Epitaxial Nickel Distanogermande [Ni(Ge$_{1-x}$Sn$_x$)$_2$] Contact Formation using Pulsed Laser Annealing

Xin Xu, Wei Wang, Yuan Dong, Eugene Yu Jin Kong, Xiao Gong, Qian Zhou, Genquan Han, Pengfei Guo, Lanxiang Wang, and Yee-Chia Yeo.*

Department of Electrical and Computer Engineering, National University of Singapore (NUS), Singapore 117576.
*Phone: +65 6516-2298, Fax: +65 6779-1103, E-mail: yeo@ieee.org

I. Introduction

Germanium tin (Ge$_{1-x}$Sn$_x$) alloy has attracted great attention as a channel material of MOSFETs for future low power and high performance logic applications, owing to its high carrier mobility [1-3]. Ge$_{1-x}$Sn$_x$ channel n-MOSFETs were recently demonstrated [4], and metallic Ni contacts n Ge$_{1-x}$Sn$_x$ S/D were used. To achieve high drive current, metal contacts with low Schottky barrier height (SBH) are needed to realize small contact resistance. Recently, laser annealing (LA) technique was used to form NiGe$_2$/n-Ge contact [5], and reduced effective electron SBH was demonstrated [6]. However, there have been no reports on Ni(Ge$_{1-x}$Sn$_x$)$_2$ formation using LA. Ni(Ge$_{1-x}$Sn$_x$)$_2$/n-Ge contacts are not well investigated.

In this paper, laser annealing technique, for the first time, was applied to form a continuous, uniform and epitaxial nickel distanogermande [Ni(Ge$_{1-x}$Sn$_x$)$_2$] film. In addition, Schottky diodes were fabricated to investigate the electrical property of the Ni(Ge$_{1-x}$Sn$_x$)$_2$ contacts on n-GeSn. Reduced effective electron SBH was achieved for laser-annealed sample as compared with the rapid-thermal-annealed one.

II. Ni(Ge$_{1-x}$Sn$_x$)$_2$ Formation and Characterization

A. As-grown Ge$_{1-x}$Sn$_x$

Ge$_{1-x}$Sn$_x$ films were epitaxially grown on p-type Ge (100) substrate using solid source molecular beam epitaxy (MBE) system at 170°C. Cross-sectional TEM image of a 38 nm-thick Ge$_{1-x}$Sn$_x$ layer is shown in Fig. 1(a). High resolution TEM (HRTEM) image in Fig. 1(b) shows defect-free Ge$_{1-x}$Sn$_x$/Ge interface and high crystallinity of Ge$_{1-x}$Sn$_x$ film. The substitutional Sn composition is 3.5% and the Ge$_{0.96}$Sn$_{0.04}$ layer is fully strained, as determined by high resolution XRD (HRXRD) image in Fig. 1(c).

B. Epitaxial Ni(Ge$_{1-x}$Sn$_x$)$_2$

After cyclic cleaning of the as-grown Ge$_{1-x}$Sn$_x$/Ge samples in DHF (H$_2$O:1=50) and DI water, 15 nm-thick Ni was deposited by sputtering. 10-pulse laser annealing (λ = 248 nm, FWHM = 23 ns) with the fluence of 300 mJ/cm$^2$ per pulse was performed in N$_2$ ambient to form Ni(Ge$_{1-x}$Sn$_x$)$_2$. The control sample was rapid-thermal-annealed at 350°C for 30 s.

Fig. 2 (a) and (b) show the XRD general area detector diffraction system (GADDS) scan of Ni(Ge$_{1-x}$Sn$_x$)$_2$ film formed by LA and rapid thermal annealing (RTA), respectively. Spots with strong intensity in Fig. 2(a) indicate that a single-crystalline film was formed by LA. The inset of Fig. 2(a) shows the integrated diffraction intensity as a function of 2θ. Two distinct Ni(Ge$_{1-x}$Sn$_x$)$_2$ peaks were identified. In contrast, diffraction rings in Fig. 2(b) indicate that a poly-crystalline Ni(Ge$_{1-x}$Sn$_x$)$_2$ film was formed by RTA. Fig. 3 shows the TEM image of a 62 nm-thick Ni(Ge$_{1-x}$Sn$_x$)$_2$ layer formed using LA. The entire Ge$_{1-x}$Sn$_x$ film was consumed during the LA step. The inset HRTEM image of interface region shows that the formed Ni(Ge$_{1-x}$Sn$_x$)$_2$ film is epitaxial. Clear epitaxial alignments between the Ni(Ge$_{1-x}$Sn$_x$)$_2$ film and the underlying substrate were observed. SIMS depth profile of Ni, Ge, and Sn for the laser-annealed Ni(Ge$_{1-x}$Sn$_x$)$_2$/Ge(100) sample is shown in Fig. 4. Microscopic four-point probe was used for sheet resistance ($R_s$) measurement. Fig. 5 shows the contour plot of $R_s$ measured in a 1 mm × 1 mm area of the 62 nm-thick Ni(Ge$_{1-x}$Sn$_x$)$_2$

film. $R_s$ values range from 8.7 to 9.3 Ω, indicating good uniformity of the Ni(Ge$_{1-x}$Sn$_x$)$_2$ film resistivity.

