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Improvement of thermal stability of nickel germanide using nitrogen plasma pretreatment for germanium-based technology

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Dear editor,

Ge has been considered as a very promising candidate as a channel material of MOSFET to extend Moore's law beyond sub-7 nm node, due to its high and symmetric mobility, as well as the compatibility with conventional Si process [1, 2]. In spite of higher carrier mobility than Si, there are still several challenges for Ge MOSFETs, such as low electrical concentration of n-type dopants and high electron Schottky barrier height, resulting in large source/drain (S/D) series resistance. With the continuous scaling of device dimension, S/D series resistance increasingly limits the device performance, which is crucial for Ge-based devices. Self-aligned metal germanide, adopted for S/D contact of Ge-based MOSFETs, is a key process to reduce S/D series resistance. Among metal germanides, nickel germanide (NiGe) is regarded as one of the most promising candidates due to its low resistivity, low formation temperature and low consumption of Ge [3]. However, NiGe film suffers from the poor thermal stability and starts to agglomerate at about 400°C due to low activation energy of agglomeration in NiGe (2.2±0.2 eV) [4]. The thermal degradation of NiGe leads to the increase of the series resistance and leakage current. Therefore, it is quite important to improve the thermal stability of NiGe. Different methods have been proposed, such as the adoption of TiN capping layer to suppress the grain-boundary grooving [5], adding ultrathin Zr, Ti, Ta, Yb, Pt or Pd interlayer to suppress the agglomeration of NiGe [3, 4]. Yet, the thermal stability of NiGe becomes severe as the downscaling of NiGe film thickness.

In this study, a simple and effective method of nitrogen plasma pretreatment (NPP) is experimentally demonstrated to improve the thermal stability of NiGe films. The film quality of NiGe is investigated with the temperature ranging from 400°C to 600°C. The impact of NPP process time on NiGe thermal stability is investigated. Further, NiGe/n-Ge Schottky diodes are fabricated. The thermal stability of NiGe is characterized by both physical and electrical methods. Finally, the mechanism is discussed.

Experiment. The n-type Ge (100) substrates are used as starting wafers. Firstly, silicon oxide is deposited on Ge substrates for isolation. Then, the diode areas are defined by lithography and etching process. After cleaned by diluted hydrochloric acid (HCl) and dried by N_2 gun, wafers are treated

