Mat. Res. Soc. Symp. Proc. Vol. 745 © 2003 Materials Research Society

Low Thermal Budget NiSi Films on SiGe Alloys

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ABSTRACT

Nickel silicides were formed on Si (100) substrates and CVD grown $Si_{0.9}Ge_{0.1}$/Si layers by low thermal budget annealing of evaporated Ni films to evaluate their utility for ultra shallow junctions. The phase formation and microstructure of silicides formed using conventional furnace and rapid thermal annealing were studied by x-ray diffraction, Rutherford backscattering (RBS), x-ray photoelectron spectroscopy (XPS) and atomic force microscopy. RBS simulations and XPS study revealed the formation of a ternary nickel germanosilicide phase for the SiGe alloy. The incorporation of Ge resulted in a higher temperature window for the stability of low-resistive monosilicide phase. Electrical properties of the grown silicides were characterized by four-probe resistivity and contact resistance measurements.

INTRODUCTION

Group-IV heterostructures based on strained $Si_{1-x}Ge_x$ alloys have become increasingly attractive for high-performance silicon HBT, CMOS, and infrared detector devices. A suitable metal silicide with a low silicidation temperature and Si consumption ratio is essential for processing SiGe ultra-shallow junction devices [1]. Although $TiSi_2$ and $CoSi_2$ are widely used in silicon technology, there are limitations for both the silicides for aggressively scaled ULSI devices [2,3]. An increase in sheet resistance has been reported for $TiSi_2$ when the lines are narrower than 0.35 μm and the phase transformation from the high-resistivity C49 to low resistivity C54-$TiSi_2$ phase is nucleation-limited in narrow lines [2]. On the other hand, the formation of $CoSi_2$ is sensitive to cleaning and ambient contamination since Co cannot reduce SiO_2. NiSi with a low resistivity of 10~14 μΩ.cm, a large formation window of 350-750°C, and lowest Si consumption (0.82) ratio compared to other commonly studied silicides such as $TiSi_2$ (0.9) and $CoSi_2$ (1.04) is an attractive choice [4,5] for ohmic contacts on shallow junction $Si_{1-x}Ge_x$ heterostructure devices.

In this paper, we present the fabrication and characterization of nickel silicide films formed using low thermal budget furnace and rapid thermal annealing that are suitable for SiGe based device applications. The interfacial reactions of Ni with Si and $Si_{1-x}Ge_x$ films in the temperature range of 400-800°C have been studied. The sheet resistivity and contact resistance of the silicides on Si and SiGe heterostructures are presented.

EXPERIMENTAL

Single crystal float-zone (10-20 kΩ-cm) p-Si (100) substrates and atmospheric pressure CVD grown 0.5 μm thick relaxed $Si_{0.9}Ge_{0.1}$ layers were used in the present study. Following the conventional chemical cleaning, the samples were dipped in 1% HF solution to remove the native oxide layer just before loading into the Ni deposition chamber. Nickel of about 70 to 150 nm thick was deposited on the samples by thermal evaporation at a base pressure of 5×10^{-7} Torr. Ni/Si and Ni/ $Si_{0.9}Ge_{0.1}$ bilayer structures were annealed isothermally in a conventional horizontal tube furnace and in a Heatpulse rapid thermal processing (RTP) system to form silicides at temperatures ranging from 400^{o}C to 800^{o}C in N_2 ambient. The annealing time for furnace annealed sample was 45 mins and that for the RTP was 60 sec with a ramp rate of 100^{o}C/sec. The phase formation and microstructure of binary silicide and ternary nickel germanosilicide at different annealing conditions were studied using x-ray diffraction, Ruhtherford back scattering (RBS), X-ray photoelectron spectroscopy (XPS), and atomic force microscopy (AFM). Electrical properties of the grown silicides were characterized by four-probe resistivity and contact resistance measurements.

RESULTS & DISCUSSION

Figure 1 shows the XRD spectra of nickel silicide films formed at different temperatures using rapid thermal annealing. The curve (a) in figure 1 for 400^{o}C annealed Ni film on Si substrate shows the formation of Ni-rich silicide (Ni_2Si) phases oriented in different directions. A mixture of NiSi and Ni_2Si phases is observed on annealing the samples at 500^{o}C [curve (b)]. As indicated in Fig. 1(c), complete transformation from Ni_2Si to NiSi phase takes place only on annealing at 600^{o}C. The preferred orientations of NiSi are in (202), (112) and (011) directions. At a higher annealing temperature (800^{o}C), the sample exhibits the formation of Si-rich disilicide phase [figure 1(d)] in different orientations.

