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

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Abstract

The thermal stability and reliability of AlGaN/GaN high electron mobility transistors (HEMTs) on Si substrates with a 2 µm-thick copper interconnection (Cu-INTC) metal were evaluated. The use of metallic copper as a 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 fabricated under the same process conditions. Thermal infrared (IR) microscopy measurements show that the Cu-INTC devices achieved a lower channel temperature ($T_{CHANNEL}$) than traditional Au-INTC devices 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 ^oC 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 of Au-INTC devices. These measured results indicated that the copper metal provides a highly potential for high-power AlGaN/GaN HEMT applications.

INTRODUCTION

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. However, even though the use of copper as interconnection metal has been adopted in GaAs device [1-3], the use of copper as interconnection metal for GaN devices has not been widely discussed yet. AlGaN/GaN high electron mobility transistors (HEMTs) are excellent candidates for use in high power, high frequency and high temperature applications owing to their unique properties, such as high critical electric field, high carrier concentration, and high saturation velocity even at high temperature. These result in realizing lower loss and higher power switching characteristics compared with those of using conventional Si devices [4-6]. For process cost and low interconnection loss considerations, Cu interconnection metallization provides a high potential for GaN semiconductor industry. Currently, GaN HEMT and its related monolithic integrated circuits adopted Ti as adhesion layer, and Au as the interconnection metallization. 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.

DEVICE DESIGN AND FABRICATION

The epi-layers of AlGaN/GaN HEMTs were grown by metal-organic-chemical vapor deposition (MOCVD) on high resistivity 4-inch Si (111) substrates. A 0.8-µm-thick undoped GaN channel layer was grown on top of a 1.8-µm-thick undoped GaN buffer layer, and an 18-nm undoped $Al_{0.27}Ga_{0.73}N$ Schottky layer was inserted between the GaN channel layer and the 1-nm undoped GaN cap layer. The designed structure exhibited a sheet charge density of 1.02×10^{13} cm^{-2} and a Hall mobility of 1522 cm^2/Vs at 300 K. 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

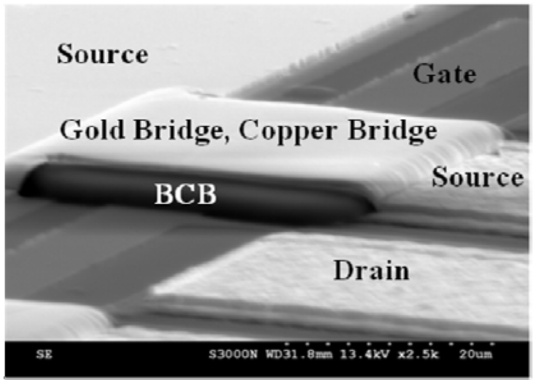

Fig. 1 The cross-sectional profile of the BCB-bridged AlGaN/GaN power HEMTs.

(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. 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 in Fig. 1.

RESULTS AND DISCUSSION

GaN power transistor consumes a lot of DC power during operation and in consequence a huge amount of heat will be generated, this affects the device reliability and electrical performance. Hence a high thermal conductivity interconnection metal was necessary. 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 the generated heat can be efficiently dissipated by Cu metal.

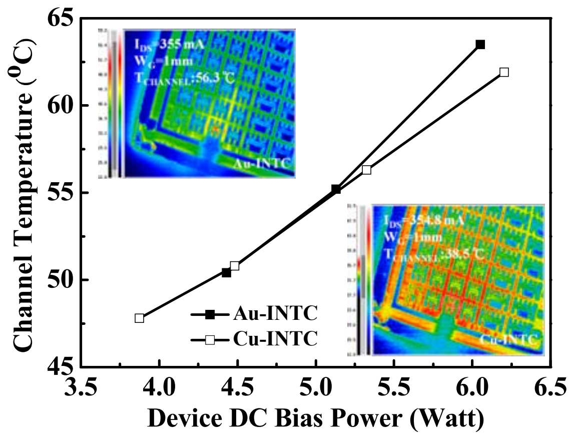

Fig. 2 Channel temperature performance of both devices versus various DC bias power values and IR images of AlGaN/GaN power devices using Au-INTC and Cu-INTC designs.

