Chapter 5  
Conclusions

InAlP schottky diodes and PHEMTs have been fabricated and characterized in this study. A thick ohmic metal scheme consisting of Ge/Au/Ni/Ti/Au(700/1400/500/200/1000A) was used and a contact resistance of $5 \times 10^{-7} \Omega \cdot \text{cm}^2$ can be reached after alloy at 450°C for 30 seconds. Furthermore, the use of citric acid solution can completely and uniformly remove GaAs cap layer. High etching selectivity was achieved which greatly improves the pinch-off voltage uniformity and the process yield across the wafer.

InAlP diodes and PHEMTs with Ti/Pt/Au, Pt/Ti/Pt/Au and W/Ti/Pt/Au schottky metals have been fabricated successfully. Material analyses and electrical characterization were also carried out to study the stability of the device performance of the schottky contacts under different thermal annealing conditions.

X-ray diffraction data of the Ti/Pt/Au contact showed no interfacial phase formed during the thermal treatment process at 200°C for 30 minutes. From the TEM image and EDX analysis of Ti/Pt/Au contact, the high leakage current of the device when annealed at 400°C for 30 minutes may be due to the intermetallic compound growth through InAlP layer, which caused the carrier tunneling effect. The high ideality factor and the low schottky barrier height may be due to the intermetallic compound formation between Ti and InAlP interface. It was found that the diffusion of
Ti into the InAlP layer is the primary degradation mechanism. The schottky diode degradation exhibits an increase in reverse gate leakage current, sheet resistance, and a decrease in schottky barrier height. EDX analysis substantiates the intermetallic formation of Ti-InAlP and Ti sinking into InAlP schottky barrier layer. Ti interdiffusion reduces the separation of the gate metal and InGaAs channel, thus leading to the positive threshold voltage shift and the increase of ideality factor and leakage current.

The EDX analysis showed diffusion of Pt into InGaAs channel layer after annealing at 400°C with Pt/Ti/Pt/Au contact. Pt is not a thermal stable schottky contact metal. The as deposited diode with Pt/Ti/Pt/Au contact showed high ideality factor and low schottky barrier height of 2.64 and 0.64eV respectively. But, the ideality factor and schottky barrier height improved with higher temperature annealing and reached a highest schottky barrier height of 0.86eV with the ideality of 1.26, this may be due to the reduced distance of Pt schottky metal and InGaAs channel or the stable compound formed at the interface. A decrease of reverse breakdown with increasing annealing temperature has also been observed, this may be due to the Pt diffusion to a depth too close to the InGaAs channel layer. Therefore, Pt diffusion deep into the InAlP schottky layer will increase the gate leakage current which is induced by the carrier tunneling effect. A decrease of leakage current could be found due to proper diffusion of Pt into InAlP layer, and the decrease of gate metal and InGaAs channel distance induced the threshold voltage shift and the transconductance increase. Pt appears to be the best choice for use as a gate metal in E-mode HEMT fabrication due not only to its large schottky barrier height, but also the positive threshold voltage shift and the transconductance increase.
The diode with W/Ti/Pt/Au contact showed near-ideal I-V characteristics with the ideality factor about 1.5 and the ideality factor and Schottky barrier height were improved after thermal annealing. The W/Ti/Pt/Au contact exhibited excellent electrical characteristics even after thermal annealing at 500°C for 30 minutes. The results reflected W is with high degree of thermal stability is a good choice for Schottky contact and it also acts as a good barrier to the diffusion of Ti, Pt and Au into the InAlP layer.

The fabricated 0.4μm×40μm D-mode InAlP/InGaAs device exhibits a maximum drain current of 241mA/mm at gate bias on +1V with a gate-to-drain breakdown voltage of -11V. The maximum transconductance of the device was 302 mS/mm and the pinch off voltage was only -0.5V. The knee voltage was about 0.3V.

I-V characteristics of the InAlP PHEMTs are gate orientation dependent. PHEMT with gate line along [0 -1-1] direction shows higher saturation current and transconductance than device along [0 -1 1] direction. The differences may be due to the orientation dependence of the electron distribution, electron mobility and the gate recess profile.

Due to the high Schottky barrier height of the InAlP layer, the high $V_{ON}$ can reduce the gate leakage current at a higher gate bias, which will be beneficial to the breakdown voltage of the device. The fabricated 0.5μm×125μm Enhancement-mode InAlP/InGaAs device can be operated with gate voltage up to 2.5V owing to its high Schottky turn on voltage.

After annealing at 250°C for 30 minutes and for 3 hours, PHEMT with Ti/Pt/Au contact exhibits a positive threshold voltage shift and the maximum $G_m$ increases. The increase in the gate leakage current may be
due to the diffusion of Ti into InAlP layer which decreases the schottky barrier height and increases the ideality factor. After annealing for 3 hours, the threshold voltage also shift positive with the Gm decrease which may be due to the over-diffusion of Ti into the InAlP layer. 

After annealing at 250°C for 30 minutes, the device with Pt/Ti/Pt/Au contact has a positive threshold voltage shift and Gm increases. The peak Gm increase and the gate leakage current decrease were due to the Pt metal diffusion. The increase in schottky barrier height and the decrease in gate-to-channel spacing resulted in the positive threshold voltage shift and the increase of Gm. However, after thermal annealing at 250°C for 3 hours, the leakage current increased rapidly and the Gm decreased. The over-diffusion of Pt would degrade the performance of the device. The condition of the thermal treatment needs to be optimized to avoid drastic degradation in performance. From this study, Pt appears to be the best choice for use as a gate metal in E-mode HEMT fabrication due to the improvement of schottky characteristics and the positive shift of threshold voltage after proper annealing conditions.

After annealing at 250°C, the device with W/Ti/Pt/Au contact exhibits performance with a positive threshold voltage shift of only 2mV. In addition, the Gm increases 21%. It shows no further shift of threshold voltage and a very small schottky barrier height and leakage current change. It reflects that the device performance remains stable when W/Ti/Pt/Au is used as the schottky contact metal.

In conclusion, InAlP/InGaAs PHEMTs have been fabricated and characterized. W/Ti/Pt/Au Schottky diode shows less degradation up to 500
annealing and W/Ti/Pt/Au InAlP PHEMT exhibits small changes in I-V characteristics after annealing at 250°C for 30 minutes when compared to the corresponding Ti/Pt/Au, Pt/Ti/Pt/Au gated devices. The results indicate that W/Ti/Pt/Au is a good Schottky metal structure on InAlP for high temperature operation. And Pt appears to be the best choice for use as a gate metal for E-mode PHEMT fabrication due not only to its large Schottky barrier height, but also because of the resulting positive shift of the threshold voltage after thermal treatment. However, the condition of the thermal treatment needs to be optimized to avoid drastic degradation in performance.