Study of Ti/W/Cu, Ti/Co/Cu, and Ti/Mo/Cu Multilayer Structures as Schottky Metals for GaAs Diodes

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Schottky structures with copper and refractory metals as diffusion barrier for GaAs Schottky diodes were evaluated. These structures have lower series resistances than the conventionally used Ti/Pt/Au structure. Based on the electrical and material characteristics, the Ti/W/Cu and Ti/Mo/Cu Schottky structures are thermally stable up to 400°C; the Ti/Co/Cu Schottky structure is thermally stable up to 300°C. Overall, the copper-metallized Schottky structures have excellent electrical characteristics and thermal stability, and can be used as the Schottky metals for GaAs devices.

Key words: Schottky, diffusion barrier, GaAs

INTRODUCTION

The copper metallization process has become popular in silicon device manufacture and has been widely studied, but there are few reports about the copper metallization process for GaAs-based devices.[1–3] In this work, copper-metallized GaAs-based Schottky diodes are studied. Traditionally, the Ti/Pt/Au Schottky contact is the most widely used structure for the fabrication of metal-semiconductor field-effect transistors, high-electron-mobility transistors, and Schottky diodes. In this study, the top gold layer of the Schottky structure was replaced by copper. This has the advantages of reducing electrical resistivity and production cost when compared with the use of gold. The Pt layer was replaced by the transition metals, such as W, Co, and Mo, due to the better antidiffusion capability and the electrical conductivity of these transition metals.

From the phase diagrams, there are no intermetallic compounds in the W/Cu, Mo/Cu, and Co/Cu binary systems. These binary systems have negligible mutual solubility. However, in the Ti/W binary system, the maximum solubility of W in αTi is approximately 0.2 at.% at 740%C and Ti has about 3 at.% solubility in (βTi-W) at 500°C. In the Ti/Mo system, there is one compound phase Mo_9Ti_4. The maximum solubility of Mo in (αTi) is approximately 0.4 at.% at 695°C. In general, both Ti/Mo and Ti/W systems have negligible mutual solubility,[4] whereas several TiCo intermetallic compounds such as Ti_2Co, TiCo, and $TiCo_3$ are formed in the Ti/Co system. In this work, Ti/W/Cu, Ti/Mo/Cu, and Ti/Co/Cu Schottky structures were studied and compared with the traditionally used Ti/Pt/Au Schottky structure.

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EXPERIMENTAL

Metal-organic chemical vapor deposition grown silicon-doped n-type (100) GaAs with thickness of 1 μm and concentration of 2.09×10^{17} cm^{-3} was used for the fabrication of Ti/W/Cu, Ti/Mo/Cu, and Ti/Co/Cu Schottky diodes. The area of the diode is 3.14 mm^2. The Ge/Au/Ni/Au ohmic metals were deposited by the electron beam evaporator and annealed by the rapid thermal annealing system at 400°C for 60 sec. The Schottky metals were deposited by sequentially DC sputtering the Ti (1000 Å), barrier layer (=W, Co, and Mo) (400 Å), and Cu (5000 Å) targets through a metal mask. The conventional Ti/Pt/Au Schottky diode was also prepared for comparison.

MEASUREMENT AND CHARACTERIZATION

Figure 1 shows the I-V characteristics of the Schottky diodes with Ti/Mo/Cu, Ti/Co/Cu, and Ti/W/Cu structures as deposited and after annealing at 200°C for 2 min. Applying thermionic emission theory and considering series resistance, the

