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Textured Ni(Pt) Germanosilicide Formation on a Condensed Si_{1-x}Ge_x/Si Substrate

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A study of Ni and Ni(Pt) germanosilicidation on a condensed Si_{1-x}Ge_x/Si substrate was performed. The partial relaxation of the condensed SiGe layer resulted in an improvement in the morphological stability of the germanosilicide through the alleviation of compressive stress. Pt alloying to the Ni film resulted in highly textured Ni(Pt) germanosilicide grains, particularly in the (002) orientation, due to the reduction in the interfacial energy caused by the presence of Pt alloy. Pt atoms diffuse slowly and result in a variation in lattice parameters in the Ni(Pt)SiGe grain as a function of depth. Nevertheless, Pt alloying has increased the morphological stability of the NiPtSiGe film.

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Si_{1-x}Ge_x is increasingly being utilized in advanced complementary metal oxide semiconductor (CMOS) devices either as a channel stressor, a virtual substrate, or a channel material.¹⁻⁶ The fact that Ge has higher carrier mobility compared to Si makes it attractive for use to further improve the transistor performance. However, unlike Si, Ge is scarce and brittle, which makes the fabrication of a large pure-Ge wafer not economically feasible and not easily handled. Therefore, in CMOS fabrication, the Ge incorporation usually takes the form of a thin epitaxial layer grown on a Si handling wafer, such as Si_{1-x}Ge_x layer on Si, Si_{1-x}Ge_x on insulator, or even pure Ge on insulator. However, growing a Si_{1-x}Ge_x layer directly on top of a Si wafer remains a challenging task.

The presence of built-in stress due to a lattice mismatch between Si_{1-x}Ge_x and Si might lead to the formation of misfit dislocations whenever there is a stress relaxation taking place. This dislocation formation has to be avoided because the presence of dislocations especially at the channel region significantly degrades the device performance. The stress relaxation can be avoided by limiting the thickness of the Si_{1-x}Ge_x layer directly grown on Si substrate to be below a certain critical thickness.⁷ Because the critical thickness of the Si_{1-x}Ge_x layer depends on the Ge content in the layer, such approach seriously limits the thickness of the usable Si_{1-x}Ge_x layer, especially for the high Ge content Si_{1-x}Ge_x layer directly grown on Si substrate. There are several methods that can be utilized to fabricate these substrates. The use of a very thick graded Si_{1-x}Ge_x buffer layer (x varies from 0 to the final intended Ge content) beneath the final Si_{1-x}Ge_x layer has been reported.^{8,9} However, this growth process of a thick graded Si_{1-x}Ge_x layer can be expensive. In this work, the condensation method was used to grow a high Ge content epitaxial Si_{1-x}Ge_x layer on a Si substrate.^{10,11} The details of the fabrication of the epitaxial Si_{1-x}Ge_x substrate used in this experiment are similar to those reported elsewhere.¹²

NiSi is replacing TiSi₂ and CoSi₂ as a contact material in nanoscale CMOS devices because of its well known advantageous properties.¹³ For SiGe-based devices, Ni germanosilicide is the strongest candidate to be used for the contact material. However, the already worrisome agglomeration issue, which occurs during NiSi formation, is exacerbated in the Ni germanosilicide formation.^{14,15} Ge out-diffusion from the Ni germanosilicide as a result of a difference in heat of formation between NiSi and NiGe and the presence of compressive stress inside the Si_{1-x}Ge_x layer are some of the key reasons behind this.¹⁶⁻¹⁸ B and Pt have been found to improve the morphological stability of Ni germanosilicide.^{19,20} Most of the previous studies on germanosilicidation of either a strained or a relaxed

Si_{1-x}Ge_x layer have only been performed on a relatively low Ge concentration.^{18,21-25} Germanosilicidation studies on high Ge content Si_{1-x}Ge_x substrate can be done on a polycrystalline Si_{1-x}Ge_x sample or relaxed SiGe grown on a thick buffer layer.¹⁵ The fabrication of a Si_{1-x}Ge_x substrate through condensation method enables the formation of a high Ge concentration strained Si_{1-x}Ge_x substrate while keeping the defect density low. This work focuses on the phase formation, morphological stability, and microstructural evolution of Ni(Pt) germanosilicide on a strained Si_{1-x}Ge_x substrate formed through condensation method with a final Ge content of ≈ 40 atom %.