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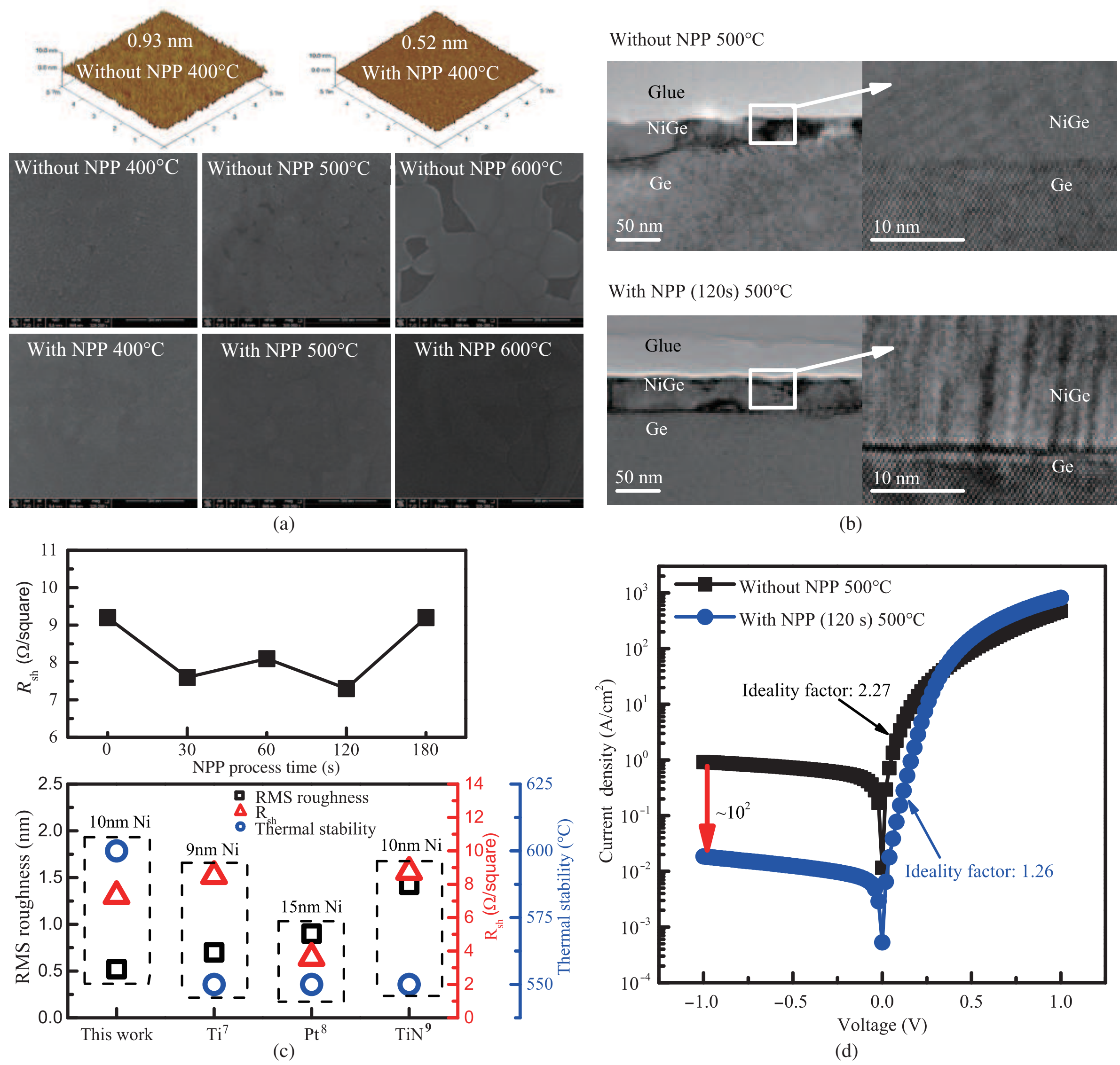

Figure 1 (Color online) Physical and electrical characteristics of NiGe film. (a) 3D AFM images (5 μm×5 μm) and SEM images of NiGe film with and without NPP formed at different temperature (400°C–600°C); (b) HRTEM images of NiGe films with and without NPP formed at 500°C; (c) sheet resistance of NiGe film formed with different NPP process time at 500°C and comparison of different methods [7–9]; (d) I-V curves of NiGe/n-Ge Schottky diodes with and without NPP (120 s).

by NPP, which is realized in an atomic layer deposition chamber. The process time of NPP is 30–180 s. The control sample has no NPP treatment. Then, samples are immediately loaded into the sputtering equipment to deposit 10 nm Ni, followed by rapid thermal annealing at 400°C–600°C in nitrogen ambient to form NiGe. Then, unreacted nickel is removed. Finally, Ti/Al and Al is respectively sputtered on the front side and backside of the sample as electrode, followed by alloying at 350°C for 30 min.

Results and discussion. The thermal stability of NiGe is characterized by physical and electrical methods, such as atomic forced microscopy (AFM), scanning electron microscopy (SEM), high resolution transmission electron microscopy (HRTEM) and current-voltage (I-V) curve measurement, as shown in Figure 1. Figure 1(a) shows the 3D AFM and SEM images of NiGe film with and without NPP formed at different temperature (400°C–600°C). The process time of NPP was 120 s. As seen from AFM images, NPP-sample formed at 400°C shows a smooth surface with low RMS roughness of 0.52 nm, 44% lower than control sample due to the suppression of NiGe agglomeration. For the control sample, protuberances and holes are observed at 400°C. The agglomeration becomes obvious as the annealing temperature rises to 500°C. For the sample with NPP, NiGe films remain uniform and continuous even at

600°C. Thus, NPP method is effective to suppress NiGe agglomeration.

To further study the impact of NPP on NiGe morphology, HRTEM was performed, as shown in Figure 1(b). For the control sample, the interface between NiGe and Ge is rough, indicating agglomeration of NiGe. In contrast, NPP-sample shows uniform surface due to the suppression of NiGe agglomeration. An ultrathin interlayer is observed for NPP-sample, which may be GeN_x. The mechanism of the suppression of NiGe agglomeration by NPP method may be attributed to the chemical bond of Ge-N formed on the surface of Ge [6]. The Ge-N bond may decrease the Gibbs energy of NiGe, thus improve the thermal stability of NiGe, which is similar to the case of Ni-Si [7]. Besides, the Ge-N bond may change the grain boundary of NiGe, making it harder for atoms to move along the boundary.

