High-Temperature Electrical Characteristics of SPDT GaAs Switches with Copper Metallized Interconnects

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Keywords: COPPER METALLIZATION, PHEMT, SWITCH, PLATINUM, SPDT, HIGH-TEMPERATURE.

Abstract

Temperature-dependent electrical characteristics of a Copper metallized AlGaAs/InGaAs psedomophic high-electron-mobility transistor (PHEMT) Single-Pole-Double-Throw (SPDT) switches utilizing platinum (Pt, 70 nm) as the diffusion barrier is reported for the first time. The thermal threshold coefficients, defined as $\partial V_{th}/\partial T$, is of -0.25 mV/K from 300 to 500 K. The Cu metallized SPDT switches exhibited performance at the ambient of 380 K with insertion loss of less than 0.5 dB, isolation larger than 40 dB at 2.5 GHz. The copper metallized switches, with the excellent sub-threshold and high-temperature RF characteristics, shows good microwave performance and material stability for high temperature applications.

INTRODUCTION

Gold is widely used as the metallization metal for GaAs based field effect transistors and monolithic microwave integrated circuits. However, the employment of copper as the metallization metal has several major advantages over gold, such as lower resistivity, higher thermal conductivity, and lower cost. We have replaced gold with copper for the HEMT devices and demonstrated good materials stability in our previous study [1][2][3]. For high power microwave monolithic integrated circuit (MMIC) applications, thermal stability of the MMICs is very important. Though copper metallization of GaAs devices have been reported, high temperature characteristics of the copper metallized transistors has never been published. Due to poor Schottky characteristics and an increase of the substrate leakage path at high temperature ambient, leakage current increases considerably with increasing temperature. Therefore, when the temperature is increased, the degradation of the device performance may include the increase of leakage current and output conductance and the decrease of breakdown voltage, Schottky barrier height, threshold voltage, and transconductance [4][5][6].

In the paper, the temperature effects on the insertion loss and isolation of the copper metallized switches are reported. The stability of the copper metallized GaAs switches and the influence of the temperature on the RF characteristics of the copper metallized switches are studied for the first time.

DEVICE STRUCTURE AND FABRICATION

The PHEMT wafer was grown by metal organic chemical vapor deposition (MOCVD) on a 4-inch semi-insulating GaAs substrate. The epi-layers of the device, from bottom to top, are composed of a 600 nm buffer, a 13 nm InGaAs channel, a 3 nm undoped AlGaAs spacer, a delta-doped layer, and a 37 nm AlGaAs schottky layer and 60nm n-GaAs capping layer. The Hall electron mobility and sheet carrier concentrations at room temperature are 6500 $cm^2/V.s$ and 3.0×10^{12} cm^{-2}, respectively. The devices fabrication for the copper metallized switches have been described in our previous study [7].

The gate dimension of the AlGaAs/InGaAs PHEMTs transistors using dual-fingers is 0.5x100 μm^2, and drain-to-source distance is 9 μm. The current-voltage (I-V) characteristics were measured by an HP4156B semiconductor parameter analyzer at different high temperature ambients.

DEVICE PERFORMANCE

The HEMTs used in the copper SPDT switches exhibited a drain saturation current density of 188 mA/mm and a transconductance of 159 mS/mm at V_{DS}=3 V at 300 K. The DC characteristics of the copper metallized transistors were measured at different temperatures from 300 to 500 K. While the background carrier concentration from the substrate rises exponentially with temperature, causing the 2 DEG concentration n_{2DEG} to increase in the active layer, the carrier velocity ν is seriously degraded by the lattice scattering and carrier-carrier scattering mechanisms [8]. Therefore, I_{DSS0} drops at high temperatures due to the enhanced scattering mechanisms even though the carrier concentration increases.

The measured threshold voltage V_{th} and the maximum transconductance $g_{m,max}$ versus temperature are illustrated in Fig. 2. The V_{th} and $g_{m,max}$ decrease with increasing temperature. As the temperature is increased, due to the leakage at the semi-insulating substrate, the leakage current increased rapidly with temperature. Therefore, Vth is relatively temperature-sensitive and decreases with temperature. The threshold voltage shift from 300 to 500 K is only -0.05 V and the calculated $\partial V_{th}/\partial T$= -0.25 mV/K. On the other hand, since the intrinsic transconductance decreases and the ohmic contact resistance increases with temperature, as verified in the previous report, there is a downward trend of extrinsic transconductance at the elevated temperature [9][10].

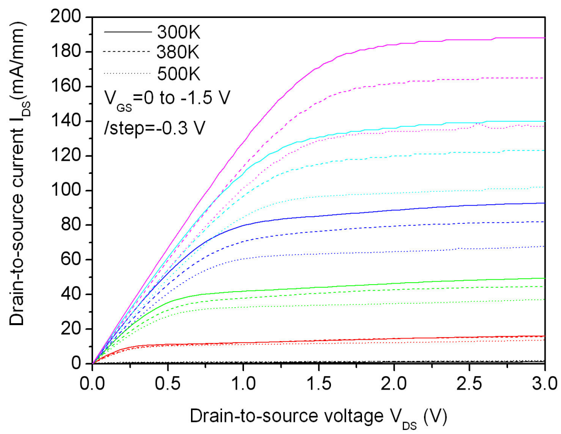

Fig. 1. I-V characteristics of the copper metallized AlGaAs/InGaAs PHEMT SPDT switches for 0.5 μm gate length at 300, 380, and 500 K, respectively.