Experimental

Before a deposition of 20 nm Ni or Ni_{1-u}(Pt)_u ($u = 0.1$ or 0.2) film, the surface of the condensed Si_{1-x}Ge_x substrate was cleaned using piranha solution (H₂SO₄:H₂O₂ = 4:1) for 10 min followed by a 1 min dip in dilute HF (1:50) to ensure the removal of the native oxide. The Ni or Ni_{1-u}(Pt)_u film was deposited using a dc magnetron sputtering system with a base pressure better than 2×10^{-6} Torr. Rapid thermal annealing (RTA) was used to perform an isotropic annealing of the samples at 400–800°C for 60 s in a N₂ purged ambient. The Raman spectroscopy was employed to analyze the mechanical strain inside the Si_{1-x}Ge_x layer. Auger electron spectroscopy (AES) depth profiling analysis was performed on the substrate to evaluate the distribution of the Ge atoms inside the Si_{1-x}Ge_x. The identification of the phase and crystallographic orientation of the germanosilicide film was carried out using X-ray diffraction (XRD) with Cu K α radiation [average wavelength (λ): 1.5418 Å]. Cross-sectional transmission electron microscopy (XTEM) analyses using a JEM 2100 transmission electron microscope were employed to evaluate the microstructure of the Ni germanosilicide formed. The surface morphology of the sample was studied using secondary electron microscopy (SEM) imaging. Four-point probe measurements were performed on the annealed samples to monitor the changes in the electrical sheet resistance.

Results and Discussion

Substrate characterizations.— The AES depth profiling of the Ge concentration in the as-grown and as-condensed Si_{1-x}Ge_x substrates is shown in Fig. 1. The maximum Ge concentration on the surface of the as-condensed sample was ~ 40 atom %. In the surface region (region I), the Ge content slowly decreased as a function of the thickness to around a depth of 50 nm where the Ge concentration was ~ 30 atom %. Beyond this point, which can be referred to as region II, the slope became three times steeper than that of region I. It can also be observed that the Ge concentration diminished to less than 5 atom % at a depth of around 85 nm before it completely disappeared at a depth of about 115 nm.

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Figure 1. (Color online) AES depth profiling analyses of an as-grown $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ substrate (■) and as-condensed $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ substrate (●). The w and maximum x values are 0.15 and 0.4, respectively. Region I and II corresponds to the region in the $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ (red) curve. The inset shows the XTEM micrograph of the as-condensed $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ sample showing the confined deep level dislocation at $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ interface.

As observed in the XTEM micrograph of the as-condensed $\text{Si}_{1-x}\text{Ge}_x$ sample shown in the inset of Fig. 1, the $\text{Si}_{1-x}\text{Ge}_x$ substrate exhibits relatively low density threading dislocations. Most dislocations present in the as-condensed substrate were accumulated at a depth of 86.8 ± 4.4 nm, with a smaller number of them appearing at a depth of 59.4 ± 2.0 nm. The depth at which most dislocations appear corresponds to the area near the $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ interface determined from the AES depth profiling analysis in Fig. 1. This is caused by a transition from Si to $\text{Si}_{1-x}\text{Ge}_x$ at the $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ interface, which results in a built-in stress caused by a lattice mismatch between Si and $\text{Si}_{1-x}\text{Ge}_x$. This stress was then released through the formation of point defects or misfit dislocations, which are confined at the $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ interface. Based on the shift in the Si-Si peak in the Raman analysis of the $\text{Si}_{1-x}\text{Ge}_x$ (not shown), the $\text{Si}_{1-x}\text{Ge}_x$ layer is in a partially compressive stress with $\varepsilon = -0.8\%$ [the calculated strain value for the fully strained $\text{Si}_{1-x}\text{Ge}_x$ ($x = 0.4$) sample is $\varepsilon_{\text{calc}} = -1.54\%$].²⁶ The analyzed sample thickness using a 488 nm laser Raman analysis is on the order of several tens of nanometers, and hence the Raman signal obtained is an average from the probed volume from the surface, which has a varying Ge concentration and a varying strain. This, together with the partial relaxation in the $\text{Si}_{1-x}\text{Ge}_x$ layer explained previously, resulted in the discrepancy between the measured and calculated strain values.

