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Material and Electrical Characterization of Nickel Germanide for *p*-channel Germanium Schottky Source/Drain Transistors

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Abstract

We have characterized the material and electrical properties of nickel germanide films as schottky source/drain contacts for Ge-MOSFETs. Ni-germanide phase formation, interfacial/surface morphologies and schottky barrier height are reported for Ni-germanide contacts formed by the solid state reaction of Ni and Ge. X-ray diffraction (XRD) confirmed that the Ni-germanide films formed in the temperature range of 250 – 600 °C are Ni-mono-germanide (NiGe). High resolution transmission electron microscopy (HRTEM) and XRD revealed the formation of highly textured NiGe films in domain epitaxy with the Ge(001) substrate. An extremely high barrier height, ~0.732 – 0.735 eV, was obtained in the NiGe/*n*-Ge(001) contacts. The observation of a Schottky barrier height larger than the bandgap (0.66 eV) of Ge indicates that NiGe is a promising Schottky S/D material for *p*-channel Ge MOSFETs.

I. Introduction

Germanium has attracted much attention as a channel material due to its higher and more symmetric low-field electron and hole mobilities [1]. Recent developments of high-κ dielectrics have led to the successful demonstration of devices employing ZrO_2 and HfO_2 gate dielectrics on Ge [2,3]. These results suggest the possibility of implementing Ge as a channel material to overcome the material limitations of Si. However, from the viewpoint of device fabrication, the low dopant solubility in Ge [4] and fast diffusion of dopants during dopant activation [5] complicate the use of conventional source/drain (S/D) junctions for Ge-MOSFETs. Therefore, integration of schottky S/D junctions for Ge-MOSFETs would be advantageous. In this paper, we report experimental results on Ni-germanide phase formation, interfacial/surface morphological evolution, and the observation of a Schottky barrier height (~0.732 -0.735 eV, obtained on NiGe on *n-type* Ge(001)) larger than the bandgap of Ge.

II. Experiments

Ge(001) *n-type* substrates (~ 0.4 Ω.cm) were used in this study. The substrates were cleaned using a dilute HF solution. Ni films of ~15 nm were then deposited by magnetron sputtering in Ar ambient with a base pressure < 5×10^{-7} torr. The current-voltage (*I-V*) characteristics were measured using circular shaped NiGe-Ge(001) junctions with an area of 7.85×10^{-3} cm^2 patterned with a shadow mask. After sputter deposition, the structures were subjected to rapid thermal anneal (RTA) in N_2 ambient at 250 – 700 °C for 20 s.

III. Results and Discussions

Interfacial microstructures of the 15 nm Ni/*n-type* Ge (001) system after RTA from 250 to 500 °C are given in Fig.1. Fig. 1(a) shows the coexistence of two phases after 250 °C: a continuous film in contact with the substrate and discrete particles with a darker contrast adjacent to the free surface. Point analysis of the former layer by EDX confirmed the formation of NiGe after 250 °C. This is further confirmed by electron diffraction of this phase (see inset in Fig.1(a)). Uniform thickness and a smooth interface with the Ge (001) substrate are the two distinctive features of this continuous film. The exact nature of the germanide particles with a darker contrast is still being investigated but these particles are suspected to be Ni-rich germanide. These randomly distributed particles were also found to decrease in density and size after 300 °C RTA. With higher annealing temperatures, only an uninterrupted NiGe film could be seen with the development of severe grain boundary grooving, especially at the substrate side after 500 °C RTA, i.e., the onset temperature for film agglomeration (i.e., breaking up of the film, see inset of Fig.1(d)), resulted in the drastic increase in sheet resistance (see Fig.2).

Fig. 3 shows the XRD spectra of the annealed NiGe film obtained in the XRD Bragg-Brentano configuration, which reveals the highly textured nature of the NiGe film with certain orientation relationships: (111) NiGe || Ge (001) and (002) NiGe || Ge (001) being dominant after 400 °C RTA. It is interesting to note the intensity of the (002) peak increases and the (111) peak decreases with increasing temperature. Detailed analysis of XRD pole figure (see Fig. 4) further unveils that the highly textured NiGe film is in domain epitaxy with the Ge(100) substrate, i.e., NiGe grains having preferred epitaxial orientation relationships of NiGe(111)[$1\bar{1}0$]||Ge(001)[110] or NiGe (002)[110]||Ge (001)[110]. This is in agreement HRTEM analysis of the NiGe film as shown in Fig. 5.