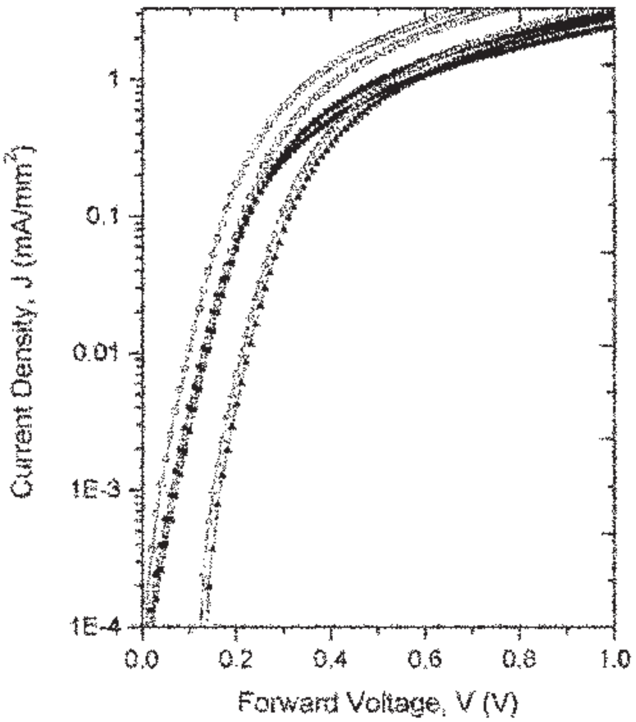

Fig. 1. Forward I-V characteristics of Ti/W/Cu, Ti/Mo/Cu, and Ti/Co/Cu structures as deposited and after annealing at 200°C for 2 min: ——○—— Ti/Co/Cu (as deposited), ——□—— Ti/Mo/Cu (as deposited), ——Δ—— Ti/W/Cu (as deposited), ——●—— Ti/Co/Cu (annealing at 200°C, 2 min), ——■—— Ti/Mo/Cu (annealing at 200°C, 2 min), and ——▲—— Ti/W/Cu (annealing at 200°C, 2 min).

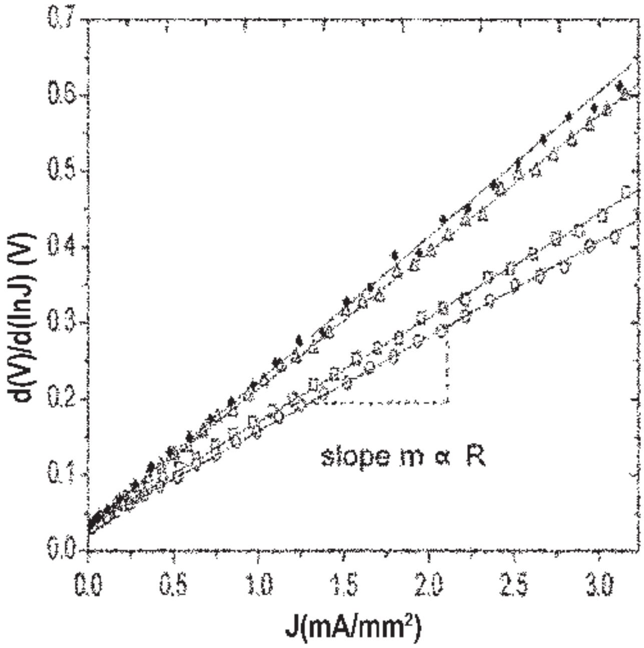

Fig. 2. Plot of d(V)/d(lnJ) versus J. The series resistances of the Ti/W/Cu, Ti/Mo/Cu, Ti/Co/Cu, and Ti/Pt/Au Schottky structures is proportional to the slope of the fitted line: ——◆—— Ti/Pt/Au (as deposited), ——Δ—— Ti/W/Cu (as deposited), ——□—— Ti/Mo/Cu (as deposited), ——○—— Ti/Co/Cu (as deposited), and ———— linear fitting.

I-V characteristic of the Schottky diode can be expressed as

$$J = J_0\left[\exp\left(\frac{q(V - JRA_{eff})}{nkT}\right) - 1\right] \quad (1)$$

where saturation current density $J_0 = A^*T^2\exp(-q\Phi_b/kT)$, q is the electron charge, V is the applied voltage, R is the series resistance, A_{eff} is the effective area of the Schottky diode, k is the Boltzman constant, T is the absolute temperature, A^* is the effective Richardson constant of 8.0375 A $cm^{-2}K^{-2}$ for GaAs, Φ_b is the barrier height, and n is the ideality factor. All the ideality factors and barrier heights were calculated within the current range of 0.01–0.0001 mA/mm^2.

Before the annealing treatment, the ideality factors and barrier height were 1.11/0.76 eV, 1.15/0.78 eV, 1.11/0.7 eV, and 1.11/0.77 eV; after annealing at 200°C for 2 min, the values became 1.09/0.77 eV, 1.05/0.92eV, 1.12/0.73 eV, and 1.05/0.69 eV for Ti/Pt/Au, Ti/Co/Cu, Ti/Mo/Cu, and Ti/W/Cu structures, respectively. The ideality factor and the Schottky barrier height remained fairly stable after annealing at 200°C for each structure. The barrier heights after annealing fall in the range of 0.7–0.9 eV, which is in the same range as the data reported by Sehgal et al.[5]