III. Ni(Ge$_{1-x}$Sn$_x$)$_2$/n-GeSn Schottky Diode

A. Device Fabrication

The key process steps for fabricating the Ni(Ge$_{1-x}$Sn$_x$)$_2$/n-GeSn diode are shown in Fig. 6. After epitaxial growth of 120 nm-thick Ge$_{0.977}$Sn$_{0.023}$ film, a phosphorus implant was carried out with a dose of 1×10$^{15}$ cm$^{-2}$ at energies of 50, 130 and 250 keV. Dopant activation was performed using RTA at 400°C for 5 minutes. After that, a 50 nm-thick SiO$_2$ isolation layer was deposited and patterned to open the active region. This was followed by the sputtering of 15 nm-thick Ni. Here, two splits were introduced in the Ni(Ge$_{1-x}$Sn$_x$)$_2$, formation step: RTA at 350°C for 30 s and 10-pulse LA at the fluence of 300 mJ/cm$^2$ per pulse. Unreacted Ni was then removed by concentrated sulfuric acid. Finally, a 200 nm-thick Al layer was deposited on the backside of the samples.

B. Electrical Characteristics

Ni(Ge$_{1-x}$Sn$_x$)$_2$/n-GeSn Schottky diodes with an active area of 75 × 75 µm$^2$ were characterized. Fig. 7 shows the I-V characteristics of Ni(Ge$_{1-x}$Sn$_x$)$_2$/n-GeSn diodes formed by LA and RTA, with the inset illustrating the Ni(Ge$_{1-x}$Sn$_x$)$_2$/n-GeSn Schottky diode structure. The reverse current of laser-annealed sample is 30 times higher than that of the rapid-thermal-annealed one at a bias of -1 V. The increased reverse current indicates that a lower effective electron SBH was achieved using LA. Fig. 8 shows the cumulative probability plot of the reverse current at a biased voltage of -1 V for laser-annealed samples and rapid-thermal-annealed ones, respectively. The tight distribution of reverse current density indicates good device-to-device uniformity for both splits.

IV. Conclusion

We report the first formation of a uniform and epitaxial Ni(Ge$_{1-x}$Sn$_x$)$_2$ film using pulsed laser annealing. Compared to the rapid-thermal-annealed Ni(Ge$_{1-x}$Sn$_x$)$_2$/n-GeSn contact, a higher reverse current was achieved in the laser-annealed Ni(Ge$_{1-x}$Sn$_x$)$_2$/n-GeSn contact, indicating a reduction in effective electron Schottky barrier height at Ni(Ge$_{1-x}$Sn$_x$)$_2$/GeSn interface.

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Reference

Fig. 1. (a) Cross-sectional TEM image of an epitaxial Ge\textsubscript{0.965}Sn\textsubscript{0.035} film grown on the Ge(100) substrate. (b) HRTEM image shows defect-free interface. (c) HRXRD (004) and (224) curves show well-defined Ge\textsubscript{0.965}Sn\textsubscript{0.035} peaks and a fully strained epitaxial Ge\textsubscript{0.965}Sn\textsubscript{0.035} layer.

Fig. 2. XRD GADDS scan of Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2} film formed by (a) 10-pulse laser annealing (LA) at the fluence of 300 mJ/cm\textsuperscript{2} per pulse and (b) rapid thermal annealing (RTA) at 350 °C for 30 s. Spots with strong intensity in (a) indicate a single-crystalline Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2} film was formed by LA. The inset of Fig. 2(a) shows the integrated diffraction intensity as a function of 2θ. Two distinct Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2} peaks were identified. Diffraction rings in (b) indicate that a polycrystalline Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2} film was formed by RTA.

Fig. 3. TEM image of a 62 nm-thick Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2} layer formed using LA. The inset shows HRTEM image of a single-crystalline epitaxial Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2} layer formed on Ge.

Key Process Steps:
- MBE growth GeSn (~120 nm) on n-type Ge (100) substrate
- Phosphorous Implant and Activation
- SiO\textsubscript{2} Deposition (~50 nm)
- Active Region Opening
- Ni Deposition (~15 nm)
- Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2} Formation
  - Splits: 1. Rapid Thermal Annealing 350 °C, 30 s
  - 2. Pulsed Laser Annealing 300 mJ/cm\textsuperscript{2}, 10-pulse
- Unreacted Metal Removal by H\textsubscript{2}SO\textsubscript{4}
- Al Deposition on backside (~200 nm)

Fig. 4. SIMS depth profile of Ni, Ge, and Sn for the laser-annealed Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2}/Ge(100) sample. The Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2}/Ge interface is observed 62 nm under the surface.

Fig. 5. Contour plot of R\textsubscript{A} measured in a 1 mm × 1 mm area of the Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2} film formed using LA. R\textsubscript{A} values range from 8.7 to 9.3 Ω, indicating good uniformity of the Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2} film.

Fig. 6. Key process steps for fabricating the Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})/n-GeSn(100) Schottky diode. Two splits were introduced in the Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})\textsubscript{2} formation step: RTA at 350 °C for 30 s and 10-pulse LA at the fluence of 300 mJ/cm\textsuperscript{2} per pulse.

Fig. 7. I-V characteristics of Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})/n-GeSn(100) diode with an active area of 75 × 75 μm\textsuperscript{2} formed by LA and RTA. The reverse current of laser-annealed sample is 30 times higher than that of the rapid-thermal-annealed one at a bias of -1 V. The inset shows the schematic of a Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})/n-GeSn Schottky diode.

Fig. 8. Cumulative probability plot of the reverse current at a biased voltage of -1 V for Ni(Ge\textsubscript{1-x}Sn\textsubscript{x})/n-GeSn diodes formed by LA (red square) and RTA (blue circle), respectively.