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Realization of hole gas accumulation in p-Si/i-Ge core-shell and p-Si/i-Ge/p-Si core-double shell nanowires

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Abstract

Core-shell nanowires (NWs) fabricated by silicon (Si) and germanium (Ge) with high carrier mobilities have been suggested as building blocks to be as the channel materials for realizing vertical-type metal-oxide-semiconductor field-effect transistors (MOSFETs) with high speed and low energy consumption. Impurity doping in the core or shell is essential to give a function in MOSFETs whereas impurity scattering need to be considered. To suppress the impurity scattering, high electron mobility transistor (HEMT) structures has to be formed in core-shell NWs. In this study, we synthesized p-Si/intrinsic (i)-Ge core-shell NWs. By applying selective doping and realizing sharp interface, we could detect hole gas accumulation in the i-Ge shell region, meaning that carrier transport region can be separated from the impurity doped region. p-Si/i-Ge/p-Si core-double shell NWs were also fabricated to more clearly demonstrate the hole gas accumulation and its enhancement in the i-Ge layer. These results show that impurity scattering can be effectively suppressed by using core-shell structures.

1. Introduction

One-dimensional (1D) structure with nanoscale diameters such as NWs has excellent potential for the application of next-generation semiconductor devices such as transistors, solar cells, sensors and so on. Si and Ge NWs, with high electron and hole mobilities, offer many advantages for realizing high-performance novel vertical-type MOSFETs. The unique configurations of Si/Ge core-shell NWs have recently attracted significant attention because carrier transport region and impurity doped region can be separated, and finally the impurity scattering can be suppressed [1,2].

In this work, we used chemical vapor deposition (CVD) methods based on the vapor-liquid-solid (VLS) growth mechanism to fabricate p-Si/i-Ge core-shell NWs with different B_2H_6 gas fluxes. The structure showed good crystallinity that performed by transmission electron microscopy (TEM) with energy-dispersive X-ray (EDX) measurement. Stress and doping effect in the core-shell structures were characterized by X-ray diffraction (XRD) measurement. Micro-Raman scattering measurements were carried out at room temperature (RT) with 532 nm excitation light, demonstrating hole gas accumulation in the i-Ge shell region of p-Si/i-Ge core-shell NWs. To confirm this result, p-Si/i-Ge/p-Si core-double shell NWs were fabricated. The hole gas accumulation clearly showed the enhancement in the i-Ge layer.

2. Experiments

p-Si/i-Ge core-shell NWs were grown on Si (111) wafers by CVD method. Prior to CVD process, Si substrates were cleaned using acetone, ethanol, H_2O_2:HSO_4=1:3 (at 120 °C for 20 min), and DI-water, respectively. Hydrogen fluoride (HF) was further used to remove the native oxide on Si surface. Then, gold nanocolloid seeds were deposited on the sample surface as catalysts for VLS growth of SiNWs. SiH_4 (100 %), GeH_4 (100 %), and B_2H_6 (1% in H_2) gases were used for p-Si/i-Ge core-shell NW formations. The core p-Si NWs with various B doping concentrations were grown at 600 °C. SiH_4 gas flux of 19 sccm with various B_2H_6 gas fluxes from 0 sccm to 0.5 sccm were supplied. The total chamber pressure was controlled at 800 Pa. After that, i-Ge shell layer was continuously formed with various thicknesses controlled by various growth times of 15 s to 90 s at 500 °C and GeH_4 gas flux of 10 sccm. STEM and TEM measurement with EDX mapping were used to observe detailed structures of the p-Si/i-Ge core-shell NWs and to detect element contents in the structures. XRD measurements with Cu Kα radiation were used to analyze the individual stress relation between the p-Si core NW and the i-Ge shell layer. The XRD data were collected with parallel beam optics on the Panalytical X'Pert Pro MRD equipment. Micro-Raman scattering measurements were performed to investigate the doping effect and the stress caused by the heterostructures. The measurements were carried out at RT using 100× objective and 532 nm excitation light source. The excitation power of 0.02 mW was applied to avoid local heating effects by excitation laser. The spectral resolution was around 0.25 cm^{-1}.

3. Results and discussion

Figure 1 showed the schematic of p-Si/i-Ge core-shell NWs grown by CVD process. The random deposition of Au catalyst decided the NW growth density and distribution. Then, the formation of p-Si/i-Ge NWs were grown by flowing SiH_4, B_2H_6 and GeH_4 gas fluxes. Figures 2a and 2b showed the TEM images of p-Si/i-Ge core-shell NW with low and high resolution. The high resolution TEM image exhibited clear lattice fringes, demonstrating high crystallinity of the core-shell NW structure. Both of core p-Si NW and i-Ge shell layer showed single crystal structures. To characterize the formation of core-shell structure, STEM (Figure 2c) and EDX measurements (Figures 2d) were carried out. In EDX mapping images, the red and green colors represent Si and Ge layers, respectively. These images clearly show the formation of Si/Ge core-shell NWs. The Si lattice constant observed by

