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Interfacial reaction and electrical characteristics of $Cu(RuTaN_x)$ on GaAs: Annealing effects

W.K. Leau[a], J.P. Chu[b,*], C.H. Lin[c]

[a] Institute of Materials Engineering, National Taiwan Ocean University, Keelung 20224, Taiwan
[b] Department of Materials Science and Engineering and Graduate Institute of Engineering, National Taiwan University of Science and Technology, No. 43, Keelung Road, Sec. 4, Taipei 10607, Taiwan
[c] Department of Environmental Engineering, Chin-Min Institute of Technology, Tou-Fen 35153, Taiwan

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ABSTRACT

This study elucidates the thermal stability and quasi ohmic contact characteristics of $Cu(RuTaN_x)$ fabricated on a barrierless GaAs substrate. $Cu(RuTaN_x)$ was prepared by cosputtering Cu, Ta, Ru, and N. The resistivity of the $Cu(RuTaN_x)$/GaAs structure annealed at 500 °C for 30 min was lower than that of the as-deposited structure, and the former was thermally stable up to 500 °C after 30 min of annealing. Further, the $Cu(RuTaN_x)$/GaAs structure exhibited electrical rectifying properties upon annealing at 550 °C for 10 min and revealed a quasi ohmic contact, as determined by the circular transmission line model (CTLM). The formation of quasi ohmic contact is further confirmed by transmission electron microscopy and energy dispersive X-ray spectroscopy.

1. Introduction

The integration of GaAs and Si semiconductors and the fabrication of optoelectronic and high-mobility heterostructures have been important research topics for several years [1–3]. The miniaturization of semiconductor devices is the main motivation for combining of materials of these two groups of materials. Cu metallization enables the easy integration of the aforementioned semiconductors, and enables high-quality semiconductor devices to be designed at low cost. Cu has been extensively applied in the metallization of Si-based integrated circuits because it is inexpensive and has low electrical resistivity as well as high electromigration resistance.

Many researchers have attempted to prevent detrimental reactions between Cu-alloy films and their substrates, and to obtain Cu films with good thermal stability. Koike et al. deposited a Cu–Mn alloy film on a Si substrate to obtain a self-formed $MnSi_xO_y$ barrier layer, which enhanced the thermal stability of the film after annealing [4]. A barrierless metallization system, to enhance thermal stability, based on a group of dilute Cu alloys, such as Cu(WN), $Cu(MoN_x)$, $Cu(ReN_x)$, Cu(VN), Cu(Ru), and $Cu(RuN_x)$, with enhanced thermal stability has been proposed [5–9].

Since Cu reacts more readily with GaAs than with Si, Cu metallization on GaAs is a promising method to improve the integration of GaAs and Si semiconductors. However, only a few reports of Cu metallization on GaAs substrates have been published. We previously deposited $Cu(TaN_x)$ films on GaAs by RF magnetron sputtering, and found that the resulting structure was thermally stable up to an annealing temperature of 450 °C [10]. In that study, the addition of TaN_x to Cu helped retard the interactions between the alloy film and the substrate, and to refine the grain structure by inhibiting grain growth during annealing. The results of that study demonstrated the advantages of depositing $Cu(TaN_x)$ on barrierless GaAs substrates and formed the basis for future studies of Si-based barrierless Cu metallization on GaAs.

Previous studies have demonstrated that Ru is negligibly soluble in Cu and has a lower resistivity than Ta; hence, Ru can be adopted as a Cu-plateable diffusion barrier [11–13]. In a sense, a Ru film can prevent the diffusion of Cu into the Si substrate [14]. Accordingly, a Ru thin film is a good candidate for a directly plateable Cu diffusion barrier. In this study, Ru, Ta, and N are co-sputtered with Cu on GaAs substrates to fabricate a $Cu(RuTaN_x)$/GaAs structure, which has better thermal stability than the previously fabricated $Cu(TaN_x)$/GaAs structure. The $Cu(RuTaN_x)$/GaAs structure is thermally stable up to 500 °C, and after 10 min of annealing at 550 °C, develops into an

* Corresponding author. Tel.: +886 2 2730 3292; fax: +886 2 27336544.
E-mail address: jpchu@mail.ntust.edu.tw (J.P. Chu).

