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Functionalization of Group IV Semiconductor Nanowire Channels for High-Speed Transistor Applications

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Abstract

One dimensional semiconducting nanowires (NWs) are considered to be used for next-generation transistors. Core-shell NWs composed of silicon and germanium can be used to realize high electron (hole) mobility transistors (HEMTs) by suppressing impurity scattering due to their band offset structure and selective doping. Boron doped p-Si/intrinsic (i)-Ge and i-Ge/p-Si core-shell NW structures were selected to study this phenomenon. To produce HEMT-type devices, hole gas accumulation must be controlled in the impurity undoped i-Ge shell and core regions. The hole gas state was clearly observed through the spectral change in Ge optical phonon peak, which is due to the Fano resonance. These results show the core-shell NWs using Si and Ge can be a candidate of next generation high-speed transistor channels.

1. Introduction

A considerable amount of work has been done regarding one dimensional semiconducting nanowires for the realization of next-generation metal-oxide-semiconductor field-effect transistors (MOSFETs), sensors, solar cells and so on [1]. Silicon and germanium nanowires (SiNWs and GeNWs) have gained attention since such NWs-based nanodevices are desirable for their compatibility with the present Si complementary metal-oxide semiconductors (Si CMOS) integrated circuit technology. Impurity doping is one of the key techniques for these applications, while the retardation of carrier mobility due to impurity scattering has to be taken into account. Core-shell NWs composed of Si and Ge are key structures for realizing high mobility transistor channels [2-5], since core-shell nanowire structures separate the carrier transport region from the impurity doped region, resulting in the suppression of impurity scattering.

In this study, two types of p-Si/i-Ge and i-Ge/p-Si core-shell NWs were formed by bottom-up and top-down methods. The status of selective B doping was demonstrated by Raman and XRD measurements, showing the bonding states and the electrical activities of impurity atoms. These methods were also applied to detect the hole gas accumulation.

2. Exeperiments

Ge/Si and Si/Ge core-shell NWs were formed on a Si substrate by bottom-up and top-down methods, respectively. Chemical vapor deposition (CVD) was used for the bottom-up method. Gold nanocolloid particles of 3 nm in diameter were used as seeds for vapor-liquid-solid (VLS) growth of core-SiNWs and core-GeNWs using 19 sccm of SiH_4 (100%) and 10 sccm GeH_4 (100%), respectively. To control the alignment of p-SiNWs, noimprint lithography and Bosch etching methods were used as a top-down method. Chemical polishing etching (CPE) and thermal oxidation were performed to remove surface damage due to the Bosch etching and reduce the diameter of the p-Si NW arrays.

After the growth and formation of core-NWs, the shell layers were also formed by the CVD method. Doping with boron (B) was performed during the growth. Diborane (1% B_2H_6 in H_2) was used for the p-type dopant The details of growth conditions have been reported elsewhere [3-5].

The structure of core-shell NWs were investigated by scanning electron microscopy (SEM), transmission electron microscopy (TEM) and energy-dispersive X-ray analysis (EDX) measurements. Micro-Raman scattering and X-ray diffraction (XRD) measurements were used to clarify the states of dopant atoms, and finally the B and P doping in the shell region.

3. Results and discussion

TEM and EDX images of core-shell NWs grown by the above-mentioned bottom-up method are shown in Fig. 1. The results clearly show the formation of i-Ge/p-Si (i: intrinsic, p: p-type) core-shell NWs as shown in a schematic illustration of Figure 1 (a). Clear lattice fringes in the core and shell regions are observed, showing the high crystallinity of core-shell NW [3].

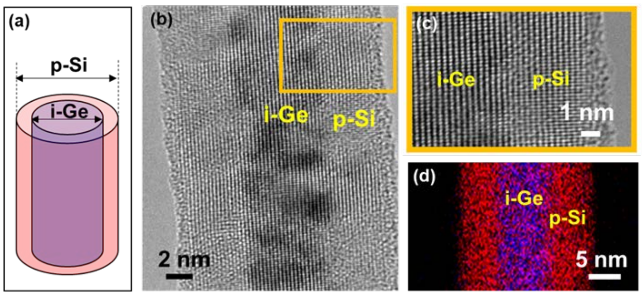

Fig. 1 (a) Schematic illustration of i-Ge/p-Si core-shell NW. (b) TEM, (c) high resolution TEM, and (d) EDX images of i-Ge/p-Si core-shell NWs synthesized by CVD (Core: 10 sccm of GeH_4 gas flux at 320 ºC, Shell: 19 sccm of SiH_4 and 0.5 sccm of B_2H_6 gas fluxes at 700 ºC).

Figure 2 also shows TEM and EDX images of core-shell NWs formed by the top-down method. Figures 2 (a) and (b) show p-SiNW arrays before and after the CPE treatment. The diameter of SiNWs dramatically decreased up to 50 nm after CPE. Clear hetero interfaces between Si and Ge were observed in Figures 2 (c)-(f). Figure 2 (e) shows Ge lattice fringes in the shell region. These results show the formation of p-Si/i-Ge core-shell NWs with high crystallinity [5].