Ni and $\text{Ni}_{1-u}(\text{Pt})_u$ germanosilicidation on a condensed $\text{Si}_{1-x}\text{Ge}_x$ substrate.—As shown in the XRD spectra in Fig. 2a, the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ formation can be detected in the sample after 400°C annealing and above. After annealing at 400°C, peaks from (102) and (202) planes were the most dominant peaks observed in the spectra. The appearance of additional peaks from (002), (202), and (013) peaks could be detected in the XRD spectra after annealing at higher temperatures, which indicates that the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ film has become less textured. XRD analyses of the same sample using a Seeman-Bohlin configuration (not shown) has revealed that the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ peaks shift toward a larger diffraction angle (i.e., a reduction in interplanar spacing) as the annealing temperature is increased from 400 to 500°C. This phenomenon is caused by Ge

Figure 2. (Color online) (a) XRD spectra of $\text{Ni}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ samples after RTA at different temperatures starting from 400 to 700°C. The XRD spectrum from the as-deposited sample is also plotted for comparison. (b) XRD spectra of the $\text{Ni}_{1-u}(\text{Pt})_u/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ sample ($u = 0.1$) after RTA at different temperatures starting from 500 to 700°C. The XRD spectrum from the as-deposited sample is also plotted for comparison.

out-diffusion from the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ crystal, which is thermodynamically driven by a difference in the heat of formation of NiSi and NiGe .¹⁷

Ni film with 10 atom % Pt alloying was used to study the effect of Pt addition during Ni germanosilicide formation. As observed in the XRD spectra depicted in Fig. 2b, the formation of $\text{Ni}_{1-z}(\text{Pt})_z(\text{Si}_{1-y}\text{Ge}_y)$ [where $z \leq 0.1$ and $y \leq 0.4$, it will be written as $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ for simplicity] was fully completed after 400°C annealing and above. Different from the pure- Ni sample, the sample with Pt alloying exhibits a clear texturing in the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ film. Initially, two diffraction peaks that originated from the (002) and (102) planes of the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ phase were observed in the XRD spectra. Annealing at higher temperature resulted in a more distinct texturing of the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ film at the (002) peak. Eventually the (102) peak disappeared, and only the diffraction peak from the (002) plane could be observed in the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ film. The mechanism of the texturing is explained in the following paragraph.

The growth of a thin film is affected by both interfacial (thickness independent) and strain energies (thickness dependent). To achieve a higher thermodynamic stability, the system always tends to proceed in a certain way to minimize the sum of these two energies. The absence of texturing in the pure-Ni sample might be caused by the interfacial energy of the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ film being similar in different planes. This results in the formation of a polycrystalline film with many different orientations, as observed in Fig. 2b. The addition of 10 atom % Pt into the film has resulted in the reduction in interfacial energy between the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ film and the substrate. It is believed that reduction in interfacial energy was more pronounced in the (002) and (102) planes; thus the nuclei were predominantly growing in these two planes. Increasing the annealing temperature caused a grain growth in the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ film as well as in its thickness. This changes the governing mechanism during the growth of the film in which the strain energy alters the preferential growth of the sample. This phenomenon is apparent in the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ sample in which the (002) peak is the only peak observed in the sample after annealing at higher temperatures. Because the SiGe substrate used in this work is epitaxially grown in (001), the (002) planes in the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ film must be in parallel position with the substrate.

