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A Study on Thermal Stability Improvement in Ni Germanide/p-Ge using Co interlayer for Ge MOSFETs

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***Abstract*—Nickel germanide (NiGe) is one of the most promising alloy materials for source/drain (S/D) of Ge MOSFETs. However, NiGe has limited thermal stability up to 450°C which is a challenge for fabrication of Ge MOSFETs. In this paper, a novel method is proposed to improve the thermal stability of NiGe using Co interlayer. As a result, we found that the thermal stability of NiGe was improved from 450°C to 570°C by using the proposed Co interlayer. Furthermore, we found that current-voltage (I-V) characteristic was improved a little by using Co/Ni/TiN structure after post-annealing. Therefore, NiGe formed by the proposed Co interlayer that is, Co/Ni/TiN structure, is a promising technology for S/D contact of Ge MOSFETs.**

***Index Terms*—Germanium, germanide, nickel, cobalt, interlayer, thermal stability**

I. INTRODUCTION

Metal–oxide–semiconductor field-effect transistors (MOSFETs) are being scaled down to increase the chip density and improve the device performance. However, enhancing the performance of Si-based devices by downscaling is constrained by limitations such as the decreased saturation current, increased leakage current, and enhanced short channel effect [1]. To overcome these limitations, research on new structures and materials is necessary. Recently, the performance of downscaled MOSFETS was shown to be more strongly influenced by carrier mobility than by drift velocity or saturation velocity [2]. Therefore, Ge is regarded as a next-generation material for MOSFETs because it has a higher carrier mobility than Si [3, 4].

To improve the device performance, Ge-based MOSFETs need to be downscaled. However, doing so can cause the short channel effect, similar to Si-based MOSFETs. The short channel effect increases the leakage current, decreases the mobility, produces the poly-depletion effect, increases the contact resistance, and changes the threshold voltage [5, 6]. To suppress the short channel effect, an ultra-shallow junction needs to be formed. However, decreasing the junction depth increases the sheet resistance [7]. To decrease the sheet resistance for a shallow junction depth, contact metallization needs to be used owing to the low sheet resistance of germanides. Therefore, research on germanides is important to reduce the S/D series resistance [8]. NiGe is likely the most promising germanide because of its many advantages such as a low formation temperature, low sheet resistance, and low substrate consumption rate [9, 10]. However, the main weakness of NiGe is its low thermal stability due to agglomeration and penetration, which increases the leakage current and sheet resistance during high temperature processes after the germanide is formed [9, 11]. Therefore, the thermal stability of NiGe is critical to

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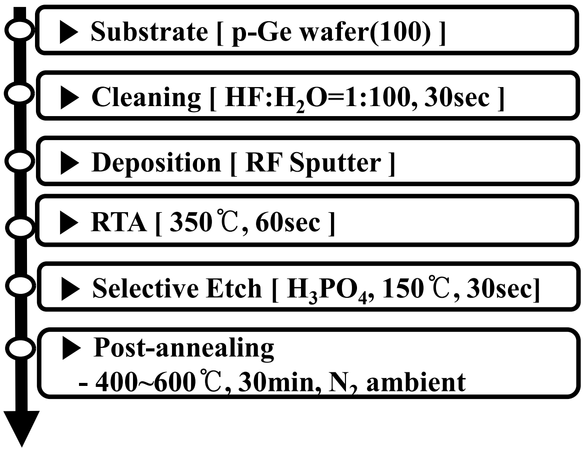

Fig. 1. Process flow for the experiments.