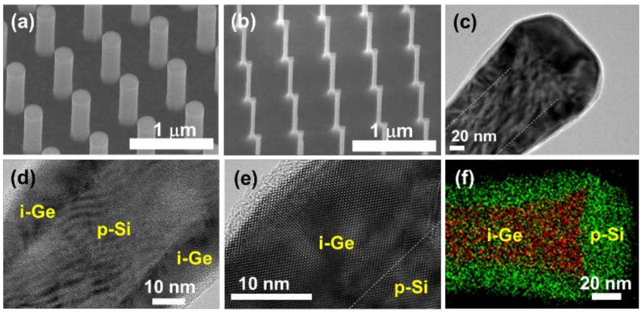

Fig. 2 SiNW array formed by nanoimprint and Bosh methods (a) before and (b) after CPE etching. TEM images of (c) top and (d) middle of p-Si/i-Ge core-shell NW. (e) High resolution TEM and EDX images of p-Si/i-Ge core-shell NW.

Figure 3 (a) shows the dependence of the Ge optical phonon peak on B_2H_6 gas flux for i-Ge/p-Si core-shell NWs grown by bottom-up method. The Ge optical phonon peak clearly shows the downshift and asymmetric broadening with increased the B_2H_6 gas flux during the formation of the p-Si shell layers. This spectral change suggest the hole gas accumulation in the i-Ge core NW region.

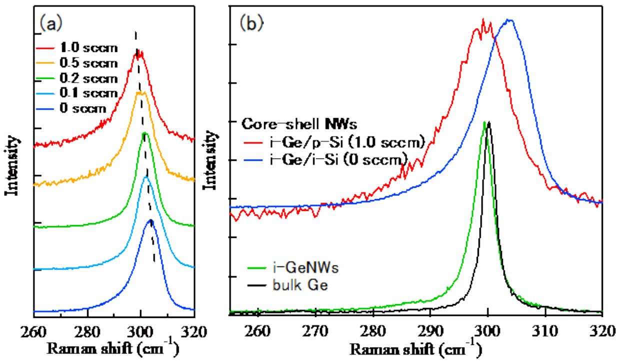

Fig. 3 (a) Ge optical phonon peak observed for i-Ge/p-Si core-shell NWs. (b) Comparison of the Ge optical phonon peaks observed for i-Ge/p-Si (1.0 sccm) core-shell NWs, i-Ge/i-Si (0 sccm) core-shell NWs, i-GeNWs, and bulk Ge. The B_2H_6 gas fluxes of p-Si layers were varied from 0 to 1.0 sccm. The shell growth time is 2 min.

To demonstrate the hole gas accumulation in the i-Ge core NW region, it is necessary to distinguish three different effects: the phonon confinement effect, the stress effect due to the heterostructures, and the Fano effect. Figure 3 (b) shows a comparison of the Ge optical phonon peaks observed for i-Ge/p-Si (B_2H_6: 1.0 sccm) core-shell NWs, i-Ge/i-Si (B_2H_6: 0 sccm) core-shell NWs, i-GeNWs, and bulk Ge. The Ge optical phonon peak for i-GeNWs shows a slight downshift and asymmetric broadening compared to bulk Ge. This spectral change is due to the phonon confinement effect, since the diameter of GeNWs is about 10 nm [3]. After the i-Si shell formation, the Ge optical phonon peak shows an upshift and asymmetric broadening. This upshift can be explained by the compressive stress applied by the i-Si shell layers, whereas the asymmetric broadening cannot be explained by compressive stress alone: it suggests the effect of hole gas accumulation in the i-Ge core NW region. The Ge optical phonon peak showed a downshift and further asymmetric broadening with increasing B concentration in the Si shell layers for the i-Ge/p-Si (B_2H_6: 1.0 sccm) core-shell NWs. This can be explained in major part by the Fano effect, showing the introduction of a high concentration of holes in the i-Ge core NW region. The result clearly demonstrates hole gas accumulation from the p-Si (i-Si) shell to the i-Ge core NW region that results from the formation of core-shell NW structures.

The same experiments were also done for p-Si/i-Ge core-shell NWs formed by top-down method. The results showed the same trend as those shown in Figure 3. These results clearly show that HEMT-type channel can be realized for i-Ge/p-Si and p-Si/i-Ge core-shell NWs. The hole accumulation in the Ge region increased with increasing B concentration in the Si regions, meaning that the hole gas density in the Ge core can be controlled by shell doping. The hole gas concentration can be roughly estimated to be in the range of 10^{17}-10^{18} cm^{-3} by analyzing the Ge optical phonon peak with Fano equation.

3. Conclusions

Two different types of radial heterostructures of i-Ge/p-Si and p-Si/i-Ge core-shell NWs were formed by bottom-up and top-down methods. The latter method realizes size and site control without the need for catalysts. A precise analysis of the Ge optical phonon peak by Raman spectroscopy was able to disentangle three effects: the phonon confinement effect, the stress effect due to the heterostructures, and the Fano effect, ultimately providing a clear demonstration of hole gas accumulation in i-Ge/p-Si and p-Si/i-Ge core-shell NWs. These results show the realization of HEMT structures in one-dimensional NWs. The concentration of hole gas was controlled by the B doping concentration in the Si shell.

Acknowledgements

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