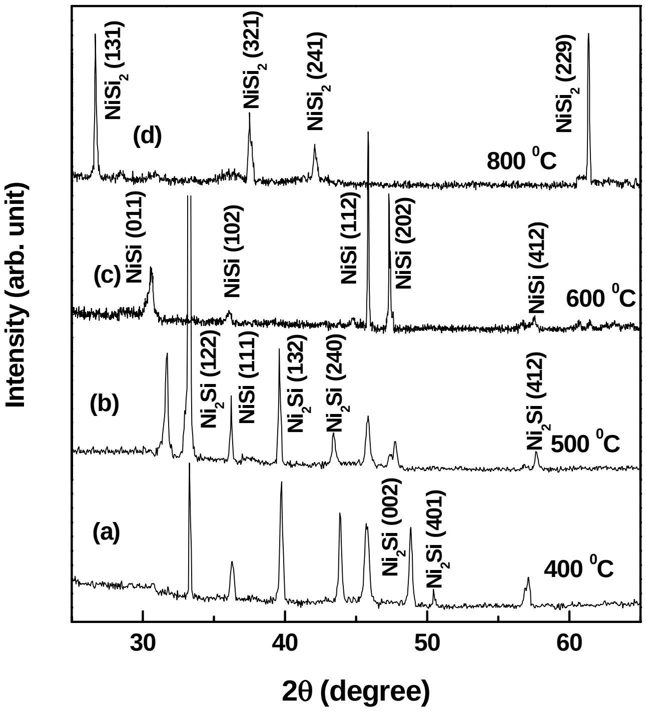

Figure 1 X-ray diffraction spectra of nickel silicide films formed on float zone Si at different temperatures by rapid thermal annealing.

X-ray diffraction spectra of Ni/$Si_{0.9}Ge_{0.1}$ samples annealed by RTP at temperatures ranging from 500^{o}C-700^{o}C are shown in figure 2. The X-ray spectrum of 500^{o}C annealed sample shows dominant peaks having a crystal structure similar to Ni_2Si. The complete transformation to a low resistive nickel germanosilicide $Ni(Si_{0.9}Ge_{0.1})$ ternary phase is observed in the sample only on annealing at 700°C. In contrast, the complete transformation to its monosilicide phase takes place at 600°C for Ni on Si. Therefore, the presence of Ge in Si increases the activation energy for monosilicide formation.

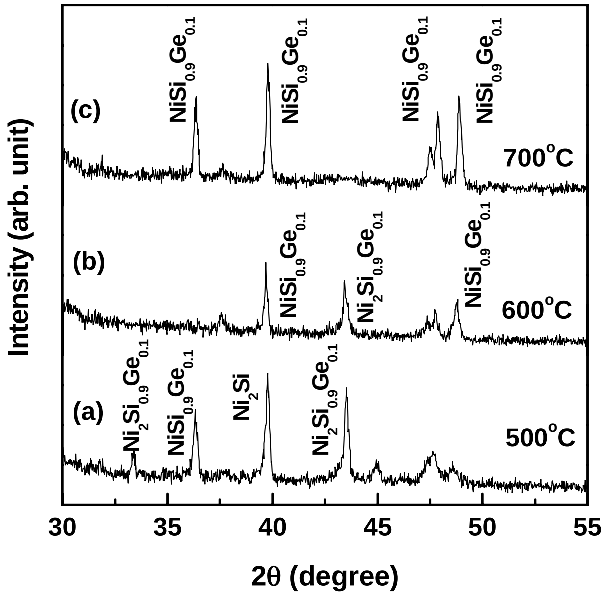

Figure 2 X-ray diffraction spectra for nickel germanosilicide films formed at different temperatures by rapid thermal annealing

Rutherford backscattering analysis has been carried out to estimate the composition and thickness of silicide films. Backscattering spectra (open triangles), shown in figure 3 are from annealed $Ni/Si_{0.9}Ge_{0.1}$ samples. Simulation of the back-scattered spectra [solid lines] has been

