Abstract – The Cu-metalized GaAs pHEMT using developed Pd/Ge/Cu ohmic contacts and Ti/Mo/Cu 150 nm T-shape gate has been successfully fabricated for high-frequency application. The fabricated Cu-metalized pHEMT has a maximum drain current of 480 mA/mm, off-state gate-drain breakdown of 7 V and a transconductance peak of 275 mS/mm at $V_{DS} = 2$ V. The maximum stable gain (MSG) value was about 15 dB at frequency 10 GHz. The current gain cut-off frequency of the copper metalized device is about 60 GHz at $V_{ds} = 2$ V and maximum frequency of oscillations is beyond 100 GHz.

1. Introduction

Wafer production cost is an important metric that measures the profitability and success of a semiconductor fab. Precious metal represents a portion of a completed GaAs wafer cost. Gold (Au) and Platinum (Pt) have market prices that fluctuate with the demand. The current economic situation has driven the price of Au and Pt up steadily over the last couple of years. Although the precious metals prices are beyond one’s control, with proper engineering, these metals can be replaced by a less expensive alternative – copper.

Copper metallization has been extensively used in the silicon integrated circuit technology since IBM announced its success in silicon very large scale integration process [1–3]. The advantages of copper metallization for Si technology include lower resistivity and higher electro migration resistance. Even though the use of copper as metallization metal has become very popular in Si devices, there were very few reports of copper metallization of GaAs devices published in the literature [4–6]. Use copper as the metallization metal instead of gold has several advantages such as lower resistivity, higher thermal conductivity, and lower cost. If Cu replaces Au as the metallization metal for the pHEMTs, then the resulting improvement in the electrical conductivity can increase the transmission speed of the circuits [7]. But copper diffuses very fast into GaAs and is a deep acceptor, moreover copper oxidized under atmosphere exposure, so copper metallization of GaAs device without a diffusion and passivation barriers degrades their electrical properties.

The purposes of the work are to develop and produce copper metalized pHEMT with Pd/Ge/Cu ohmic contacts and Ti/Mo/Cu 150 nm T-gate; to investigate the DC and RF parameters of fabricated Cu-metalized GaAs pHEMT.

2. Experimental techniques

The fully Cu-metalized GaAs pHEMT was formed on the AlGaAs/InGaAs/GaAs pseudomorphic structures have been grown by using molecular beam epitaxy (MBE). A 200 nm thick undoped GaAs buffer layer and ten AlGaAs–GaAs superlattices are grown on 3-inch diameter semi-insulating GaAs substrates, followed by a undoped GaAs layer. The thickness of the In$_{0.22}$Ga$_{0.78}$As channel layer is 12 nm. The planar doping layer with Si of a 2 \cdot 10^{17} \text{cm}^{-2} density is separated from the active layer by a thin undoped Al$_{0.22}$Ga$_{0.78}$As spacer and a 32 nm thick Al$_{0.22}$Ga$_{0.78}$As Schottky layer is grown. To reduce parasitic resistance, the 50 nm thick GaAs cap layer is highly doped with Si of 6 \cdot 10^{18} \text{cm}^{-3}.

After mesa isolation the source and drain ohmic metals were formed. There were used Pd/Ge/Cu (15 nm/150 nm/150 nm) ohmic contacts deposited by the electron beam evaporation under a vacuum of 10$^{-6}$ torr. After the ohmic contact structure was formed using the lift-off method a rapid thermal annealing was carried out. Annealing was performed ex situ in a single high temperature stage in an inert gas environment. Pd/Ge/Cu ohmic contacts were annealed at a temperature $T = 250$ °C for a period of $t = 20$ min. 150 nm Ti/Mo/Cu T-shape gates were fabricated by electron beam lithography, e-beam evaporation and lift-off process. There was used a tri-layer resist stack of 950 PMMA/LOR 5B/495 PMMA (from bottom to top). The resists were spin coated onto the substrate. Each resist layer was baked for a 5 min at 180 °C on the hotplate. The Raith-150$^{\text{two}}$ e-beam nanolithography system was used for a single exposure of the resist with a 30 kV electron beam. The gate pattern consists of three patterns. The optimum conditions, to define T-shape gates at 150 nm level for pHEMTs were obtained when the footprint dose is 600 $\mu$C/cm$^2$, the head dose is 140 $\mu$C/cm$^2$. The top layer was developed in mixture of MIBK/IPA for 60 s and then rinsed in IPA and blown dry in nitrogen. The second layer was developed in MF-319 developer and then rinsed in
water. The third layer was developed for 30 s in MIBK:IPA followed by rinsing in an IPA and blown dry with nitrogen. Then recess etching was performed using citric acid based solution as an etchant to remove GaAs cap layer. After that T-gate metallization of Ti/Mo/Cu (20 nm/20 nm/400 nm) was deposited by e-beam evaporation under a vacuum of $5 \times 10^{-7}$ torr and lifted off.