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Table 1
Elemental film compositions (atomic ratio: %) of the Cu(RuTaN$_x$)/GaAs, Cu(TaN$_x$)/GaAs, Cu(Ta)/GaAs, and Cu/GaAs structures, as determined by EPMA.

Film structure	Cu	Ru	Ta	N
Cu(RuTaN$_x$)	98.33	0.65	0.26	0.76
Cu(TaN$_x$)/GaAs	97.85	–	1.41	0.74
Cu(Ta)/GaAs	98.44	–	1.56	–
Cu/GaAs	100.00	–	–	–

ohmic contact as verified by the circular transmission line model (CTLM). The wider bandgap of GaAs allows GaAs to be operated at a higher temperature than Si. Consequently, devices that incorporate GaAs can typically be utilized in the military, automobile, and aerospace industries. This article reports the high thermal stability and high-temperature characteristics of ohmic contacts fabricated on the GaAs substrate.

2. Experiment

To produce a Cu alloy film with the best possible thermal stability on barrierless GaAs substrates, four structures—Cu/GaAs, Cu(Ta)/GaAs, Cu(TaN$_x$)/GaAs, and Cu(RuTaN$_x$)/GaAs—were fabricated by co-sputtering Cu (99.995%), Ta (99.95%), and Ru (99.95%) in a mixed Ar/N$_2$ atmosphere at a working pressure of ~7 mTorr on well-cleaned GaAs(1 0 0) wafers by RF magnetron sputtering. The film thickness of the Cu; Cu(Ta); and Cu(TaN$_x$) are ~400 nm, the film thickness of Ru(TaN$_x$) is ~270 nm. The atomic percentages (used throughout this paper) of various elements in the films were determined by electron probe microanalysis (EPMA). The sample was annealed in a vacuum of 10^{-7} Torr at various temperatures up to 550 °C for 30 min. The chemical depth profiles of the samples were characterized by secondary-ion mass spectroscopy (SIMS) with Cs ion bombardment. Crystallographic analysis was performed using an X-ray diffractometer (XRD) with Cu Kα radiation at low (glancing) angles of incidence. Focused ion beam (FIB) microscopy was utilized to analyze the microstructure of the samples and to investigate the reactions that occurred at the film–substrate interface. The electrical resistivity of the samples was determined using the four-point probe method. To investigate the formation of a quasi ohmic contact in the annealed Cu(RuTaN$_x$)/GaAs structure, data obtained from the current–voltage (I–V) curve was measured using the circular line transmission method (CTLM). First, we designed a mask and then generated the pattern on the GaAs substrate by optical lithography. The structure was then sputtered, followed by annealing at different temperatures. The current–voltage (I–V) characteristics were analyzed using an Agilent Technologies E5270B system. The prepared samples were also analyzed by cross-sectional transmission electron microscopy (TEM) and energy dispersive X-ray spectroscopy (EDS).

3. Results and discussion

Table 1 presents the amounts of various elements present in the Cu/GaAs, Cu(Ta)/GaAs, Cu(TaN$_x$)/GaAs, and Cu(RuTaN$_x$)/GaAs alloy films. Minor amounts of solid solutes are present in the major Cu solution—0.26% Ta, 0.65% Ru, and 0.76% N in 98.33% Cu for Cu(RuTaN$_x$)/GaAs; 1.41% Ta and 0.74% N in 97.85% Cu for Cu(TaN$_x$)/GaAs; 1.56% Ta in 98.44% Cu for Cu(Ta)/GaAs; pure Cu for Cu/GaAs. Fig. 1 shows the SIMS depth profile of the as-deposited Cu(RuTaN$_x$) structure. Intensities that correspond to all elements are consistent with the EPMA results; the secondary ion intensities for the minor elements are low, although they are within the detection limits of the instrument.