NiGe/*n*-Ge(100) junctions annealed at 400 °C was found to possess the best NiGe film quality based on the material analysis conducted and electrical characterization was performed on these samples. Fig 6 shows the typical *I-V* plots of NiGe/*n*-Ge(001) and it can be seen that the plots are almost identical and linear under forward bias but exhibits an appreciable amount of scatter under reverse bias. In addition, an ideality factor of 1.02 is obtained from the *I-V* measurements. This suggests that the dominant carrier transport at these junctions consists of majority electrons across the NiGe-Ge schottky barrier. Fig. 7 shows the Richardson plots of forward saturation current I_s and reverse current at -0.2 V. An effective barrier height ~ 0.735 eV is obtained from the Richardson plot of I_s while an activation energy of 0.732 eV is extracted from the ln($I(V_c = -0.2\text{V})$) vs. 1000/T plot. The extremely high Schottky barrier height (~ 0.732 - 0.735 eV), which is larger than the bandgap (0.66 eV) of Ge, implies that NiGe forms a negative barrier to inverted *p*-channel, thus making it an ideal candidate as Schottky S/D material for Ge-based *p*MOSFETs. It must be pointed out that the actual barrier height in NiGe/*n*-Ge(001) is probably even larger than the measured value ~ 0.732 -0.735 eV due to the substantial reduction in barrier height by the presence of extremely high electrical field at metal/semiconductor interface (because of minority carrier accumulation). It is also worthy to note that a work-function value of 5.2 eV was reported previously for NiGe[6], which gives a Schottky barrier of 1.2 eV for NiGe/*n*-Ge(001) if simple Schottky-Mott model is applied.

IV. Summary

Nickel germanide films are explored for integration as schottky source/drain contacts in Ge-MOSFETs. The excellent epitaxial NiGe-Ge(100) interface formed is probably responsible for the high electron barrier height ~0.732 -0.735 eV extracted for the NiGe/*n*-Ge(100) junctions. The observation of a barrier height larger than bandgap in NiGe/*n*-Ge implies that NiGe is an ideal schottky source/drain contact in *p*-channel Ge-MOSFETs due to the absence of an energy barrier between NiGe and *p*-Ge.

References

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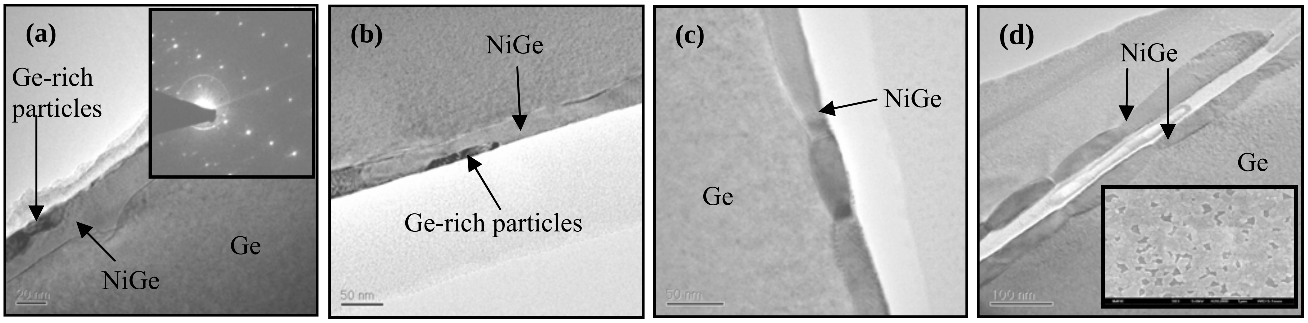

Fig. 1 Interfacial microstructure evolution of NiGe-Ge(100) interface after rapid thermal annealing at (a) 250 °C, (b) 300 °C, (c) 400 °C, (d) 500 °C. Inset in (a) shows the electron diffraction micrograph of Ni films annealed at 250 °C, which confirms the formation of nickel mono-germanide. Inset in (d) shows the plane-view SEM image obtained for Ni films annealed at 500 °C with exposed Ge observed indicated by the darker regions.

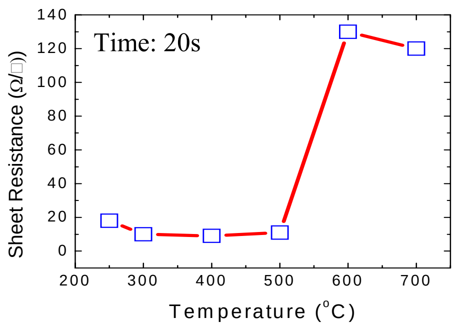

Fig. 2 Sheet resistance values measured on NiGe films as function of RTA germanidation temperatures.

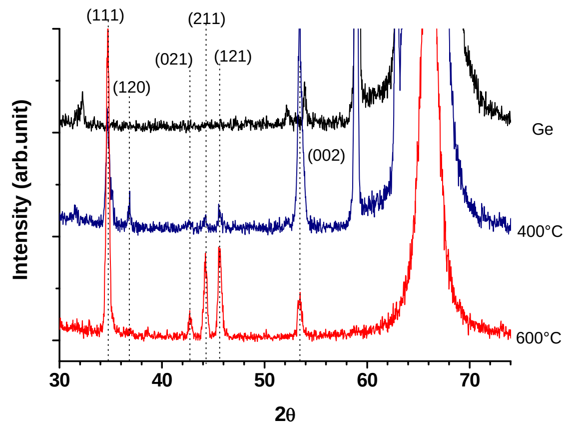

Fig. 3 XRD in the Bragg-Brentano configuration for Ge(100) substrate and NiGe RTA at 400 °C and 600 °C.

