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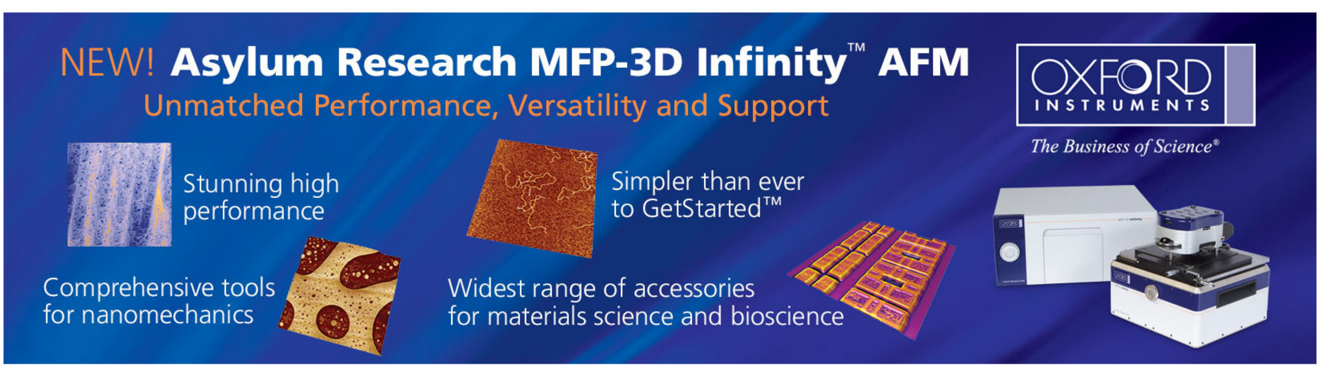

Thermal stability of Ti/Pt/Cu Schottky contact on InAlAs layer

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Electrical characteristics and thermal stability of the Ti/Pt/Cu Schottky contact on InAlAs were investigated. The Ti/Pt/Cu Schottky contact had comparable electrical properties compared to the conventional Ti/Pt/Au contact after annealing. As judged from the material analysis, the Ti/Pt/Cu on InAlAs after 350 °C annealing showed no diffusion sign into the InAlAs. After 400 °C annealing, the interfacial mixing of Cu and the underlying layers occurred and resulted in the formation of Cu_4Ti. The results show that Ti/Pt/Cu Schottky contact using platinum as the diffusion barrier is very stable up to 350 °C annealing and can be used for InAlAs/InGaAs high-electron mobility transistors and monolithic microwave integrated circuits. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2338567]

Copper metallization has been widely used in silicon integrated circuit industry ever since IBM announced its success in very large scale integration process.[1,2] This is because copper has a low bulk resistivity (1.68 $\mu\Omega$ cm) (Ref. 3) and excellent electromigration resistance.[4] However, it is well known that copper diffuses very easily into silicon and silicon oxide at a temperature as low as 200 °C if without any diffusion barrier.[5,6] As in silicon case, copper also diffuses into GaAs if without any diffusion barrier.[7] In recent years, the studies of backside copper metallization of GaAs field-effect transistors[8] (FETs) and copper airbridge for low-noise GaAs high-electron mobility transistors[9] (HEMTs) have been reported. The use of copper metallization for GaAs devices also requires suitable diffusion barriers which are compatible with the GaAs FET processes to prevent copper interdiffusion into the underlying semiconductor layers.

Cu-metallized Ohmic contact to *n*-type GaAs using Cu_3Ge (Ref. 10) and nonalloyed Ohmic contact to *n*-type InGaAs using Ti/Pt/Au (Refs. 11 and 12) have been reported. Cu Schottky contact on GaN-based HEMT with low gate leakage current has been demonstrated.[13] On the other hand, the effect of interdiffusion of the Ti/Pt/Au gate on the performance of the GaAs HEMTs and InGaAs/InAlAs/InP HEMTs has been studied.[14,15] In this work, the electrical characteristics and thermal stability of the Ti/Pt/Cu Schottky contact on InAlAs are investigated. The use of copper as the metallization metal for high frequency HEMT devices has the following advantages over gold: lower resistivity, higher thermal conductivity, and lower cost. Pt is used as the diffusion barrier because it has a high melting point, is compatible with the lift-off process, and is a good diffusion barrier for preventing Au from diffusing into the conventional Ti/Pt/Au Schottky and Ohmic structure.[16] The study of the electrical characteristics and the thermal stability of the Ti/Pt/Cu Schottky contact on *i*-InAlAs is indispensable for the realization of the gold-free fully Cu-metallized InAlAs/InGaAs-based HEMTs and monolithic microwave integrated circuits (MMICs).

