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Multilayer TiNi Alloys as Gate Metal for InGaAs MOS devices

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Abstract

The multilayer TiNi alloys have been successfully applied as the gate metals for $HfO_2/In_{0.53}Ga_{0.47}As$ MOS devices in this study. The EWF of TiNi alloys was found to increase from 4.41eV for as-deposited sample to 4.62eV after the alloy was annealed due to the diffusion of Ni atoms into Ti layer. The multilayer TiNi alloy remained amorphous-phase with small WFV until annealed at 600°C. The TiNi alloy is thermally more stable as compared to either Ti or Ni metal because the TiO_xNi interfacial layer prevents the diffusion of Ni atoms into HfO2 film and the further reaction of Ti with HfO_2.

1. Introduction

Metal gate on high-k dielectrics is currently an important issue needed to be solved for III-V MOS devices. The low work function (WF) metals such as Ti, Al, and Ta react easily with O in metal/oxide interface while the high WF metals such as Ni and Pt diffuse easily into the oxide layer. The binary alloys of low WF metals and high WF metals were adopted on oxide/Si substrate to overcome the above problems. However, the results cannot be directly applied to HfO_2/InGaAs structure due to the different channel materials. The amorphous metal used as gate material provides a small threshold voltage variation [1]. In this study, the EWF of multilayer TiNi alloys on $HfO_2/In_{0.53}Ga_{0.47}As$ is investigated. The TiNi alloy is chosen due to its flexibility in tuning EWF based on inter-diffusion technique.

2. Experimental

The epitaxial wafers used in this study consisted of 100 nm InGaAs layer on n^+-InP substrate ($5\times10^{17}/cm^3$ Si-doped n-type wafer) grown by solid source molecular beam method. 3 samples with different HfO_2 thicknesses were prepared (7.76 nm, 11.64 nm, and 15.52 nm). The samples were annealed in forming gas (FG) at 450°C for 5 minutes by rapid thermal annealing (RTA) after oxide deposition. The multilayer TiNi alloys of 38 at. %, 52 at. %, and 80 at. % Ti (namely S_1, S_2, and S_3, respectively) were deposited on HfO_2/InGaAs using alternate deposition of 5 Ti layers and 5 Ni layers by E-gun evaporation.

$$Ti \text{ at. } \% = \frac{1}{1+1.61\times\frac{H_{Ni}}{H_{Ti}}}\times100\%, \quad (1)$$

50 nm Ni (sample CS_1) and 50 nm Ti (sample CS_2) were also deposited as gate metals for HfO_2/InGaAs MOS structure as controlling samples.

3. Result and discussion

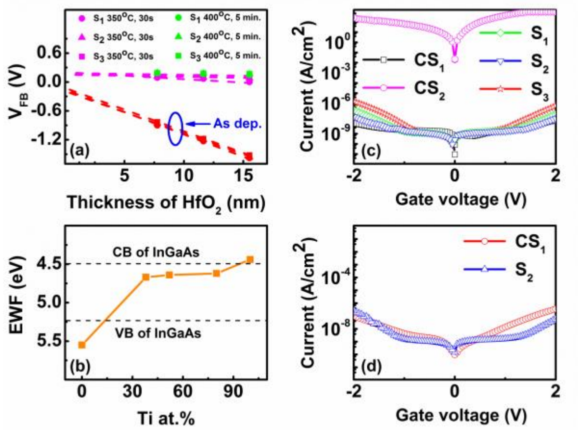

Fig. 1 (a) The flat band voltage versus HfO_2 thicknesses used to extract EWF of the samples S_1, S_2, and S_3 as deposited, annealed at 350°C for 30s in FG, and further annealed at 400°C for 5 minutes in FG; (b) the EWF of TiNi alloys versus atomic percentage of Ti, the Ti EWF was extracted from as deposited sample; (c) J-V curves of samples CS_1, CS_2, S_1, S_2, and S_3 with 7.76 nm HfO_2 after annealing at 350°C for 30s in FG, respectively; (d) J-V curves of samples CS_1, and S_2 with 7.76 nm HfO_2 after further annealing at 400°C for 5 minutes in FG.

Fig. 1(a) shows the flat band voltages of samples S_1, S_2, and S_3 versus HfO_2 thickness. The intercept of V_{FB} of samples S_1, S_2 and S_3 shifted ~ 0.21 V (from – 0.11 V to + 0.10 V) after annealing. This phenomenon was not observed for sample CS_1 (data not shown). The EWF of sample CS_1 was reported to be 5.55 eV in our previous study [2]. The changes in V_{FB} intercept of samples S_1, S_2, and S_3 after annealing are due to the diffusion of Ni atoms into Ti layer. Fig. 1(b) shows the EWF of alloys versus atomic percentage of Ti. Note that the EWF of sample CS_2 in Fig. 1(b) is extracted from as deposited sample because the tremendous reaction of Ti with HfO_2 layer leads to the breakdown of CS_2 MOSCAP after annealing shown in Fig. 1(c). The EWF of the annealed alloy was found to be around 4.62 eV which is close to the conduction band of InGaAs. The results indicate that first Ti layer contacting the HfO_2 layer determines the EWF of the alloy. The samples CS_1 and S_2 were further annealed at 400°C in FG for 5 minutes by RTA. The leakage current of the sample CS_1 was found to increase to ~10^{-8} A/cm^2 at V_{FB} + 1 (V) while that of sample S_2 remained at ~10^{-9} A/cm^2 as shown in Fig. 1(d). The stability of TiNi/HfO_2 interface (due to the formation of the TiO_xNi interfacial layer) prevents the additional diffusion of Ni atoms into HfO_2 film and keeps the gate leakage current of sample S_2 unchanged.