The surface morphology of the annealed ohmic contact pads was examined by method of the scanning electronic microscopy (SEM). Specific contact resistance $\rho$ was measured by the TLM method. The accuracy of the specific contact resistance measurement was 30%.

The device DC properties were measured with a Tektronix 370 A. The microwave S-parameter measurement has been carried out by using a ZVA-40 network analyzer.

3. Results and discussion

In Figure 1 the results of the specific contact resistance measurements of the Pd/Ge/Cu ohmic contacts produced by e-beam evaporation and RTA annealed in nitrogen environment are presented.

![Fig. 1. Dependence of the specific contact resistance of Pd/Ge/Cu ohmic contacts versus the annealing temperature ($t = 20$ min)](image)

The temperature dependences has a traditionally curves shape with the $\rho$ value minimum. With the annealing temperature raise the interdiffusion between multilayer metals film and GaAs is increase. This leads to reduction of the specific contact resistance, down to minimal value of $\rho$. The subsequent growth of the temperature leads to $\rho$ increasing. It may be caused by the copper penetration from the top layer to the GaAs surface.

The minimal value of the specific contact resistance for Pd/Ge/Cu ohmic contacts is $1 \times 10^{-6}$ Ohm $\cdot$ cm$^2$ after annealing at $T = 250$ $^\circ$C during $t = 20$ min.

In Figure 2 the pad surface morphology of annealed Pd/Ge/Cu ohmic contacts is presented.

![Fig. 2. SEM image of the Pd/Ge/Cu ohmic contact pads surface annealed at 250 $^\circ$C during 20 min](image)

The Pd/Ge/Cu ohmic contacts have a uniform and smooth surface morphology. The small size copper crystal grains are visible there.

The non-alloyed Pd/Ge/Cu ohmic contacts offer opportunity to minimize the thermal budget of III-V HEMT process flow which can be important in aggressive scaling where layer thickness and dopant plane placement are crucial to device operation. In addition, moving to low temperature ($250$ $^\circ$C) process flow enables the gate to be definite before the Ohmic contacts. Thereby removing the concern about gate resist thickness uniformity in a source drain gap.

Figure 3 shows the SEM image of fabricated 150 nm Ti/Mo/Cu T-gate.

![Fig. 3 Cross-section SEM image of fabricated copper metalized GaAs pHEMT with 150 nm T-gate](image)

The Ti/Pt/Au Shottky contact on $n$-GaAs is the most widely used Shottky structure in the GaAs HEMT fabrication. In present study, the thick overcoat gold layer was replaced with copper. And Pt layer was replaced with the transition metal such Mo. The choice of the refractory metals was based on their resistivity and the capability as the diffusion barrier. The resistivity of Mo metal is much lower than Pt, therefore fabricated Ti/Mo/Cu T-gate has a smaller gate resistance. It is can improve the DC and RF parameters of GaAs pHEMT.
Figure 4 shows the SEM image of topology Cu-based GaAs pHEMT.

DC characteristics of fabricated Cu-based pHEMT indicates excellent performance with maximum drain current of 480 mA/mm, off-state gate-drain breakdown of 7 V and a transconductance peak of 275 mS/mm at $V_{ds} = 2$ V.

Figures 5 and 6 show the microwave characteristics of Cu-based GaAs pHEMT.

The device performance was measured for pHEMT with 150 nm gate length and a total gate width of 100 µm. The maximum stable gain (MSG) value was about 15 dB at frequency 10 GHz. The current gain cut-off frequency of the copper metalized device is about 60 GHz at $V_{ds} = 2$ V and maximum frequency of oscillations is beyond 100 GHz.

4. Conclusion

In the work the copper metalized pHEMT with Pd/Ge/Cu ohmic contact and Ti/Mo/Cu 150 nm T-gate was successfully produced. The fabricated Cu-based pHEMT has a maximum drain current of 480 mA/mm, off-state gate-drain breakdown of 7 V and a transconductance peak of 275 mS/mm at $V_{ds} = 2$ V. The maximum stable gain (MSG) value was about 15 dB at frequency 10 GHz. The current gain cut-off frequency of the copper metalized device is about 60 GHz at $V_{ds} = 2$ V and maximum frequency of oscillations is beyond 100 GHz.

References