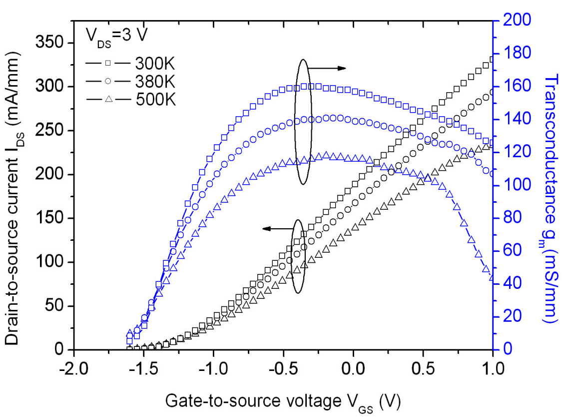

Fig. 2. Transconductance and drain-source current vs V_{GS} bias characteristics of the copper metallized AlGaAs/InGaAs PHEMT SPDT switches for 0.5 μm gate length at 300, 380, and 500 K, respectively.

Fig. 3 shows that insertion loss and isolation versus frequency of the SPDT switches with copper metallizations from 300 to 380 K. The V_{th} decreased with increasing temperature due to the leakage current from semi-insulating substrate. The isolation characteristics of the copper metallized switches degraded slightly because of small variation of the threshold voltage. This isolation is closely related to the off-state threshold voltage. Although isolation of the copper metallized switch was influenced by the thermal effect, it still maintained excellent isolation of higher than 40 dB. On the other hand, the transistor has a small on-state resistance which results in low insertion loss. The on-state resistances of the copper metallized switches measured at V_{gs}=0 V and V_{ds}=0.5 V increased gradually from 300 to 500 K. The carrier transport velocity in the channel degraded due to the lattice scattering and carrier-carrier scattering at elevated temperatures and the increase of the electrode contact resistance with temperature was verified in the previous report [11]. This phenomenon led to the slight degradation of the insertion loss. The increase in insertion loss is only 0.08 dB at 380 K as compared to 300 K. For high temperature operation, the copper metallized switch had an insertion loss of 0.46 dB, and an isolation of 42.79 dB (Control Voltage=+3/0 V, Input Power=0 dBm) at 2.5 GHz at the temperature up to 380 K. It is demonstrated that the copper metallization could be applied to the interconnects of the SPDT switches at high temperatures without effecting the switch performance.

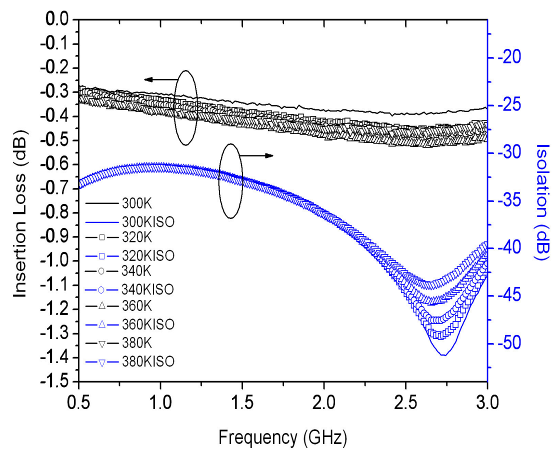

Fig. 3. Insertion loss and isolation vs frequency of the SPDT switches with copper metallizations from 300 to 380 K.

CONCLUSIONS

The temperature effect on the insertion loss and isolation of the copper metallized switches is investigated for the first time. It is observed the on-state resistance and the threshold characteristics of the transistors degraded with increasing temperature for the copper metallized SPDT switches using Pt as the diffusion barrier. However, the RF characteristics of the copper metallized SPDT switch still maintained steady and exhibited an insertion loss of 0.46 dB and an isolation of 42.79 dB at 2.5 GHz up to 380 K. It is evident that the material system of the copper metallized switches was quite stable which exhibited stabilized sub-threshold characteristics and resulted in excellent RF performance at high temperature applications.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Dr. S. H Tsai and H. C. Huang for experiment assistance and support from the National Science Council, and the Ministry of Economic Affairs, Taiwan, R.O.C., under the contracts: NSC 94-2752-E-009-001-PAE and 94-EC-17-A-05-S1-020.

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ACRONYMS

PHEMT: Psedomophic High-Electron-Mobility Transistor
SPDT: Single-Pole-Double- Throw
MMIC: Microwave Monolithic Integrated Circuit
MOCVD: Metal Organic Chemical Vapor Depositin