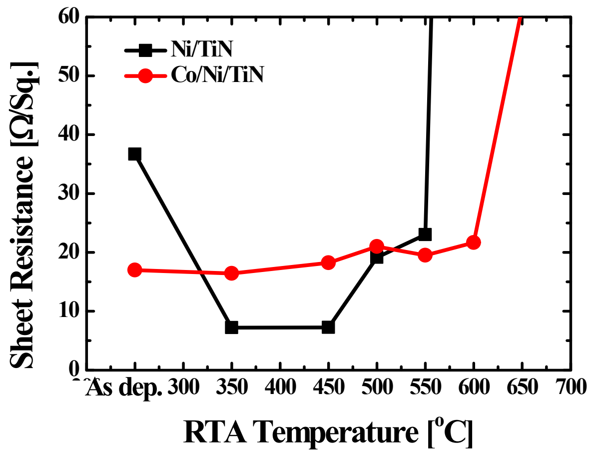

Fig. 2. Relationship between the sheet resistance of NiGe and the RTA temperature.

the development of Ge MOSFETs. To improve the thermal stability of NiGe, the alloying method has been proposed and widely studied. Co-sputtering and inserting interlayers, such as Ni(Zr), Ti, Yb, or Pd, are common alloying methods that can delay agglomeration and improve thermal stability [12-15].

Cobalt germanide (CoGe) has disadvantages, such as a higher substrate consumption and higher formation temperature than NiGe similar to cobalt silicide. Furthermore, CoGe has a higher resistivity than NiGe. Therefore, CoGe is unsuitable for application as an S/D contact of Ge MOSFETs. However, CoGe has a higher thermal stability than NiGe. Thus, Co may significantly help improve the thermal stability of NiGe [16].

In this study, NiGe with a Co interlayer is proposed for high performance Ge MOSFET technology. It is shown that the thermal stability of the proposed NiGe with Co interlayer was improved a lot compared with NiGe without Co intelayer. The proposed NiGe also showed enhanced ohmic contact characteristics.

II. Experimental

Ga-doped p-Ge (100) wafers were used as the substrate for thermal stability analysis. Fig. 1 summarizes the experimental process flow. A p-Ge wafer was cleaned to remove native oxide by using a diluted hydrofluoric acid ($HF:H_2O$ = 1:100) solution. Then, a 5-nm-thick Co interlayer was deposited on the substrate, followed by the in-situ deposition of 15-nm-thick Ni and 10-nm-thick TiN layers. For comparison with the effect of the Co interlayer, a reference sample was prepared by depositing pure Ni and TiN. The TiN capping layer is commonly used to prevent oxygen contamination. After metal deposition, a one-step rapid thermal annealing (RTA) process was carried out to form NiGe. After germanidation, the unreacted metal and TiN capping layer were selectively etched in phosphoric acid (H_3PO_4) solution at 150°C for 30 s. To evaluate the thermal stability of the NiGe, high-temperature post-annealing was carried out from 400 to 600°C for 30 min in nitrogen ambient. A reference sample was also prepared for comparison.

The sheet resistance was monitored using four-point measurements. Cross-sectional FE-SEM was employed to study the surface of the NiGe. The NiGe phase was studied using XRD. The depth profile was analyzed using SIMS. Moreover, the current–voltage characteristics of the formed NiGe were measured with an Agilent 4156A semiconductor parameter analyzer.

III. Results and Discussion

Fig. 2 shows the dependence of the NiGe sheet resistance on the RTA temperature for pure Ni and Ni with a Co interlayer. The pure Ni structure exhibited a stable RTA window from 350 to 550°C, while the sheet resistance for Ni with Co interlayer appeared to be more stable. The increase in resistance above 600°C can be attributed to the agglomeration or penetration of NiGe.

