Interlayer Dielectric Capping Effect on Thermal Stability of Ni Germanide on Doped Ge-on-Si Substrate for Nano-scale Ge MOSFETs

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***Abstract*— Analyzed herein is the influence of interlayer dielectric (ILD) oxide capping layer on thermal stability of Ni germanide formed on B_{11}-, BF_2-, and As-doped Ge-on-Si substrates. The thermal stability of Ni germanide has a strong dopant dependence after post-germanidation annealing and the doped samples with ILD have better thermal immunity than those without ILD. The B_{11}- and BF_2- doped samples with ILD oxide capping layer show lower sheet resistance, more uniform interface and more smooth surface images up to 575°C. Therefore, the ILD oxide capping is promising for thermal stability improvement of Ni germanide on doped Ge-on-Si substrate for nano-scale germanium metal oxide semiconductor field effect transistors (Ge MOSFETs).**

***Index Terms*— Ge-on-Si substrate, Interlayer dielectric (ILD) capping, Ni germanide, post-germanidation annealing, thermal stability**

I. INTRODUCTION

Germanide, like silicide, is attracting great interest as ohmic contact for high speed germanium metal oxide semiconductor field effect transistors (Ge MOSFETs) which is considered to be promising candidate to replace silicon (Si) MOSFET due to its two times higher mobility for electrons and four times for holes in Ge than in Si [1]-[3]. Among various germanides, Ni germanide seems to be the best candidate, like Ni silicide in Si MOSFET, because Ni germanide has advantages over other germanides, i.e., low formation temperature, stable phase over wide temperature range, and low resistivity [5]-[6]. The low processing temperature is effective to prevent the degradation of high-k gate stack on Ge substrate and makes Ni germanide more suitable for Ge device fabrication. However, its poor thermal stability owing to Ni germanide agglomeration and penetration [7] impedes its application to nano-scale Ge MOSFETs. Several studies to improve the thermal stability of Ni germanide on un-doped substrate, such as using Ni-Ta [8], Ni-Zr [9] alloy, or using Pt [10], Ti [11] incorporation layer, have been reported. Our group has also studied the thermal stability of Ni germanide on un-doped Ge-on-Si substrate by using Ni-Pd [12], Ni-Pt [13] alloy, or using Yb [14], Co [15] incorporation layer.

Silicon oxide (SiO_2) films are widely used as an interlayer dielectric (ILD) layer for multi-level metallization [16]. We have studied the ILD influence on Ni germanide on un-doped substrate [17], but it is necessary to study the effect of ILD on Ni germande formed on doped substrate because Ni germanide must be formed on doped source/drain regions. In this paper, Ni germanide was formed on B_{11}-, BF_2-, and As-doped substrates and the influence of ILD oxide capping layer on the Ni germanide was analyzed. Results show that the thermal stability of Ni germanide has dependence on the dopant and the doped samples with ILD layer have better thermal immunity than those without ILD. Therefore, the oxide capping is necessary for the improvement of the thermal stability of Ni germanide for nano-scale Ge MOSFETs.

II. EXPERIMENTS

100 nm thick Ge layer was epitaxially grown on 8” p-type Si(100) substrates using a ultra high vacuum chemical vapor deposition (UHV-CVD) system. B_{11}, BF_2, and As were implanted on Ge-on-Si substrate and their ion implantation conditions are summarized in Table 1. Fig. 1 shows SIMS depth profiles of B_{11}, BF_2 and As implants before and after the dopant activation with a rapid thermal process (RTP) at 550 °C for 60 sec. In the Ge region, the dopant concentration is over 10^{18} cm^{-3}. The un-doped substrates are also used for references. A key process flow for experiments is summarized in Fig. 2. The doped Ge-on-Si substrate was cleaned and dipped in diluted HF solution to remove the native oxide. Then, 10 nm thick Ni and 10 nm thick TiN capping layers were sequentially deposited using RF magnetron sputtering system with a base pressure of 5 × 10^{-7} Torr and a working pressure of 1 mTorr. For the formation of

Table 1. Ion implantation conditions for the dopants used in the experiments.