Fig. 2 plots the measured electrical resistivity of each of the aforementioned structures (in the as-deposited condition) versus annealing temperature. The resistivity of the as-deposited Cu(RuTaN$_x$) structure is ~55.39 μΩ cm, which is less than that of the Cu(TaN$_x$) structure (~58 μΩ cm as-deposited). The resistivity of the Cu(RuTaN$_x$)/GaAs structure decreases as the annealing temperature increases, falling to ~11.35 μΩ cm at 500 °C. The resistivity of the Cu(TaN$_x$) structure is ~11 μΩ cm at an annealing temperature of 450 °C. The results obtained for the Cu(TaN$_x$) and Cu(RuTaN$_x$) structures reveals that the maximum stability temperature of the latter increases from 450 to 500 °C, presumably because of solid solution and the finer structure. Due to these factors, the resistivity of the Cu(RuTaN$_x$) structure is decreased to ~11 μΩ cm after annealing at 500 °C, whereas the resistivity of the Cu(TaN$_x$) structure is ~82 μΩ cm, because in the case of the former, the RuTaN$_x$ phase retards the interactions between film and substrate during annealing. In particular, annealing at 550 °C yields a resistivity of the Cu(RuTaN$_x$)/GaAs structure, which is less than that of the Cu(TaN$_x$)/GaAs structure annealed at 500 °C. As reported previously [10], the extensive reactions between Cu(TaN$_x$) and GaAs taken place during annealing at 500 °C yield the increases in the resistivity. The Cu(Ta)/GaAs structure is more thermally stable than the Cu/GaAs structure, because the Ta atoms in the Cu solid solution inhibit the diffusion of Cu into GaAs. Adding N and Ta to Cu alloys

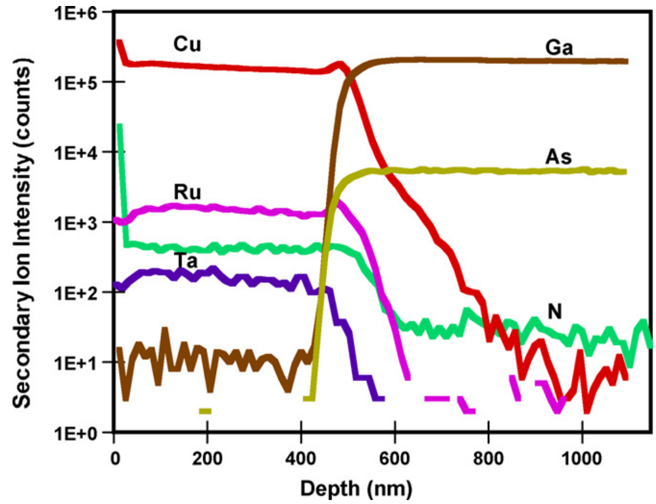

Fig. 1. SIMS depth profile of as-deposited Cu(RuTaN$_x$)/GaAs structure.

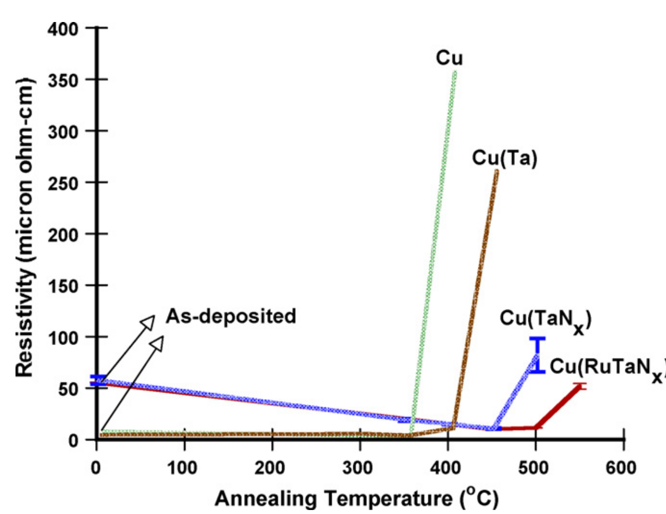

Fig. 2. Electrical resistivity of Cu/GaAs, Cu(Ta)/GaAs, Cu(TaN$_x$)/GaAs, and Cu(RuTaN$_x$)/GaAs structures in as-deposited and annealed conditions at various temperatures.