As shown in Fig. 1, for each diode structure at the same applied forward voltage, the diode current decreased after annealing at 200°C for 2 min. The Ti/Co/Cu structure shows the most serious degradation (59.0% at 0.7 V), whereas the Ti/W/Cu structure has little change in current (17.2% at 0.7 V) after annealing treatment. The different characteristics of the I-V curves for each Schottky diode are due to the different material structures and the related series resistances of the diodes. In order to extract the series resistance of each diode from the I-V curve, a method proposed by Cheung and Cheung[6] is used. Rearranging and differentiating Eq. 1, we can obtain

$$\frac{d(V)}{d(\text{In}J)} = RA_{eff}J + \frac{nkT}{q} \quad (2)$$

The slope of the line of d(V)/d(lnJ) versus J is equal to RA_{eff}. Thus, we can easily determine R by Eq. 2. Figure 2 shows the plot of d(V)/d(lnJ) versus J of the Schottky diodes. The series resistances calculated are 39.92ohn, 43.72ohn, 57.41ohn, and 60.74ohn for Ti/Co/Cu, Ti/Mo/Cu, Ti/W/Cu, and Ti/Pt/Au as-deposited structures, respectively. From the data of the resistance, all three of the copper-metallized Schottky structures have lower series resistance than the conventionally used Ti/Pt/Au structure.

X-Ray Diffraction Analysis

Glancing angle x-ray diffraction (XRD) with Cu K_α radiation was used to identify the material phases. The annealing treatment was done up to 500°C for 30 min. The Ti/Co/Cu Schottky structure

Table I. Summary of XRD Results for Ti/W/Cu, Ti/Mo/Cu, and Ti/Co/Cu Schottky Structures after Annealing at 200–500°C for 30 min

Annealing Temperature (°C) \ Schottky Structure	Ti/W/Cu	Ti/Mo/Cu	Ti/Co/Cu
200	Stable	Stable	Stable
300	Stable	Stable	Stable
400	Stable	Stable	Formed CoTi phase
500	Formed CuTi phase	Formed Ti_4Mo_9 phase	Formed CoTi phase

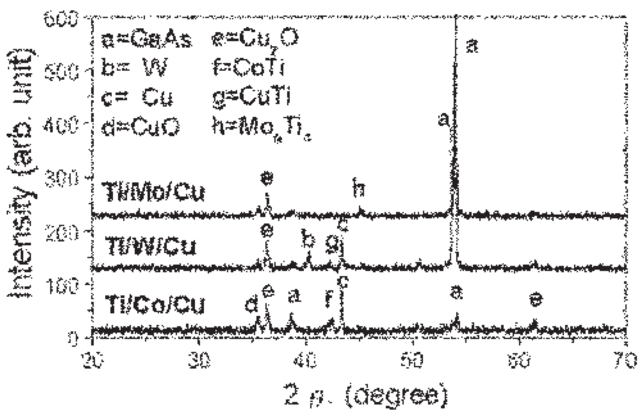

Fig. 3. XRD patterns of Ti/W/Cu, Ti/Mo/Cu, and Ti/Co/Cu structures after annealing at 500°C for 30 min.

formed CoTi phase after annealing at 400°C. All these Schottky structures showed atomic interdiffusion after annealing at 500°C for 30 min. Figure 3 shows the XRD results of the Ti/W/Cu, Ti/Mo/Cu, and Ti/Co/Cu Schottky structures after annealing at 500°C. For the Ti/W/Cu Schottky structure, the CuTi phase was formed after 500°C annealing. Ti_4Mo_9 phase was formed in the Ti/Mo/Cu structure and CoTi phase was formed in the Ti/Co/Cu structure after annealing at 500°C. From the XRD results, the Ti/W/Cu and Ti/Mo/Cu Schottky structures were thermally stable after annealing up to 400°C for 30 min; Ti/Co/Cu Schottky structure was thermally stable only up to 300°C after annealing for 30 min. Table I is a summary of XRD results for the structures after annealing at different temperatures from 200°C to 500°C for 30 min.

CONCLUSIONS

GaAs Schottky structures with copper and refractory metal were evaluated. The Ti/Co/Cu Schottky structure shows the lowest series resistance, but the change of ideality factor is larger than the other structures after annealing treatment at 200°C. From the XRD results, the Ti/W/Cu and Ti/Mo/Cu Schottky structures are thermally stable after annealing up to 400°C, and Ti/Co/Cu Schottky structure is thermally stable after annealing up to 300°C. Experimental results show that the copper-metallized Schottky structures have comparable electrical characteristics and thermal stability as compared to the traditional Ti/Pt/Au structure. The Ti/Co/Cu, Ti/Mo/Cu, and Ti/W/Cu metal stacks can be used as Cu metallization of the Schottky structures for GaAs devices.

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