However, if NPP process time is too long, a thick interfacial layer of GeN_x may form and lead to the degradation of NiGe films. So the process time should be optimized. The sheet resistance of NiGe formed with different process time at 500°C and the comparison of different methods with similar NiGe thickness are illustrated in Figure 1(c) [7–9]. The sheet resistance is relatively low with NPP time of 30–120 s, especially with NPP time of 120 s, 21% lower than control sample (NPP time = 0 s). While the resistance increases significantly with the process time up to 180 s. This may result from the thick GeN_x interfacial layer on the surface of Ge. So the optimized process window of NPP is 30–120 s. Among different methos, NPP method illustrates the lowest RMS roughness, best thermal stability and relatively low sheet resistance. Besides, smooth surface morphology and good electrical characteristic are both important for high performance device. The NPP method obtains better trade-off between RMS and sheet resistance as well as better thermal stability, indicating the improvement of both physical and electrical characteristics.

Figure 1(d) shows I-V characteristics of NiGe/n-Ge Schottky diodes formed at 500°C with and without NPP. The NPP-sample shows higher ON-current and much lower OFF-current compared with the control sample, indicating the enhanced rectifying performance. And the leakage current is reduced by about two order of magnitude by NPP method. Besides, the NPP-sample shows lower ideality factor of 1.26 than the control sample (2.27), which indicates the effectiveness of NPP method to improve electrical characteristics of Ge-based devices.

Conclusion. In summary, an effective and simple method of NPP has been experimentally demonstrated to improve thermal stability of NiGe film. The thermal stability of NiGe is improved to at least 600°C by NPP. Better thermal stability and better trade-off between RMS roughness and sheet resistance are obtained compared with other reported methods. And the NiGe/n-Ge Schottky diode with NPP shows better electrical characteristic than control sample. Besides, the NPP process window is given to be 30–120 s. The result indicates the potential of this technique for the fabrication of Ge-based device.

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References

1 Deleonibus S. Looking into the future of nanoelectronics in the diversification efficient era. Sci China Inf Sci, 2016, 59: 061401

2 Lin M, An X, Li M, et al. Ge surface passivation by GeO_2 fabricated by N_2O plasma oxidation. Sci China Inf Sci, 2015, 58: 042403

3 Tang M R, Huang W, Li C, et al. Thermal stability of nickel germanide formed on tensile-strained Ge epilayer on Si substrate. IEEE Electron Device Lett, 2010, 31: 863–865

4 Zhang Q C, Wu N, Osipowicz T, et al. Formation and thermal stability of nickel germanide on germanium substrate. Jpn J Appl Phys, 2005, 44: L1389–L1391

5 Chou C H, Tsai Y H, Hsu C C, et al. Experimental realization of thermal stability enhancement of nickel germanide alloy by using TiN metal capping. IEEE Trans Electron Devices, 2017, 64: 2314–2320

6 Kashihara K, Yamaguchi T, Okudaira T. Improvement of thermal stability of nickel silicide using N_2 ion implantation prior to nickel film deposition. In: Proceedings of International Workshop on Junction Technology, Shanghai, 2006. 176–179

7 Zhu S Y, Yu M B, Lo G Q, et al. Enhanced thermal stability of nickel germanide on thin epitaxial germanium by adding an ultrathin titanium layer. Appl Phys Lett, 2007, 91: 051905

8 Zhang Y Y, Oh J, Li S G. Improvement of thermal stability of Ni germanide using a Ni-Pt(1%) alloy on Ge-on-Si substrate for nanoscale Ge MOSFETs. IEEE Trans Nanotechnol, 2010, 9: 258–263

9 Kang M H, Zhang Y Y, Park K Y, et al. Suppression of nickel-germanide (NiGe) agglomeration and Ni penetration by hydrogen (H) ion shower doping in NiGe on a thin epitaxial Ge-on-Si substrate. J Korean Phy Soc, 2009, 55: 221–226