	Dose[/cm^2]	Energy [keV]
B_{11}	1 X 10^{15}	5
BF_2	1 X 10^{15}	20
As	1 X 10^{15}	20

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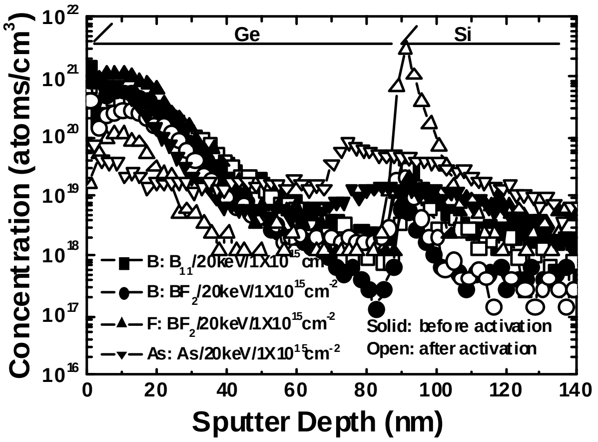

Fig. 1. SIMS depth profile of B_{11}, BF_2 and As doped on Ge-on-Si substrate before and after the dopant activation with a RTP at 550 ^oC for 60 sec.

Ni germanide, one-step RTP was carried out at 400 ^oC for 30 sec. Un-reacted metal layer was selectively removed using H_3PO_4 solution at 150 ^oC for 30 sec. After that, 1000 Å thick SiO_2 layer for ILD layer was deposited by plasma enhanced chemical vapor deposition (PECVD). Samples without the SiO_2 layer were also fabricated for comparison. Finally, samples were furnace annealed in N_2 ambient at different high temperatures for 30 min (post-germanidation annealing in short) to evaluate the thermal stability of Ni germanide. Wet etching of the SiO_2 layer was carried out using buffered oxide etch (BOE) solution for 1 min to measure the sheet resistance of Ni germanide.

Secondary ion mass spectrometer (SIMS) was performed to investigate doping depth profile of implants. Sheet resistance was measured using conventional four point probing method. Thin-film X-ray diffraction (XRD) was performed to investigate phase identification. The uniformity of interface and surface morphology of Ni germanide were observed using field emission scanning electron microscopy (FESEM).

III. Results and discussion

The sheet resistance window of NiGe with and without the oxide capping layer on doped Ge-on-Si substrate as a function of post-germanidation annealing temperature is shown in Fig. 3. Ref. in x-axis is defined as the sheet resistance value before post-germanidation annealing. Although for all doped and un-doped substrates have similar Ref. sheet resistance, sheet resistance exhibits the strong dopant dependence after post-germanidation annealing. In case of samples without oxide capping layer, BF_2-doped sample showed the best thermal stability characteristics up to 550^oC while As-doped and un-doped samples exhibited the poorest thermal stability. However, oxide capping layer affected differently on the doped samples. First, B_{11}- and BF_2-doped samples exhibited similar dependence of sheet resistance on the annealing temperature, which suggests the stronger effect of capping layer on the B_{11}-doped substrate than BF_2-doped one. Second, As-doped case showed uniform sheet resistance up to 500 ^oC annealing while un-doped case up to only 475 ^oC, which also suggest different effect of the oxide capping layer on Ni germanide. However, As-doped sample still exhibits much narrower stable window than B_{11}- and BF_2-doped samples.

Fig. 4 shows the XRD spectra of Ni germanide with and without oxide capping layer on doped Ge-on-Si substrate before and after post-germanidation annealing. The normal spectrum for a random powder of NiGe [18] is also included in Fig.4 for reference. Only NiGe phase appeared and no other Ni germanide peaks were observed for all un-doped and doped substrates regardless of the oxide capping layer, which is consistent with previous results [5]-[6].

Cross-sectional and plan-view FESEM images for un-doped and B_{11}-, BF_2- and As-doped substrates before post-germanidation annealing, after post-germanidation annealing without oxide capping layer and after post-germanidation annealing with oxide capping layer are shown in Fig. 5, Fig. 6, and Fig. 7, respectively. Before post-germanidation annealing, i.e., after germanide formation, the uniform NiGe interface in Fig. 5 (a) - (d) and smooth surface in Fig. 5 (e) - (h) can be obtained from all un-doped and doped substrates, which is in agreement with the low Ref. sheet resistance value in Fig. 3. However, after post-germanidation annealing without oxide capping layer,

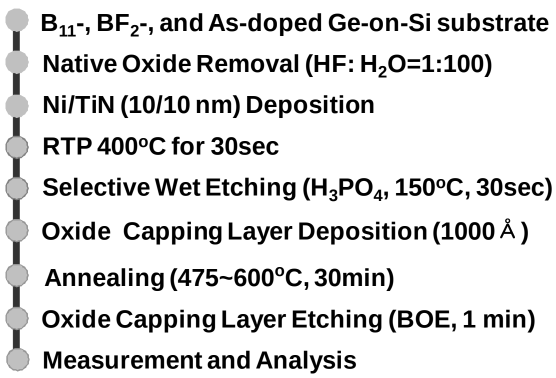

Fig. 2. Process flow for experiments.

