A Gold-free Fully Copper Metalized AlGaN/GaN Power HEMTs on Si substrate

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Abstract

Thermal stability and reliability of AlGaN/GaN high electron mobility transistors (HEMTs) on Si substrates with 2 μm-thick copper interconnection (Cu-INTC) metal were evaluated and studied. The usage of copper metal as conducting metal has the advantages of higher thermal conductivity, low cost and low sheet resistance. For comparison, traditional gold metal interconnection (Au-INTC) devices were also fabricated with the same process conditions. Thermally infrared (IR) microscopy measurement shows that the Cu-INTC devices achieved a lower channel temperature ($T_{CHANNEL}$) compared to traditional Au-INTC ones with the identical drain current density. It is owing to its low metal resistivity. The typical peak transconductance (g_m), output power (P_{OUT}), power gain (Gp) and power-added-efficiency (PAE) at 100 ^{o}C operation were 87.53 mS/mm, 22.85 dBm, 11.1 dB and 25.9 % for 1 mm gate width Cu-INTC power device and these measured results were better than those in Au-INTC devices. These measured results indicated that the copper metal provides a highly potential for high-power AlGaN/GaN HEMT applications.

Copper (Cu) interconnects metallization has been successful demonstrated in the silicon integrated circuits technology. Low resistivity, inertness to most wet chemicals and suitability for wire bonding are the reasons that the gold (Au) has remained the metal choice for forming the interconnections in the compound semiconductor industry. In this study, the 2 μm-thick Cu-INTC was demonstrated by electron-beam evaporation and lift-off process and Ti was still adopted for the adhesion and diffusion barrier layer. The thermal conductivity and resistivity of the traditional gold metal are 318 W/mK and 22.14 nΩ·m and these values are 401 W/mK and 16.78 nΩ · m for copper metal, respectively. Therefore, the thermal dissipation efficiency and signal propagation can be improved simultaneously by adopting Cu-INTC technology. Based on the transmission electron microscopy (TEM) images and material analysis, the Cu interconnection line with Ti diffusion barrier layer on GaN buffer layer achieved a negligible metal diffusion under 1A DC current stress at 100^{o}C for 48 hours.

For devices fabrication, the active region was protected by a photoresist and the mesa isolation region was removed using BCl_3 + Cl_2 mixed gas plasma in a reactive ion etching (RIE) chamber. Ohmic contacts of the Ti/Al/Ni/Cu (30nm/125nm/50nm/100nm) metals were formed by electron beam evaporation, and patterned by conventional optical lithography with lift-off. The contacts then underwent rapid thermal annealing (RTA) at 850 ^{o}C for 30 seconds in a nitrogen-rich chamber. Then the 1 μm gate-length (Ni/Cu =20 nm/200 nm) gate electrodes were deposited on the center position of 5μm drain-to-source spacing. In this study, the air-bridged connection for source pads of 1mm gate width power transistor was replaced by BCB-bridge technology for reliability consideration [1]. The BCB exhibits several merits for microwave power devices, including low dielectric constant (2.7), low dielectric loss tangent (0.0008), low curing temperature, low water up-take and simple manufacturing process. The 2μm thick BCB was coated on the wafer by a spin coater and those BCB films were defined by g-line photolithography as the supporting material beneath the 1 μm-thick interconnection metals. Finally, a 1μm thick top Cu layer (Cu-INTC) with 50nm Ti diffusion barrier metal were evaporated for connecting the source pads. For comparison, the conventional Au interconnection metal (Au-INTC) GaN power devices were also fabricated. The scanning electron microscope (SEM) image of interconnection bridge with BCB supporting film was shown Fig. 1.

Fig. 1 The cross-sectional profile of the BCB-bridged AlGaN/GaN power HEMTs.

In order to measure experimentally the temperature distribution within the HEMT, an infrared (IR) thermography system with micro-Raman spectroscopy was adopted and the device IR radiation is detected by a Neo Thermal TVS-700 detector. The channel temperature map is derived from the IR-radiation intensity after an emissivity calibration which was performed for the unpowered device at various I_{DS}. Fig. 2 shows the channel temperature of both devices versus various DC bias powers and the Cu-INTC GaN power HEMT has relative high thermal dissipation ability during high power operation. These IR thermography images also showed that

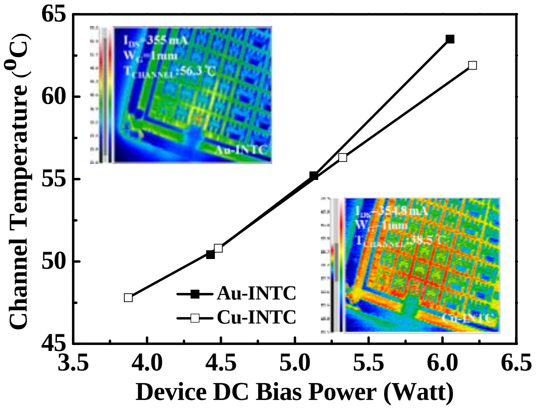

Fig. 2 Channel temperature performance of both devices versus various DC bias power values and IR images of AlGaN/GaN power devices using Au-INTC and Cu-INTC designs.