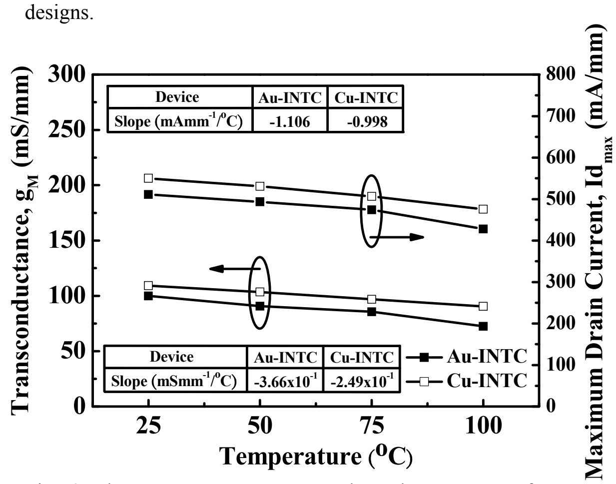

Fig. 3 The g_m, I_{Dmax} temperature dependency curves for Au-INTC and Cu-INTC power HEMTs.

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 ^{o}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 ^{o}C).

The small-signal current gain (H_{21}) is calculated to determine the current gain cut-off frequency (f_T) and the power gain cut-off frequency (f_{max}). Figure 4 plots the f_T and f_{max} of the Au-INTC and Cu-INTC power devices versus their operating temperature from room temperature to 100 ^oC. Both f_T and f_{max} revealed that the Cu-INTC power HEMTs were more thermally stable than the traditional Au-INTC power HEMTs. The low resistivity and high thermal dissipation coefficient of the Cu interconnections not only maintained stable microwave performance at high temperature but also suppressed the parasitic resistance of the metal line.

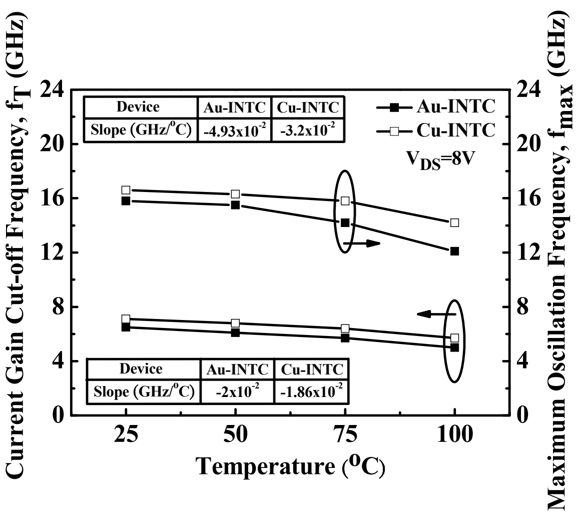

Fig. 4 The temperature dependent of f_T, f_{max} for both devices.

Temperature-dependent microwave power measurements were performed by a load-pull system with automatic tuners to measure the optimum load impedance for the maximum output power. 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. 5, by raising the device temperature up to 100 ^oC, 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 ^oC. 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/^{o}C while this value is much higher (-2.6 dBm/^{o}C) for Au-INTC ones. Besides that the microwave power performance of GaN HEMTs is heavily dominated by the device current density and microwave parameters, thermal stability of the device also needs to be emphasized because the GaN power HEMTs generate huge amount of heat during operation. Cu-INTC power HEMTs indeed demonstrated better DC and microwave characteristics due to not only its high electrical conductivity, but also the high thermal stability obtained at high temperatures.

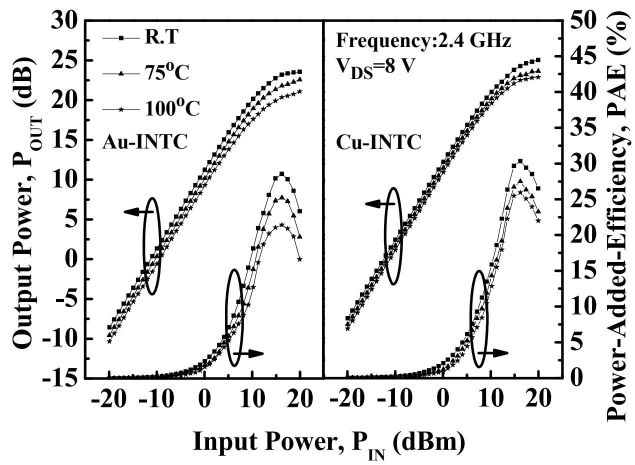

Fig. 5 Power performance of AlGaN/GaN power HEMTs with Au-INTC and Cu-INTC versus temperatures at 2.4 GHz.

CONCLUSIONS

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.

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ACRONYMS

HEMT: High Electron Mobility Transistor

INTC: Interconnection

MOCVD: Metal-organic Chemical Vapor Deposition

SEM: Scanning electron microscope