Fig. 3 shows the thermal stability of NiGe formed by RTA at 350°C. Deposition of the Co interlayer clearly improved the thermal stability of NiGe. Ni with the Co interlayer structure showed a lower sheet resistance and

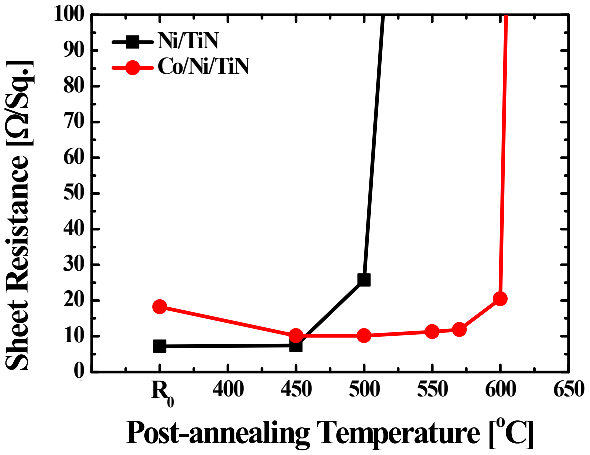

Fig. 3. Relationship between the sheet resistance of NiGe and the post-annealing temperature.

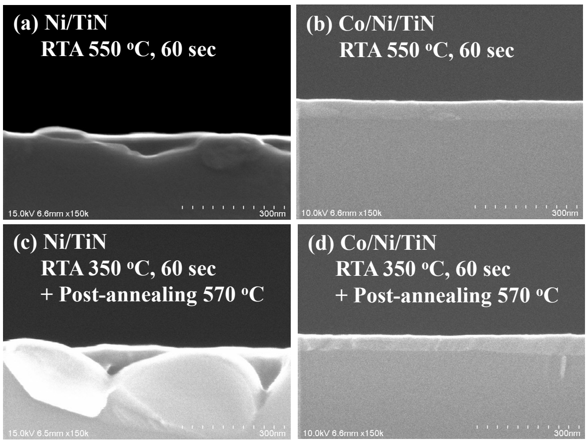

Fig. 4. FE-SEM cross-sectional images of NiGe (a) Ni/TiN structure of NiGe with RTA at 550°C, (b) Co/Ni/TiN structure of NiGe with RTA at 550°C, (c) Ni/TiN structure with post-annealing at 570°C, (d) Co/Ni/TiN structure with post-annealing at 570°C.

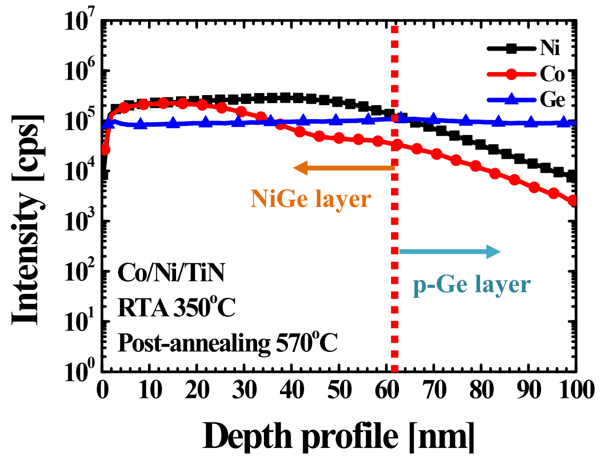

Fig. 5. SIMS depth profiles of NiGe with Co interlayer after post-annealing at 570°C for 30 min.

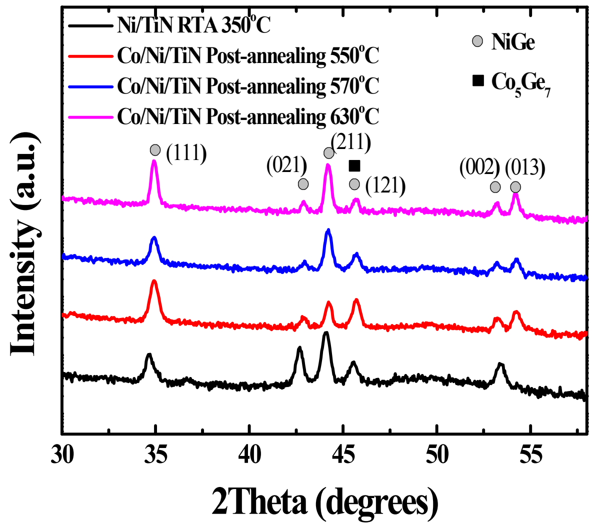

Fig. 6. XRD spectra of NiGe formed from Ni/TiN and Co/Ni/TiN structures.

much wider post-annealing temperature window than the pure Ni structure.