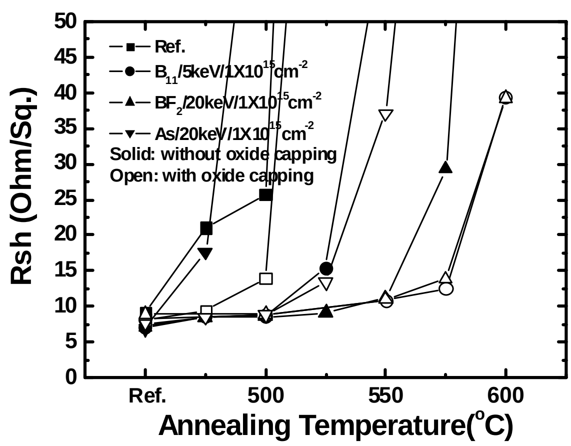

Fig. 3. Sheet resistance of NiGe with and without oxide capping layer on doped Ge-on-Si substrate as a function of post-germanidation annealing temperatures.

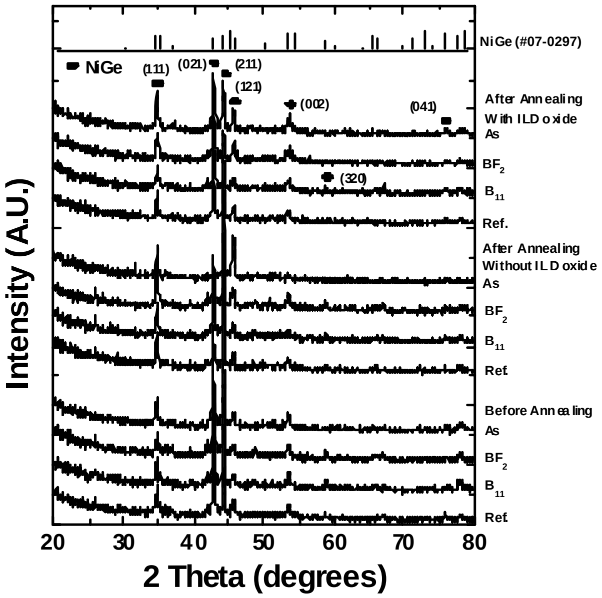

Fig. 4. XRD spectra of Ni germanide with and without oxide capping layer on un-doped, B_{11}-, BF_2-, and As-doped substrates before and after post-germanidation annealing.

the un-doped (Fig. 6(a) and (e)) and As-doped (Fig. 6(d) and (h)) samples show agglomeration islands at 500°C. The B_{11}- (Fig. 6(b) and (f)) and BF_2- (Fig. 6(c) and (g)) doped samples show much better interface and more continuous morphological images at 525 and 550°C, respectively. The samples with oxide capping layer show more enhanced interface and surface images as shown in Fig. 7. The un-doped sample with oxide capping layer shows more uniform interface (Fig. 7 (a)) and smoother surface (Fig. 7 (e)) than those without oxide capping layer at 500 °C (Fig. 6(a) and (e)). The B_{11}- (Fig. 7(b) and (f)) and BF_2- (Fig. 7(c) and (g)) doped samples have also more uniform interface and morphological images even at 575°C, while the As-doped sample shows little

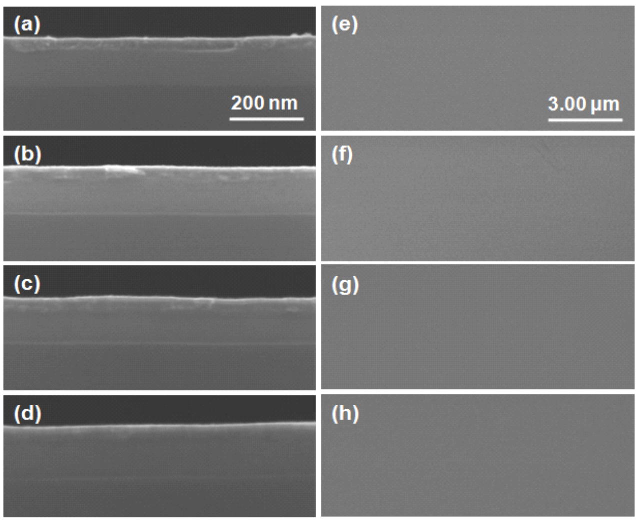

Fig. 5. Cross-sectional (a-d) and plan-view (e-h) FESEM images after germanide formation, i.e., before post-germanidation annealing for un-doped (a, e) and B_{11}- (b, f), BF_2- (c, g) and As- (d, h) doped substrates.