XRD was increased with increasing the shell growth time when the shell growth time is shorter than 60 s, indicating that the tensile stress from the i-Ge shell layer increases with increasing the shell growth time. Contrary to the i-Ge shell layer, the lattice constant of core Si NWs depends on the B_2H_6 gas flux. This can be explained by the lattice contraction due to the B doping into the core Si NWs because the B atom has a smaller diameter than the Si atom. Figure 3 shows the Ge optical phonon peaks of p-Si/i-Ge core-shell NWs shifted to lower wavenumbers with increasing the B concentration in the p-Si region, which were attributed to Fano effect that caused by hole gas accumulation in Ge shell layer [1,2]. The optical phonon peak related to GeSi alloy was not clearly observed at around 400 cm^{-1}, indicating no intermixing of Ge and Si layers at the interface of core-shell NWs. Figure 4 shows the comparison of the Ge optical phonon peaks observed for p-Si/i-Ge core-shell NWs and p-Si/i-Ge/p-Si core-double shell NWs. The Ge optical phonon peak of p-Si/i-Ge/p-Si core-double shell NWs showed more downshift and asymmetric broadening compared to that of p-Si/i-Ge core-shell NWs. This result clearly shows the increase of hole gas accumulation by forming the outer p-Si shell layer.

4. Conclusions

We fabricated the p-Si/i-Ge core-shell NWs on Si (111) substrate by CVD method. To realize HEMT type devices, selective doping and sharp interface between the Si core and the Ge shell were realized. The downshift and asymmetric broadening were observed by Raman scattering measurement, which were attributed to Fano effect. The hole gas accumulation in the i-Ge shell regions were demonstrated, indicating the carrier transport region can be separated from the impurity doped region by forming the core-shell NW structure. Moreover, the p-Si/i-Ge/p-Si core-double shell NWs were grown, which showed the enhancement of Fano effect. This result clearly demonstrates the realization of HEMT type structures in p-Si/i-Ge core-shell NWs.

References

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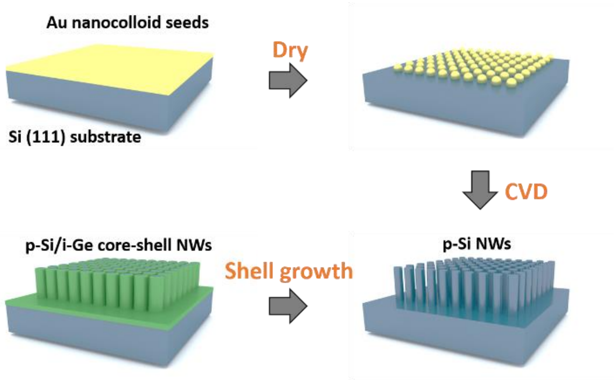

Figure 1. The schematic of p-Si/i-Ge core-shell NWs CVD

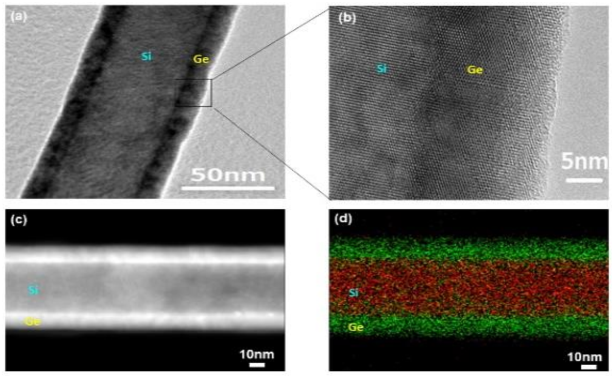

Figure 2. (a) Low and (b) high resolution TEM images of p-Si/i-Ge core-shell NW.

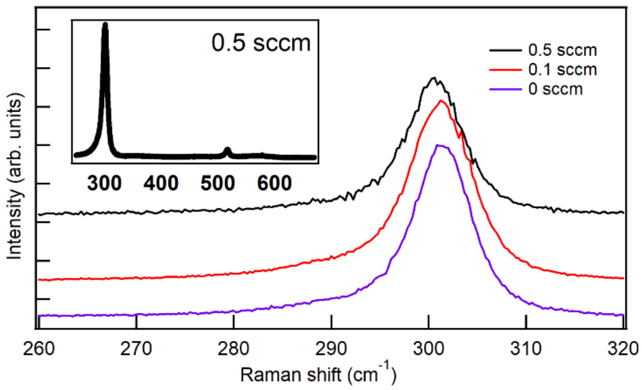

Figure 3. Ge optical phonon peaks of p-Si/i-Ge core-shell NWs with various B_2H_6 fluxes from 0 sccm to 0.5 sccm.

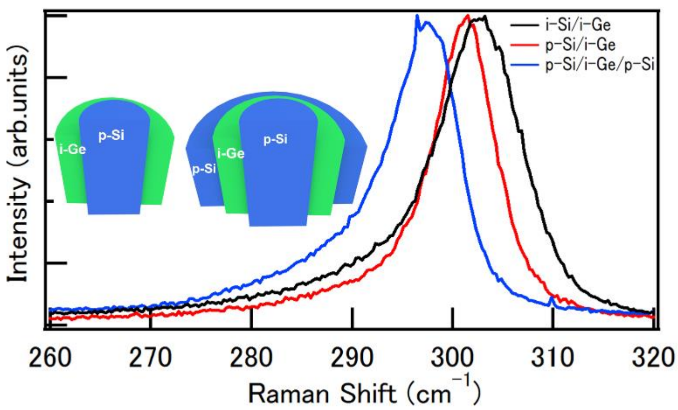

Figure 4. The Ge optical phonon peaks observed for i-Si/i-Ge, p-Si/i-Ge core-shell NWs, and p-Si/i-Ge/p-Si core-double shell NWs.