Fig. 4 shows the NiGe cross-section after germanidation and post-annealing. As shown in Fig. 4(a), agglomeration occurred at the interface of the Ni/TiN structure. Fig. 4(c) shows that agglomeration and penetration of NiGe occurred after post-annealing at an RTA temperature of 350°C. However, NiGe with Co interlayer demonstrated no agglomeration, as shown in Fig. 4 (b) and (d). Therefore, the Co interlayer appears to have suppressed the agglomeration.

Fig. 5 shows the SIMS depth profile of NiGe with Co interlayer after post-annealing at 570°C for 30 min. The concentration of Co atoms increased at the surface of the NiGe layer. The distribution of Co atoms may explain the improved thermal stability by the phase transformation of Co atoms. The coexistence of Co and Ni atoms may indicate the formation of NiGe with the Co layer.

Fig. 6 shows the XRD spectra of NiGe formed from Ni/TiN and Co/Ni/TiN structures. Similar NiGe peaks were observed from the two structures. For the Co/Ni/TiN structure, the Co_5Ge_7 and NiGe phases were observed, as shown in Fig. 6. Thus, Co_5Ge_7 may help improve the thermal stability of NiGe.

Fig. 7 shows the electrical characteristics of the fabricated metal-semiconductor junction diode. The current–voltage characteristics were measured at room

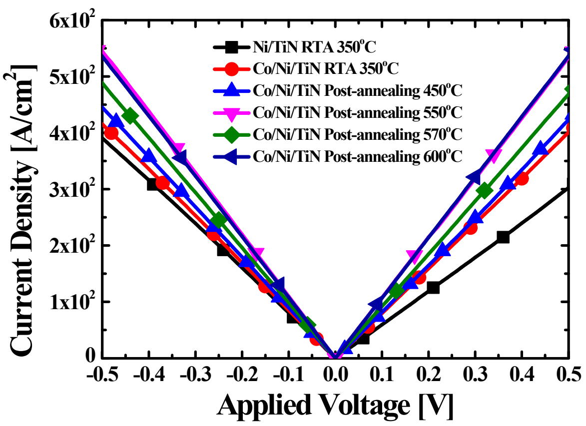

Fig. 7. Relationship between the sheet resistance of NiGe and the post-annealing temperature.

temperature for a pattern size of 100 μm×100 μm. The sample with the Co interlayer showed a higher current than the reference sample. In addition, the electrical characteristics of the sample with the Co interlayer showed that enhanced ohmic characteristics relative to those of the reference sample. After post-annealing, the current level was higher than that of the sample without post-annealing, which implies that NiGe with a Co interlayer appears to have enhanced current and ohmic characteristics relative to NiGe with pure Ni.

IV. CONCLUSIONS

In this study, the thermal stability of NiGe was improved using the proposed Co/Ni/TiN structure to incorporate Co into NiGe. The Co/Ni/TiN structure showed a wider RTP window for stable sheet resistance and was thermally more stable than the Ni/TiN structure. The proposed Co/Ni/TiN structure indicated the formation of CoGe in the NiGe layer, which may improve the thermal stability of NiGe. Moreover, the Co/Ni/TiN structure showed enhanced current and ohmic characteristics relative to the Ni/TiN structure. Therefore, the proposed Co/Ni/TiN structure is promising for application in high-performance Ge MOSFET technology.

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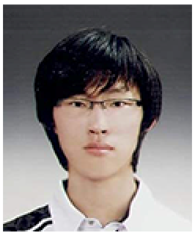

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