The structure of the samples consists of a 30 nm Si-doped *n*-InGaAs (2×10^{18} cm^{-3}) on top of a 15 nm undoped InAlAs Schottky layer on the GaAs substrate which is similar to the conventional InAlAs/InGaAs HEMT structure. AuGeNi metals were evaporated on *n*-InGaAs and were annealed at 300 °C to form Ohmic contacts (8.7×10^{-7} Ω cm^2). The top *n*-InGaAs layer was selectively etched over the InAlAs layer using succinic acid and H_2O_2 mixture. After the etching process, the Ti/Pt/Cu (80/80/200 nm) was deposited on the undoped InAlAs layer to form the Schottky diode. The properties of the Schottky contact are sensitive to the surface condition since InAlAs is reactive and tends to be oxided easily, the oxided layer on top of InAlAs should be removed before the metal deposition. Two different surface treatments including dilute HCl (1:10) dipping for 15 s and N_2 plasma (30 W) etching for 60 s before Ti/Pt/Cu deposition were tried. The thermal stability and the Schottky characteristics of the samples with different surface pretreatments were compared. After metal evaporation and lift-off, SiN_x was deposited on the samples for passivation. The Schottky diodes had a diameter of 200 μm for current-voltage (*I-V*) measurement. To investigate the diffusion barrier property of platinum, the samples were annealed at various temperatures for 30 min in N_2 ambient for material analysis. X-ray diffraction (XRD), Auger electron spectroscopy (AES), transmission electron microscopy (TEM), and energy-dispersive x-ray analysis (EDX) were used for the material stability study.

The barrier heights (ϕ_B) and the ideality factors (n) of the Ti/Pt/Cu and the Ti/Pt/Au Schottky contact on InAlAs under various annealing temperatures are summarized in Table I. For the as-deposited Ti/Pt/Cu contact, the barrier

TABLE I. Barrier heights (ϕ_B) and ideality factors (n) of the Schottky contact under various annealing temperatures.

	Ti/Pt/Au on InAlAs		Ti/Pt/Cu on InAlAs	
Temp.	n	ϕ_B (eV)	n	ϕ_B (eV)
As deposited	1.27	1.01	1.25	1.01
200 °C	1.27	1.00	1.25	1.02
300 °C	1.26	1.01	1.26	1.01
350 °C	1.27	0.99	1.28	0.99
400 °C	1.45	0.87	1.51	0.86

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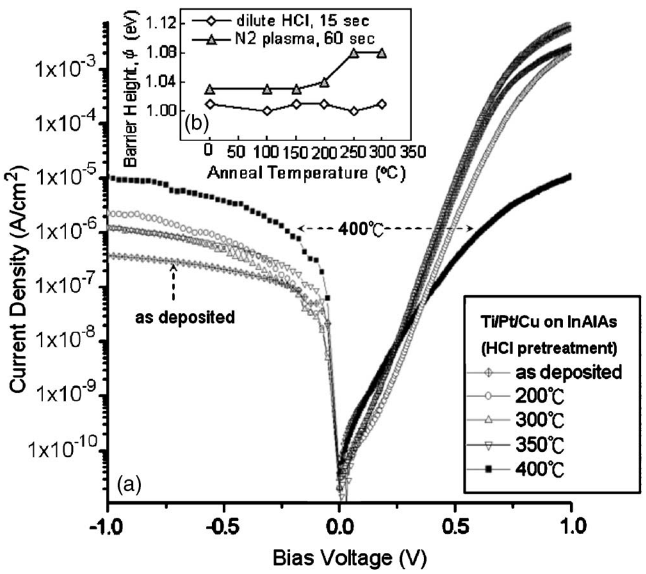