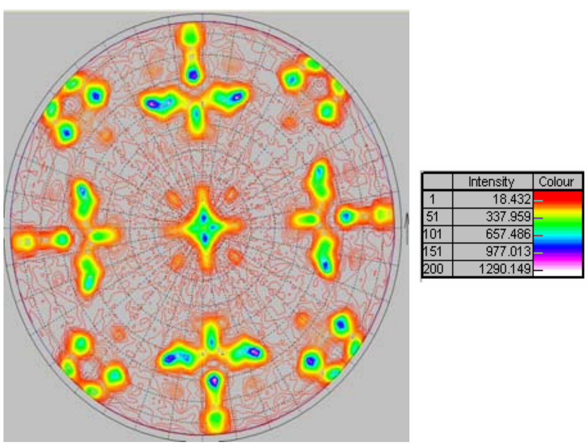

Fig. 4 X-ray pole figure of NiGe RTA at 400 °C taken at the (111) diffraction plane

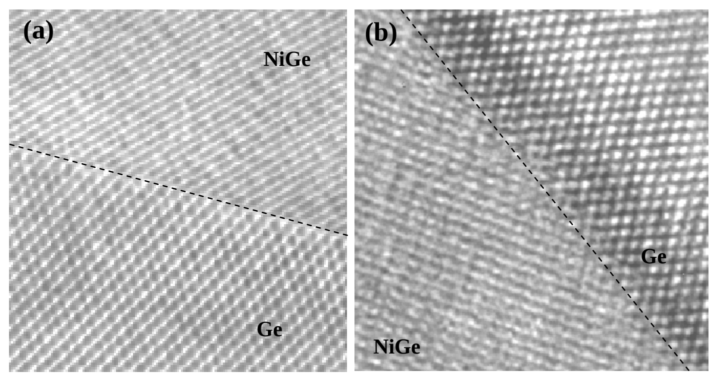

Fig. 5 HRTEM cross-sectional micrograph of NiGe RTA at 400 °C (a) (001) plane and (b) (111) plane parallel to the substrate (100) plane.

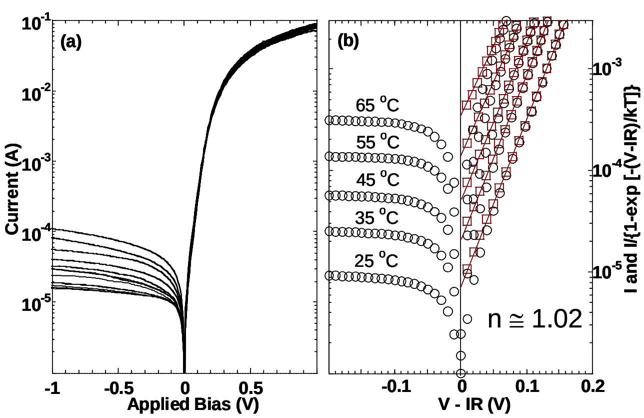

Fig. 6 (a) Typical log*I*-*V* curves measured on different NiGe/*n*-Ge(100) junctions at 25 °C. (b) Temperature-dependent *I*-*V* (labeled with □ symbol) and *I*/(1-exp(-(*eV*-*IR*)/*kT*) vs. *V*-*IR* (labeled with O symbol) semi-log plots measured on the NiGe/*n*-Ge(100) junctions with lowest leakage current. *R* is the series resistance calculated from the linear *I* – *V* plots at high currents and was found to be in the range of 8.4 – 10.4 Ω.

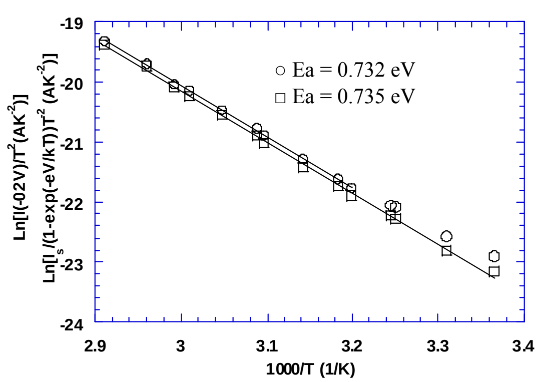

Fig. 7 Richardson plots of forward saturation current I_s (labeled with □ symbol) and reverse current at -0.2 V (labeled with O symbol) measured on the diode with lowest leakage current.