As expected, the peak positions of $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ at 400°C were shifted toward a lower diffraction angle as compared to that in the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ sample. The Pt alloying caused the further dilation of the lattice constant of the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ and its corresponding d -spacing. All $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ diffraction peaks did not shift to a higher diffraction angle after annealing at higher temperatures up to 600°C, which is different from that of the $\text{Ni}/\text{Si}_{1-x}\text{Ge}_x$ samples. The absence of any peak shift in the annealed $\text{Ni}_{1-u}(\text{Pt})_u/\text{Si}_{1-x}\text{Ge}_x$ samples indicates that with Pt addition, the Ge out-diffusion phenomenon is significantly reduced.

A high resolution transmission electron microscopy (HRTEM) micrograph of the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ film after annealing at 600°C is shown in Fig. 3a. The $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ grains were in the form of big crystals and appeared to be highly textured. This observation agrees well with the XRD results shown in Fig. 2b. Because the $\text{Si}_{1-x}\text{Ge}_x$ substrate has a varying Ge content, it is of interest to evaluate whether the Ge and/or Pt atoms inside the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ sample were distributed evenly throughout the germanosilicide grain. The grain was aligned to a [110] zone axis to facilitate lattice spacing measurement. The normalized lattice spacing of the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ grain as a function of depth at the location near the grain boundary (■) and in the middle of the germanosilicide grain (▲) was measured, as shown in Fig. 3b. The measurement location “near the grain boundary” was around 5 atomic spacings away from the grain boundary, whereas the “middle of the grain” was at the middle area of the grain, which, in this case, was around 30 nm away from the grain boundaries. It is apparent that the lattice spacing inside a single-crystal $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ decreases as a function of depth. The secondary-ion mass spectrometry depth profiling analysis of the sample (not shown) revealed that the Pt atoms did not diffuse as fast as the Ni atoms and were accumulated near the surface region, which resulted in the variation observed in the lattice parameter of the germanosilicide film. The fact that the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ grains are textured and large plays an important role in preventing the out-diffusion of Ge atoms to the grain boundaries (due to a limited grain boundary area).

To further evaluate the effect of the Pt alloying during $\text{Ni}(\text{Pt})$ germanosilicidation, another set of samples with a 20 atom % Pt alloying was prepared. The annealing conditions were similar to other sets of samples described previously. The XRD spectra of the $\text{Ni}_{1-u}(\text{Pt})_u/\text{Si}_{1-x}\text{Ge}_x$ ($u = 0.2$) samples before and after RTA annealing processes are shown in Fig. 4. The sample with higher Pt alloying exhibits an even more textured $\text{Ni}_{1-z}(\text{Pt})_z(\text{Si}_{1-y}\text{Ge}_y)$ film [where $z \leq 0.2$ and $y \leq 0.4$, it will be written as $\text{Ni}(\text{Pt})_{0.2}(\text{Si}_{1-y}\text{Ge}_y)$ for simplicity]. Again the y value here might or might not be exactly the

Figure 3. (a) HRTEM micrograph of the $\text{Ni}_{1-u}(\text{Pt})_u/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ sample ($u = 0.1$) after annealing at 600°C showing a huge single-crystal $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ grain aligned in a zone axis. The marking indicates the depth as measured from the surface. (b) The lattice parameters of the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ grain at different depths at the location near grain boundary and in the middle of the grain.

same as the one in the $\text{Ni}(\text{Pt})(\text{Si}_{1-y}\text{Ge}_y)$ sample, especially for the high temperature annealing processes. No formation of PtSi or PtGe could be observed from the XRD analysis. This indicates that the Pt atoms were still incorporated inside the germanosilicide grains even at the 20 atom % of Pt alloying. This result is expected because all NiSi, NiGe, PtSi, and PtGe phases have a similar orthorhombic $pmna$ structure, and hence a complete miscibility is possible throughout the whole range of atomic composition.