FIG. 1. (a) *I-V* characteristics of the Schottky diodes with various annealing temperatures; (b) barrier height vs annealing temperature for the diodes with two different surface pretreatments.

height and the ideality factor were 1.01 eV and 1.25, respectively, while they were similarly 1.01 eV and 1.27 for Ti/Pt/Au. Both Ti/Pt/Cu and Ti/Pt/Au exhibited an excellent thermal stability up to 350 °C annealing. It means that Ti/Pt/Cu on InAlAs is a good Schottky contact and has comparable electrical performance as the conventional Ti/Pt/Au on InAlAs. The corresponding *I-V* characteristics of the Ti/Pt/Cu Schottky diodes as a function of the annealing temperature were shown in Fig. 1(a). The leakage current density of the as-deposited sample was about 3.8×10^{-7} A/cm^2 at -1 V bias. However, the characteristics of the Ti/Pt/Cu contacts became Ohmic-like behavior when the annealing temperature exceeded 400 °C. Figure 1(b) shows the barrier heights of the samples subjected to two different surface pretreatments before the deposition of the Ti/Pt/Cu. In Fig. 1(b), the pretreatment using N_2 plasma increased the barrier heights from 1.03 to 1.08 eV after 300 °C annealing. It might be due to the defects generated on the InAlAs layer by the ion bombardment caused by the N_2 plasma. The barrier height of the sample using HCl pretreatment remained stable (1.01 eV) even after 300 °C annealing. As a result, the HCl pretreatment was applied for the Ti/Pt/Cu Schottky contact fabrication and material analysis in this study.

Figure 2 shows the AES depth profiles for the Ti/Pt/Cu as deposited and after annealing. As can be seen from Fig. 2(b), the interface of Ti/Pt/Cu on InAlAs remained sharp after 350 °C annealing, indicating that the Pt was an effective diffusion barrier after 350 °C annealing. However, the Cu atoms began to penetrate through Pt layer after 400 °C annealing, as shown in Fig. 2(c). Moreover, some Cu atoms and accumulated Ti atoms were found at the interface between Ti and InAlAs layers in Fig. 2(c). A mechanism proposed in the recent work[14] revealed the Ti interdiffusion and possible formation of $TiAs_x$ in the Ti/InAlAs interface resulted in the degradation of Ti/Pt/Au gate on InAlAs/InGaAs HEMTs. This is consistent with the degradation of the Ti/Pt/Cu Schottky characteristics that were found in this study with the barrier height dropped to 0.86 eV and the ideal factor increased to 1.51 after 400 °C annealing, as shown in Table I. Figure 3 are the cross-