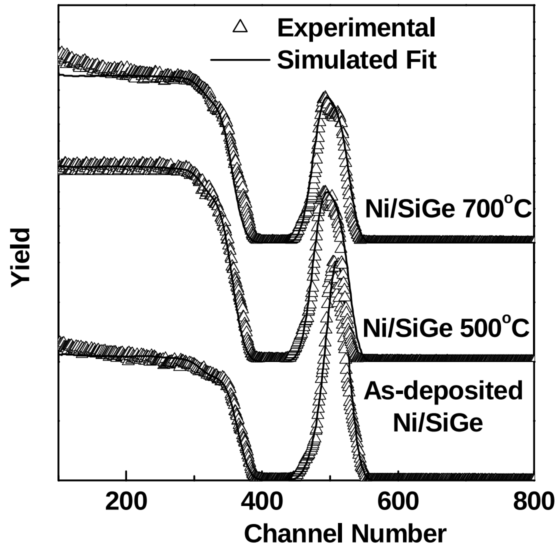

Figure 3 RBS spectra of annealed nickel germanosilicide films

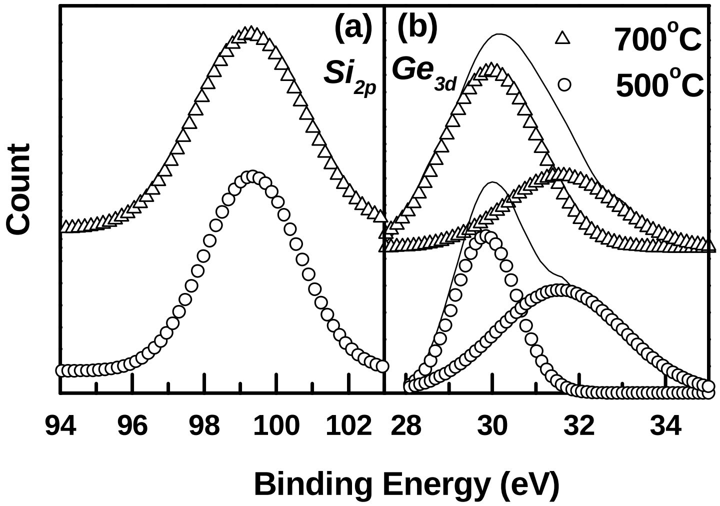

Figure 4 XPS binding energy of (a) Si 2p and (b) Ge 3d electrons of nickel germanosilicide films.

carried out to obtain the thickness and composition of different layers. Experimentally obtained RBS data match very well with the simulated curves by considering the presence of a ternary germanosilicide phase [5] for Ni/$Si_{0.9}Ge_{0.1}$ structure. The simulation shows that the nickel-rich germanosilicide phase is dominant in 500°C annealed film. The complete transformation to nickel mono-germanosilicide phase on increasing the annealing temperature to 700°C in Ni/$Si_{0.9}Ge_{0.1}$ sample corroborates our XRD results.

XPS and AFM analysis

High-resolution x-ray photoelectron spectroscopy (XPS) measurements were made to investigate the chemical structure of the films from the shift of the core-level binding energy of constituent elements. An XPS (VG Scientific ESCALAB MK-II) spectrometer equipped with a concentric hemispherical analyzer with MgK_{α} radiation (12 keV, 10 mA) was used for the study. High-resolution spectra were recorded at a constant analyzer pass energy of 20 eV. In order to study the interfacial reactions between Ni and $Si_{1-x}Ge_x$, XPS analysis was performed using RTA annealed Ni/$Si_{0.9}Ge_{0.1}$/Si films. Any unreacted nickel was removed from the samples using piranha etch before XPS analysis. All the samples were *insitu* sputter-cleaned by using Ar^+ ion for 5 mins before analysis through which the presence of native oxide could be avoided. Figure 4 shows the XPS spectra of (a) Si *2p* and (b) Ge *3d* electrons of Ni/$Si_{0.9}Ge_{0.1}$ samples annealed at 500°C and 700°C using RTA. A chemical shift of Si *2p* by 0.2 eV with respect to the binding energy of bulk Si is observed. The Ge *3d* peak from the samples has been shown after the deconvolution of experimental spectra indicated by solid lines in figure 4(b). The deconvoluted spectra (open circles and triangles) show a peak at 29.9 eV for both the samples, which is related to the bulk Ge. The appearance of a new Ge 3d peak at an energy that is 1.6 eV higher than the bulk Ge indicates the incorporation of Ge into the silicides forming nickel germanosilicides.

The surface morphology of nickel silicide and nickel germanosilicide films was analyzed by atomic force microscopy (AFM). The variation of surface roughness with temperature for nickel silicide and nickel germanosilicides formed by furnace (FA) and rapid thermal annealing is shown in figure 5. The rms roughness of the as-deposited nickel films on Si and $Si_{0.9}Ge_{0.1}$ are measured to be 0.376 and 0.716 nm, respectively. In all the cases, the surface roughness increases with increasing annealing temperature. While the RTA samples show a saturation of the roughness, the same decreases with further increase in temperature for FA samples. The gradual increase of surface roughness of Ni/Si and Ni/SiGe samples with temperature is attributed to the formation of Ni_2Si and $Ni_2(Si_{0.9}Ge_{0.1})$ phases at lower annealing temperatures, and NiSi and $Ni(Si_{0.9}Ge_{0.1})$ phases at higher temperatures. Comparatively lower surface roughness in germanosilicide film indicates that Ge reduces the reaction rate of silicidation, which is beneficial for increasing the temperature window of the metastable monosilicide phase.