After 400°C annealing, the XRD spectra of the $\text{Ni}_{1-u}(\text{Pt})_u/\text{Si}_{1-x}\text{Ge}_x$ ($u = 0.2$) is dominated by the appearance of high intensity double peaks at around 2θ angle of 29–31°. The peaks could be attributed to the (011) and (002) peaks of the $\text{Ni}(\text{Pt})_{0.2}(\text{Si}_{1-y}\text{Ge}_y)$ phase. As the annealing temperature increases, the (002) peak becomes dominant, and eventually only the diffraction peak from this plane is observable in the XRD spectra. These

Figure 4. (Color online) XRD spectra of the $\text{Ni}_{1-u}(\text{Pt})_u/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ sample ($u = 0.2$) after RTA at different temperatures starting from 400 to 700°C. The XRD spectrum from the as-deposited sample is also plotted for comparison.

observations indicate that the $\text{Ni}(\text{Pt})_{0.2}(\text{Si}_{1-y}\text{Ge}_y)$ film is highly textured or epitaxial to the substrate with the $(001)\text{Ni}(\text{Pt})_{0.2}(\text{Si}_{1-y}\text{Ge}_y)\parallel(001)\text{SiGe}$ relationship. The texturing of the germanosilicide grain with Pt addition was evaluated further through the XRD pole figure analysis. The XRD pole figure measurements of all samples after annealing at 500°C were carried out in a high resolution XRD system under Schultz geometry. They were acquired in steps of 3° in χ scan ($0^\circ \leq \chi \leq 90^\circ$) and steps of 4° in ϕ scan ($0^\circ \leq \phi \leq 360^\circ$). Figure 5a-c shows the Ni-germanosilicide (002) pole figures taken at the 2θ value of 30.13°. In the pure-Ni sample, there was no texturing of the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ grains detected (Fig. 5a). The pole figure exhibits a twofold rotational symmetry, which is expected from the crystal with an orthorhombic crystal structure. Adding Pt resulted in texturing in the (002) plane and also affected the rotational symmetry of the germanosilicide. With 10 atom % Pt alloying, texturing starts to form, which becomes more prominent for the 20 atom % Pt sample (refer to Fig. 5b and c). The $\text{Ni}(\text{Pt})_{0.1}(\text{Si}_{1-y}\text{Ge}_y)$ film generally still exhibits a twofold rotational symmetry with an appearance of grain texturing along the (002) plane. The rotational symmetry of the $\text{Ni}(\text{Pt})_{0.2}(\text{Si}_{1-y}\text{Ge}_y)$ film eventually changed to a fourfold rotational symmetry, which is a result of the epitaxial alignment with the SiGe substrate. Pt addition has altered the interfacial energy and the lattice dimension of the germanosilicide, thus allowing it to form a textured film on the substrate.

Morphology of germanosilicide on condensed SiGe.—The onset of agglomeration of the $\text{Ni}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ sample could be detected after annealing at temperatures as low as 500°C. Annealing at higher temperatures, i.e., 600°C, resulted in a severe islanding of the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ film (see Fig. 6a). As reported previously, the agglomeration of $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ formed on $\text{Si}_{1-x}\text{Ge}_x$ substrate is affected both thermodynamically and mechanically.^{16,18} From the thermodynamic point of view, the explanations used for the agglomeration of Ni germanosilicide with low Ge content are still valid as Si is still the majority element in the $\text{Si}_{1-x}\text{Ge}_x$ substrate used. Compressive stress adversely affects the agglomeration in the Ni germanosilicide through a stress release mechanism. Ni germanosilicide acts as a fast diffusion medium of both Si and Ge atoms for releasing the stress, which at the same time affects the mechanical stability of the germanosilicide film.¹⁸ The compressive stress in a $\text{Si}_{1-x}\text{Ge}_x$ layer is

Figure 5. (Color online) Pole figures of (a) $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$, (b) $\text{Ni}(\text{Pt})_{0.1}(\text{Si}_{1-y}\text{Ge}_y)$, and (c) $\text{Ni}(\text{Pt})_{0.2}(\text{Si}_{1-y}\text{Ge}_y)$ after RTA at 500°C. The pole figures were taken at 2θ value of 30.13°, which corresponds to the (002) plane of the NiSi-based phase.