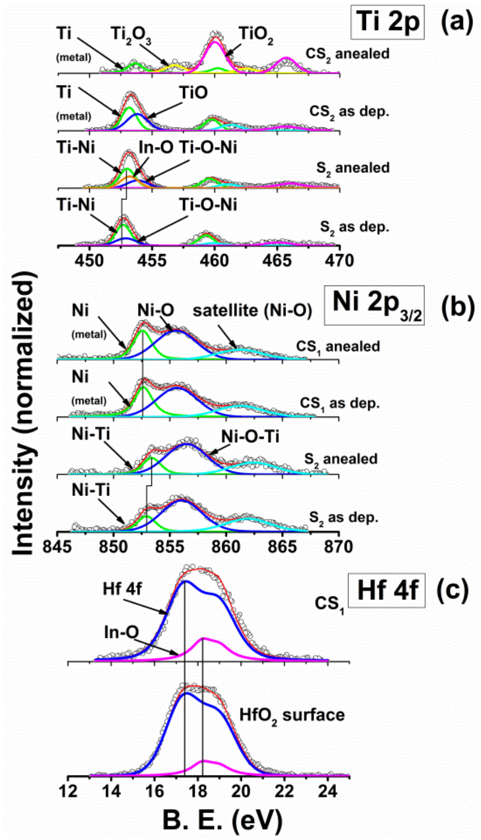

Fig. 2 XPS spectra of (a) Ti 2p peaks of Ti/HfO_2 and TiNi/HfO_2 interfaces of samples CS_2 and S_2 as deposited and after annealing, (b) Ni $2p_{3/2}$ peaks of Ni/HfO_2 and TiNi/HfO_2 interfaces of samples CS_1 and S_2 as deposited and after annealing, (c) Hf 4f peaks of Ni/HfO_2 interface of samples CS_1 and the clean HfO_2 surface after annealing, respectively.

Fig. 2(a) and Fig. 2(b) show that the Ti $2p_{3/2}$ and the Ni $2p_{3/2}$ peaks of sample S_2 shifted 0.28 eV after annealing. These shifts are comparable to that of V_{FB} intercept shown in Fig. 1(a). The binding energy of Ni $2p_{3/2}$ peak of sample CS_1 remained unchanged after annealing as shown in Fig. 2(b) and the Hf $4f_{7/2}$ peak positions of samples CS_1 and clean HfO_2 surface are kept the same as shown in Fig. 2(c), indicating that the shift of V_{FB} intercept shown in Fig. 1(a) is due to the diffusion of Ni atoms into Ti layer rather than the gate-metal/oxide reaction. The In–O bond was observed in sample S_2 and the Ni/HfO_2 interface after annealing shown in Fig. 2(a) and (c), respectively.

Fig. 3 shows the grazing angle X-ray diffraction (GXRD) spectra of sample S_2. The as-deposited sample reveals no crystalline peak, suggesting that the as-deposited alloy has nano-crystalline structure. The sample was annealed at 300°C to 800°C for 30s in FG. The crystalline peak is not found until annealed at 600°C, indicating that the alloy has amorphous phase due to the inter-diffusion of Ni and Ti. Literature reported that the amorphous phase or nano-crystalline structure of metal alloy induces a small EWF variation [1]. The results demonstrate that the EWF variation of TiNi alloy is still small until annealed at 600°C. The inset of Fig. 3 shows the GXRD spectra of sample S_2 after annealing at 350°C for 30s in FG and further annealing at 400°C for 5 minutes in FG. After further annealing, the sample S_2 is found to remain the amorphous-phase which has a small EWF variation.

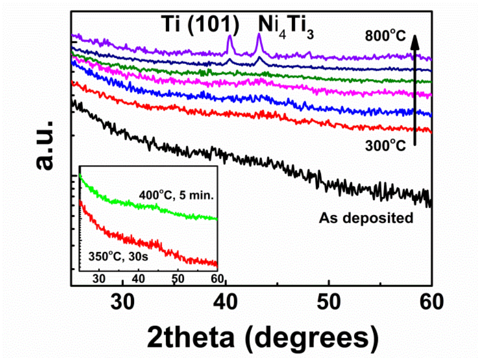

Fig. 3 The GXRD for as deposited and annealed multilayer TiNi alloy; inset: the Grazing XRD for sample S_2 after annealing at 350°C for 30s and further annealing at 400°C for 5 min. in FG.

3. Conclusion

In conclusion, the properties of TiNi alloys have been studied for $In_{0.53}Ga_{0.47}As$ NMOS devices. It is found that the EWF of the TiNi alloys increased from ~ 4.41 eV in as-deposited sample to ~ 4.62 eV after annealing. The multilayer TiNi alloy exhibited amorphous-phase which has small work function variation until annealed at 600°C.

Acknowledgements

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References

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