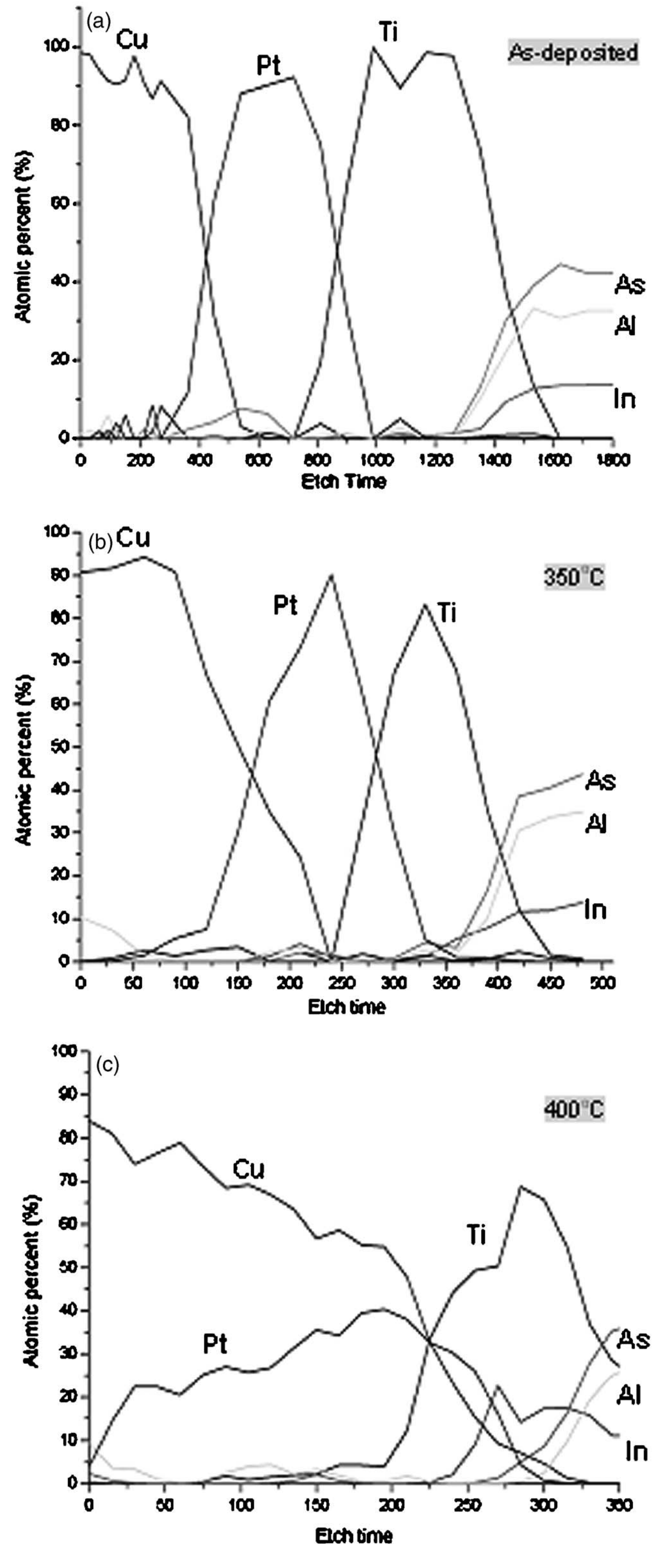

FIG. 2. Auger depth profiles of the Ti/Pt/Cu on InAlAs (a) as deposited, (b) after annealing at 350 °C, and (c) after annealing at 400 °C.

sectional TEM micrographs of the Ti/Pt/Cu on InAlAs after 350 and 400 °C annealings for 30 min, respectively. No significant interface reaction between the Ti/InAlAs and Ti/Pt interfaces was observed in Fig. 3(a). The interface of Cu/Pt was no longer distinguishable after 400 °C annealing in Fig. 3(b). A dark area observed at the InAlAs layer close to the Ti/InAlAs interface is due to the diffusion of Ti and Cu into Ti/InAlAs interface region as judged from the AES depth profile in Fig. 2(c). This resulted in the degradation of the

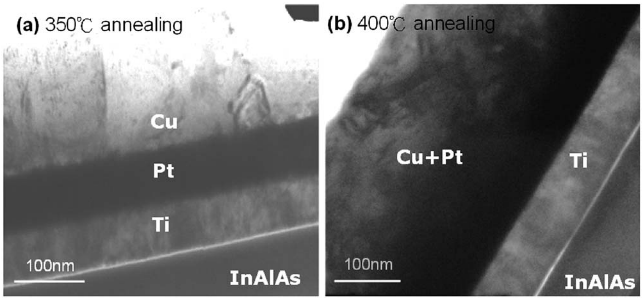

FIG. 3. Cross-sectional TEM micrographs of the Ti/Pt/Cu on InAlAs (a) after 350 °C annealing and (b) after 400 °C annealing.

Schottky characteristics. Figure 4 shows the XRD results of the Ti/Pt/Cu samples as deposited and after annealing for 30 min. From the XRD data, the Ti/Pt/Cu on InAlAs structure was quite stable up to 350 °C annealing and the peaks of Cu, Pt, and Ti remained unchanged. Additional peaks in the XRD pattern emerged after 400 °C annealing. The additional two peaks were identified as the orthorhombic Cu_4Ti(011) and Cu_4Ti(102) phases (Ref. 17). The new formation of the phases was due to the Ti interdiffusion and Ti reaction with Cu that resulted in the decrease of the intensity of the Ti peak. This was further investigated using EDX in the Ti layer of the InAlAs/Ti/Pt/Cu structure after 350 and 400 °C annealings, as shown in Figs. 5(a) and 5(b), respectively. Cu signal appeared only in Fig. 5(a) and not in Fig. 5(b). The XRD and EDX data indicate that the Pt is a good diffusion barrier for preventing Cu from diffusing into the Ti/Pt/Cu Schottky structure up to 350 °C. However, atomic interdiffusion occurred after 400 °C annealing. The formation of Cu_4Ti implies that Cu atoms had diffused through the Pt layer and reacted with the Ti layer at 400 °C. The results show good consistency with the AES depth profile and the TEM data in Figs. 2 and 3.