directly affected by the amount of Ge in the $\text{Si}_{1-x}\text{Ge}_x$. The presence of a Ge concentration gradient inside the condensed $\text{Si}_{1-x}\text{Ge}_x$ layer, as observed by the AES depth profiling analysis (Fig. 1) especially after a depth of 50 nm, results in a varying compressive stress with a maximum stress very near to the surface area (highest Ge content and then diminishes as a function of depth). The presence of the Ge gradient in the $\text{Si}_{1-x}\text{Ge}_x$ film is beneficial in alleviating the adverse

Figure 6. SEM micrograph of (a) the $\text{Ni}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ sample, (b) the $\text{Ni}_{1-u}(\text{Pt})_u/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ sample ($u = 0.1$), and (c) the $\text{Ni}_{1-u}(\text{Pt})_u/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ sample ($u = 0.2$) after annealing at 600°C. There is enhanced improvement in the morphological stability of the sample with increasing Pt concentration.

Figure 7. (Color online) Sheet resistance of the $\text{Ni}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ (■), $\text{Ni}_{1-u}(\text{Pt})_u/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ ($u = 0.1$) (●), and $\text{Ni}_{1-u}(\text{Pt})_u/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ ($u = 0.2$) (▲) samples after annealing at different annealing temperatures (400–700°C).

effect of stress release induced agglomeration, which usually occurs during the Ni germanosilicide formation on the fully strained $\text{Si}_{1-x}\text{Ge}_x$ film.

The morphological stability of the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ improves with the addition of more Pt alloying into the Ni film. As can be observed in Fig. 6c, the agglomeration of the $\text{Ni}(\text{Pt})_{0.2}(\text{Si}_{1-y}\text{Ge}_y)$ film is still suppressed up to 600°C annealing compared to that of 10% Pt (Fig. 6b), whereas the surface morphology of the pure-Ni sample has badly agglomerated (Fig. 6a). This indicates that the agglomeration of the $\text{Ni}(\text{Pt})_{0.2}(\text{Si}_{1-y}\text{Ge}_y)$ film is further delayed to higher temperatures of approximately 50–100°C higher than the sample with 10 atom % Pt, which has gained a 100°C stability compared to pure Ni. Figure 7 compares the sheet resistances of the pure-Ni germanosilicide with those of the Ni germanosilicide with 10 and 20 atom % of Pt alloying. The sheet resistance of the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ sample reaches the lowest value after annealing at 400°C. It gradually increased with annealing temperature before it rose abruptly to a very high value of 57.3 $\Omega/\square$ after annealing at 700°C. This is caused by an agglomeration of the $\text{Ni}(\text{Si}_{1-y}\text{Ge}_y)$ film, which occurred after annealing at 500°C and above. The presence of the Pt atoms did not affect the resistivity of the growing silicide because, at 500°C annealing, the sheet resistance of all samples has comparable values. The samples with Pt alloying have a considerably higher thermal stability as compared to the pure-Ni sample. However, clearly the sheet resistance of the 10 atom % Pt sample gradually departs from that of the 20 atom % Pt sample toward a larger value, indicating that the morphological stability of $\text{Ni}(\text{Pt})$ germanosilicide of the 10 atom % Pt alloying sample degrades at a lower temperature than that of the sample with 20 atom % Pt alloying.

Conclusion

The presence of a Ge gradient in the SiGe substrate as a function of depth resulted in a partial relaxation of the SiGe layer, which

improves the morphological stability of the germanosilicide through the elimination of the compressive stress. Slow diffusion of Pt atoms during the $\text{Ni}(\text{Pt})$ germanosilicide formation resulted in the formation of $\text{Ni}(\text{Pt})$ germanosilicide film with varying lattice parameters, with its biggest near the surface and its smallest near the substrate. Alloying with higher Pt concentration resulted in highly textured grains with a better morphological stability of the $\text{Ni}(\text{Pt})$ germanosilicide sample. The dominant texturing orientation of the $\text{Ni}(\text{Pt})$ germanosilicide grain was in the (002) direction, which is parallel to the substrate surface $\text{Si}(001)$.

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