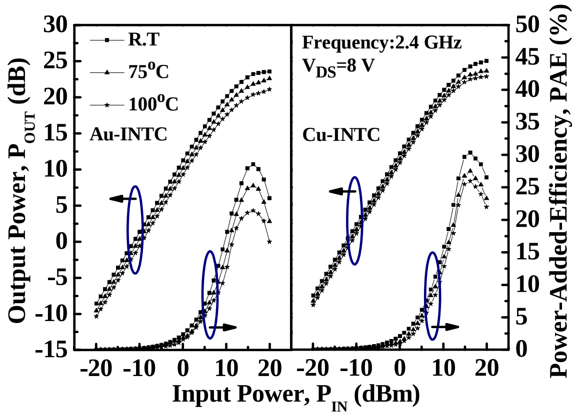

Fig. 4 Power performance of AlGaN/GaN power HEMTs with Au-INTC and Cu-INTC versus temperatures at 2.4 GHz.

the generated heat can be efficiently dissipated by Cu metal.

The temperature-dependent g_m and I_{DS} performance of both devices are shown in Fig. 3. The Cu-INTC power device exhibits a 17 % g_m reduction at high temperature operation (from 109.18 mS/mm at room temperature to 90.53 mS/mm at 100 °C); while there is almost 30% drop for Au- INTC power device (from 99.96 mS/mm at room temperature to 72.49 mS/mm at 100 °C).

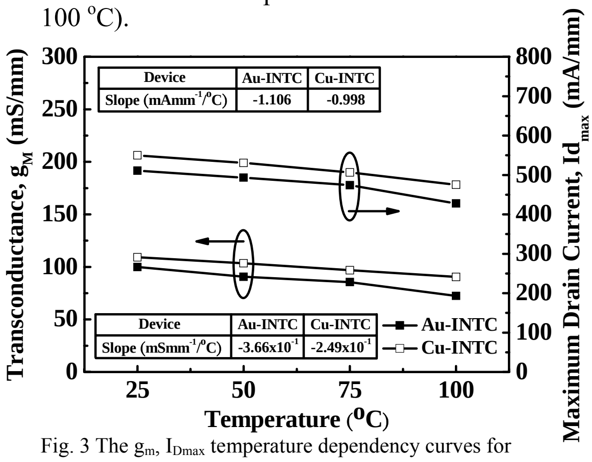

Fig. 3 The g_m, I_{Dmax} temperature dependency curves for Au-INTC and Cu-INTC power HEMTs.

The microwave load-pull power performance was evaluated at 2.4 GHz, with a drain bias of 8 V for both devices. As shown in Fig. 4, by raising the device temperature up to 100 °C, the Cu-INTC power HEMTs reveal an output power (P_{OUT}) shift from 25.02 dBm to 22.85 dBm, a linear power gain (Gp) shift from 12.43 to 11.1 dB, and a power added efficiency (PAE) degradation from 30.32% to 25.94 %. For the Au-INTC power HEMTs temperature dependent results, these microwave power characteristics peformed a significant 10.5-25 % drop by increasing the operation temperature to 100 °C. Moreover, the temperature degradation slop of the output power at P_{in}=0 dBm in Cu-INTC power HEMTs exhibited a slope of only -1.73 dBm/°C while this value is much higher (-2.6 dBm/°C) for Au-INTC ones.

Fig. 5 shows the Cu interconnection line and Au interconnection line was biased with 1A/cm^2 current density at 100°C environment for 48 hours continuous stress. Based on the TEM image and energy-dispersive x-ray spectroscopy (EDX) analysis, both Au and Cu achieved a negligible diffusion phenomenon by inserting a Ti diffusion barrier layer between interconnection metal and GaN. The TEM samples was attached on the Cu substrate, therefore, the Cu signal has a background signal for EDX analysis. In addition, in the Cu-INTC TEM image, the Cu metal layer shows a low diffusion phenomenon with GaN, however, Cu metal formed the metal clusters after high current stress at high temperature due to metal oxidation with oxygen. Therefore, the final passivation is necessary to prevent the oxidation of Cu metal.

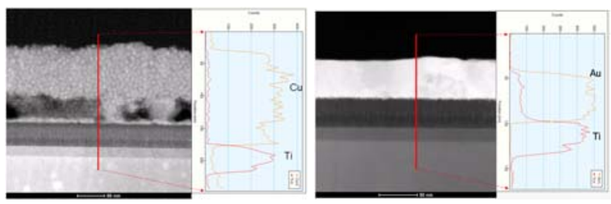

Fig. 5 The TEM images of Cu/Ti/GaN and Au/Ti/GaN interfaces after DC stress at high temperature.

In summary, the comprehensive temperature-dependent device performances of AlGaN/GaN Au-INTC and Cu-INTC power HEMTs have been evaluated. The device thermal performances of both are studied based on the electrical DC characterization, IR thermography, microwave measurement and load-pull power measurement system. The Cu-INTC BCB-bridged power HEMTs exhibited a better thermal stability due to the device dc and microwave parameters were less influenced by temperatures. In addition, the Cu interconnection also achieved a low inter-diffusion property with GaN which is important to keep device reliable after high DC stress at high temperature. These superior thermally stable properties, together with the high current driving capability, prove that the Cu interconnection technology is very promising candidate for power device applications.

References

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