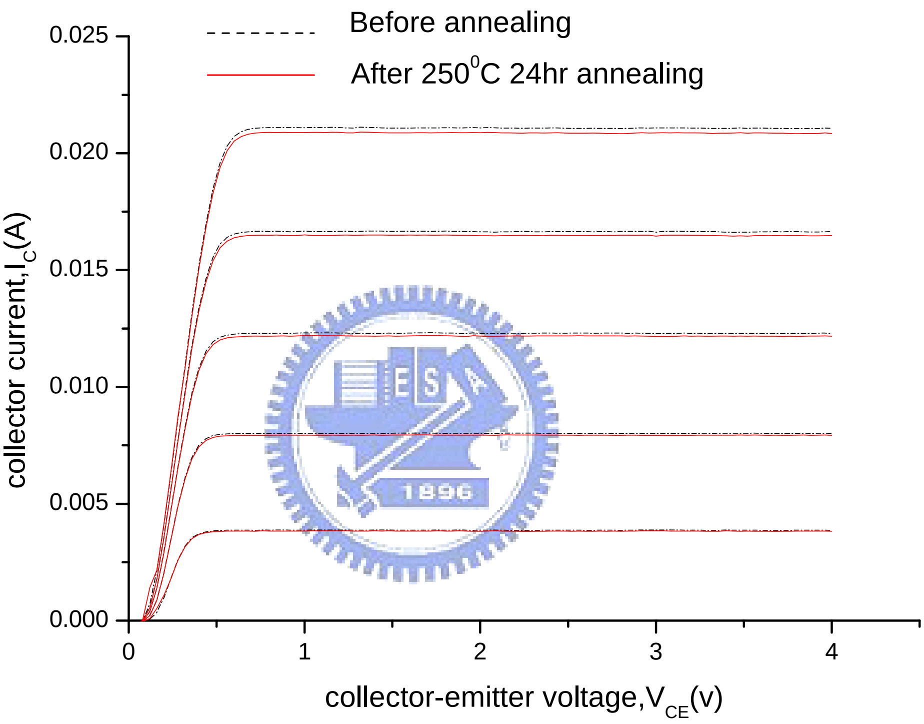

Fig.3.8. Common-emitter I-V curves of HBT with Cu/Mo/Ge/Pd ohmic contact before and after annealing at 250℃ for 24 h.

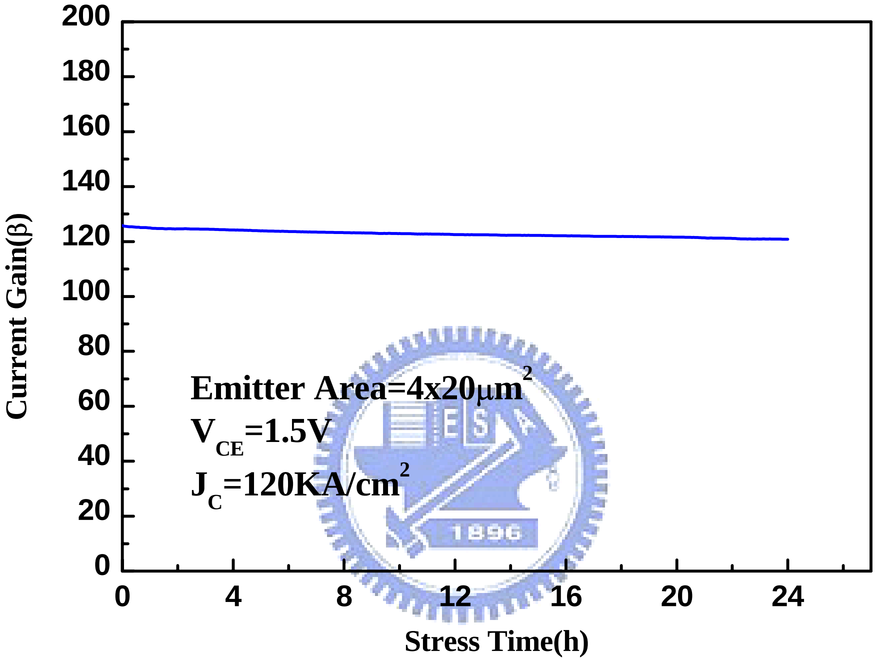

Fig.3.9. Current gain as function of stress time at constant I_B for 4 × 20-μm-emitter-area Cu/Mo/Ge/Pd HBT.