Excellent electrical characteristics of the Ti/Pt/Cu Schottky contact on InAlAs were observed with the ideality factor and the barrier height of 1.25 and 1.01 eV, respectively, and the data remained almost the same after 350 °C annealing. The material analysis showed that no interfacial phase was formed after 350 °C annealing and that Pt had successfully blocked the Cu diffusion into the underlying layers. After 400 °C annealing, the Cu began to penetrate

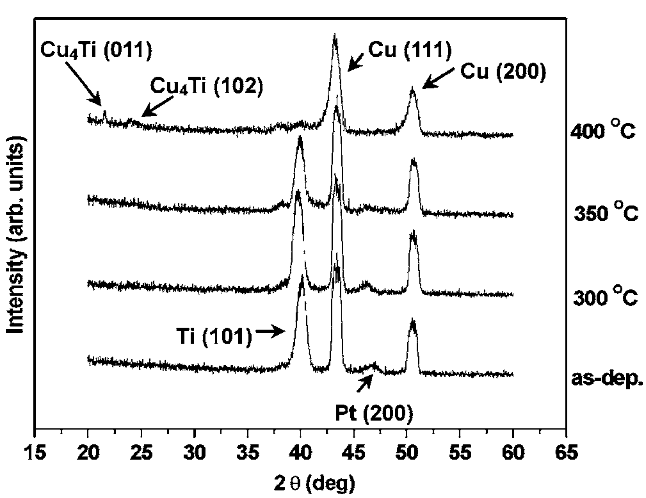

FIG. 4. XRD results of Ti/Pt/Cu on InAlAs with various annealing temperatures.

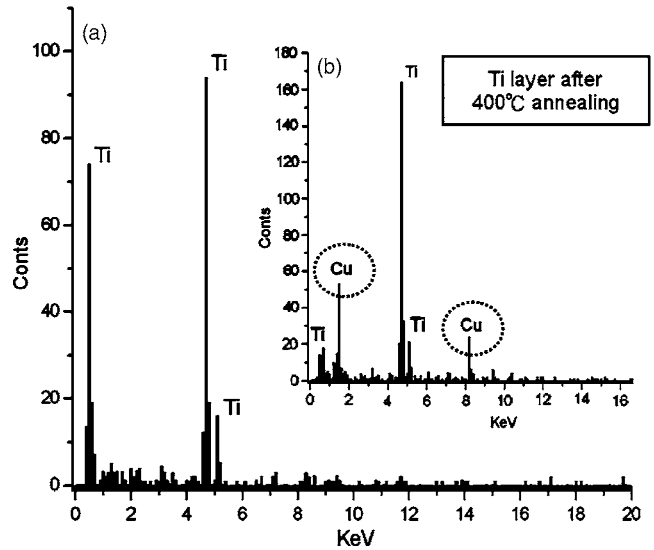

FIG. 5. EDX of the Ti layer of the InAlAsTi/Pt/Cu structure after annealing at (c) 350 °C and (d) 400 °C.

through the diffusion barrier and formed intermetallic compound of Cu_4Ti. Meanwhile the diffusion of Ti and Cu into Ti/InAlAs interface region was observed in AES depth profile, which was responsible for the rise of the ideal factor and the lowering of the effective barrier height. The results show that Ti/Pt/Cu Schottky contact to InAlAs is very stable up to 350 °C annealing and that Cu metallization using Pt as the diffusion barrier can be integrated into the front-side metallization for the InAlAs/InGaAs HEMTs and MMICs.

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