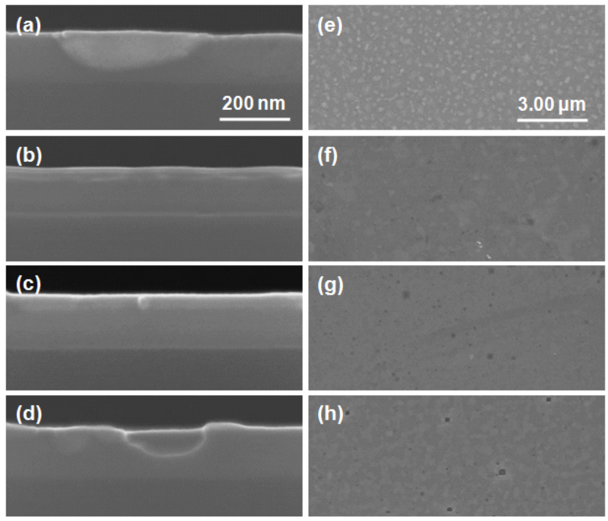

Fig. 6. Cross-sectional (a-d) and plan-view (e-h) FESEM images after post-germanidation annealing without oxide capping layer for un-doped (a, e) at 500°C and B_{11}- (b, f) at 525°C, BF_2- (c, g) at 550°C and As- (d, h) doped substrates at 500°C.

improvement. Therefore, it can be said that oxide capping layer is efficient to improve morphological characteristics of Ni germanide for all dopants.

It has been demonstrated that the degradation of the sheet resistance value by high temperature annealing can be explained by two mechanisms, agglomeration or phase transformation in the Ni/Si system [19]. The low-resistivity NiSi phase transforms into a high-resistivity $NiSi_2$ phase during high-temperature annealing. However, in the Ni/Ge system, there is no $NiGe_2$ phase according to the Ni-Ge phase diagram. Therefore, the only possible sheet resistance degradation mechanism observed in our measurement is due

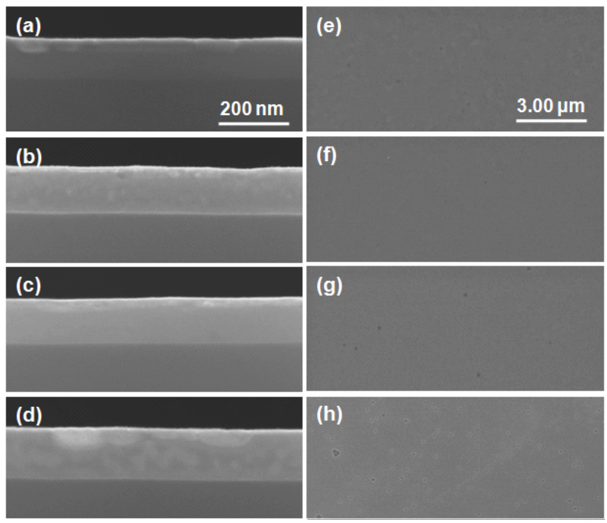

Fig. 7. Cross-sectional (a-d) and plan-view (e-h) FESEM images after post-germanidation annealing with oxide capping layer for un-doped (a, e) at 500°C and B_{11}- (b, f) at 575°C, BF_2- (c, g) at 575°C and As- (d, h) doped substrates at 550°C.

to the agglomeration of NiGe. From the above analyses, we can obtain that the cause of improved thermal stability of NiGe due to oxide capping layer is attributed to the retardation of NiGe agglomeration. That is, Ni germanide with oxide capping layer shows less agglomeration and smooth morphological image and thus reduces the sheet resistance of NiGe.

IV. Conclusion

In this paper, the influence of ILD oxide capping layer on thermal stability of Ni germanide which formed on Ge-on-Si substrate with various kinds of doping was studied. The doped samples showed much more thermal stability than un-doped one. And the samples with oxide capping layer showed better thermal stability than without one. B_{11}- and BF_2-doped samples with oxide capping layer showed the best thermal stability up to 575^{o}C, i.e., lower sheet resistance and more uniform interface and more smooth surface images. Although As-doped samples showed improved thermal stability, sheet resistance begins to increase from 525 ^{o}C annealing. XRD analyses showed that only NiGe phase can be detected and the cause of improved thermal stability of NiGe due to ILD oxide capping is attributed to the retardation of NiGe agglomeration. Although oxide capping layer can improve thermal stability of Ni germanide, dopant dependence of Ni germanide should be paid attention for high performance nano-scale Ge MOSFETs.

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