Thesis title

Planar and Non-Gold Metal Stacks Processes and Conduction Mechanisms for AlGaN/GaN High-electron-mobility Transistors on Silicon

Abstract

AlGaN/GaN high-electron-mobility transistors (HEMTs) have demonstrated great potentials in high voltage and high frequency applications due to the advantage in their intrinsic material properties such as wide band gap, high electron saturation velocity, high sheet carrier density, etc. Conventionally, AlGaN/GaN HEMTs are realized in III-V fabrication line using the processes that cannot be used in Si CMOS line, e.g. mesa isolation, gold-based ohmic contacts and gate electrodes etc.

With the advances of epitaxial growth technology, the crack-free AlGaN/GaN heterostructure can be realized in large diameter (200 mm) Si substrate with low wafer bowing values, which provides the possibility of fabricating devices with high throughput to satisfy the rapidly increased market of GaN electronics. In recent years, CMOS-compatible processes have received considerable attentions. This approach allows high-volume low-cost fabrication of AlGaN/GaN HEMTs by utilizing the existing Si foundries. Also, the CMOS-compatible processes offer the opportunity of on-chip integration of GaN devices with Si integrated circuits (ICs).

In this thesis, the focus is to develop the key process modules which will be CMOS compatible for AlGaN/GaN HEMTs. The three process modules include planar isolation by ion-implantation, non-gold ohmic contact, and non-gold Schottky gate. In addition, the conduction mechanisms and its physical origin are also

systematically analyzed to understand the impact of developed processes to the characteristics of fabricated AlGaN/GaN HEMTs on Si substrate.

The planar isolation is achieved in AlGaN/GaN HEMTs using multi-energy ultra-heavy $^{131}Xe^{+}$ ion-implantation. About an order of magnitude lower buffer leakage current, and an order of magnitude higher buffer sheet resistance and ON/OFF current ratio are observed in the implant-isolated HEMTs when compared to the conventional mesa-isolated HEMTs. The Arrhenius plot reveals an activation energy (0.513 eV) that belongs to the lattice damage caused by heavy ions, which is the origin of the high resistivity in the implanted region. The implant-isolated AlGaN/GaN HEMTs exhibit comparable DC output and transfer characteristics to the mesa-isolated HEMTs. Due to the elimination of leakage paths at the mesa side wall, the buffer breakdown voltage is almost not changed with and without Si_3N_4 passivation, the OFF-state breakdown voltage is also improved and the gate leakage current is reduced.

The reproducible non-gold ohmic contacts are realized by Ta/Si/Ti/Al/Ni/Ta metal stacks with a low contact resistance (~0.22 Ω·mm) and a smooth surface morphology. The low contact resistance is attributed to the formation of low work function Titanium Silicides ($TiSi_x$) at the metal-semiconductor (M-S) interface. As the AlGaN/GaN epi-layers are protected by the refractory bottom-Ta layer, the metal stacks do not react with (Al)GaN. Hence, the conduction mechanism of AlGaN/GaN HEMTs with our non-gold metal stacks is confirmed to be thermionic emission (TE) through a low energy barrier (~0.113 eV) at the M-S interface, which is different from the thermionic-field emission (TFE) observed in conventional gold-based ohmic contacts.

The non-gold Schottky gate is realized by sputtered TiN with an improved Schottky barrier height (SBH ~1.1 eV) as compared to other reported TiN-based gates. The improvement of SBH may be due to the incorporation of oxygen, the surface crystal orientation, or the relatively high N_2 ratio in the total gas flow. The study on gate leakage current reveals that the conduction mechanism is dominated by Poole-Frenkel emission at low reverse bias (-3.2 V < V_R < 0) through an interface state of 0.53 eV, and by trap-assisted tunneling at high reverse bias (-20 V < V_R < -3.2 V) through another interface state of ~0.115 eV. The AlGaN/GaN HEMTs with sputtered TiN gate demonstrate comparable DC output and transfer characteristics and dynamic/static ON-resistance ratio, improved OFF-state breakdown voltage, and reduced gate leakage current as compare to the device with conventional Ni/Au gate.

In summary, three important and challenging process modules in developing CMOS-compatible processes for the fabrication of AlGaN/GaN HEMTs on Silicon substrate have been systematically studied and reported in this thesis. The multi-energy ultra-heavy $^{131}Xe^{+}$ implantation, ohmic contacts with non-gold metal stacks (Ta/Si/Ti/Al/Ni/Ta), and non-gold Schottky gate (sputtered TiN) are demonstrated with improved device performance. The conduction mechanism of both ohmic and Schottky contacts is also systematically studied. The findings in this thesis provide valuable solutions for the development of CMOS-compatible processes, which can be potentially used for the high-volume and low-cost fabrication of AlGaN/GaN HEMTs in Si foundries for commercial applications.