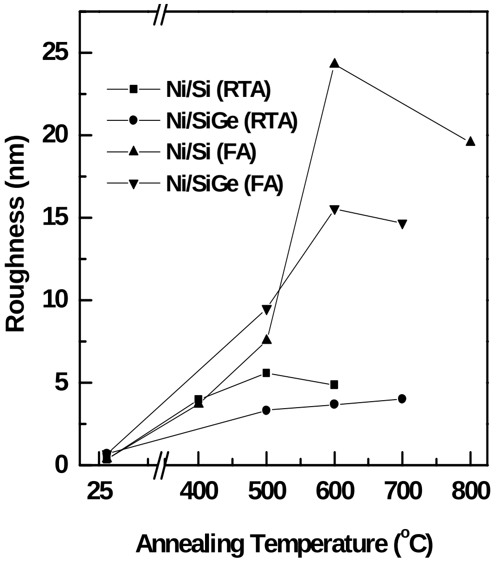

Figure 5 RMS roughness as a function of annealing temperature for Ni/Si and Ni/SiGe films annealed by RTA and in a furnace (FA).

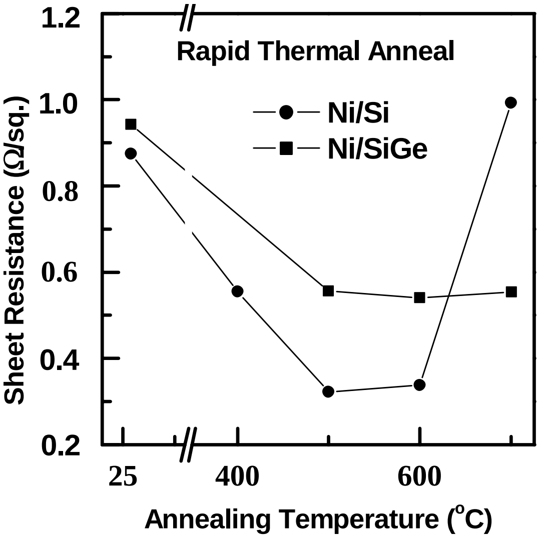

Figure 6 Sheet resistance vs. RTA annealing temperature of nickel silicide and nickel germanosilicide films.

Electrical properties

Figure 6 shows the sheet resistivity (ρ_s) of as-deposited Ni and RTA annealed Ni/Si and $Ni/Si_{0.9}Ge_{0.1}$ samples. The annealed samples exhibit a minimum resistivity in the temperature range between 500 and 600°C. A sharp drop in ρ_s is found as the annealing temperature is increased above 400°C, indicating the onset of conversion of Ni to NiSi or Ni(SiGe). The sheet resistance remains almost constant in the range of 500-600°C for all the samples, implying complete conversion into low-resistivity NiSi and Ni(SiGe) phases. The sheet resistance of NiSi samples rises sharply above 600°C. The increase is attributed to the formation of high-resistivity $NiSi_2$ phase [6], which has been identified by XRD and RBS analyses. The notable point is that resistivity of Ni/SiGe samples remain constant up to an annealing temperature of 700°C. Therefore, although NiSiGe exhibit higher resistivity compared to NiSi, the presence of Ge results in a higher temperature window for low-resistivity monosilicide phase.

Specific contact resistance associated with metal semiconductor contacts plays a crucial role in determining the parasitic series resistance of submicron semiconductor devices. Contact resistance was measured using the standard *transfer length method* (TLM). Each contact pad in the TLM pattern was 50 μm×100 μm with variable separation between them. The NiSi sample annealed at 600°C shows the lowest contact resistivity of 1.75×10^{-5} Ω.cm^2, which supports the formation of a good quality ohmic contact.

CONCLUSIONS

The formation of low thermal budget nickel silicides on Si and $Si_{0.9}Ge_{0.1}$ alloy has been studied for ultra shallow junction applications. Although NiSi is found to form at annealing temperatures as low as 400°C, the complete transformation to the low-resistivity NiSi phase only occurs at 600°C and at 700°C for $Si_{0.9}Ge_{0.1}$. Annealing at higher temperatures results in a Si-rich high-resistivity $NiSi_2$ phase. RBS simulations have revealed the formation of a ternary nickel germanosilicide phase for the SiGe alloy. A shift of the binding energy of Ge 2p electrons in XPS spectra confirms the incorporation of Ge into the silicide. AFM analysis of the films as a function of annealing temperature shows a slower grain growth in the Ge-incorporated layer as compared to the binary silicide, resulting in a higher temperature window for the monosilicide phase. This is corroborated by sheet resistivity measurements, where the low-resistivity temperature window is found to be higher for germanosilicides. Sheet and contact resistivities as low as 12-15 $\mu\Omega$-cm and 17.5 $\mu\Omega$.cm^2, respectively, have been obtained for the silicides.

ACKNOWLEDGEMENTS

This work is supported by Air Force funded DARPA contract: F19628-00-C-0005 under the Terahertz program.

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