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Characterization of selective doping and stress in Ge/Si core-shell nanowires

Yu Mingke[1], Wipakorn Jevasuwan[1] and Naoki Fukata[1]

[1]National Institute for Materials Science (NIMS), 1-1 Namiki, Tsukuba, 305-0044, Japan
Phone: +81-29-860-4769 E-mail: YU.Mingke@nims .go.jp

Abstract

Core-shell nanowires (NWs) using silicon (Si) and germanium (Ge) are one of the key structures for realizing high mobility transistor channels, since the selective doping and band-offset in core-shell NWs separate the carrier transport region from the impurity doped region, resulting in the suppression of impurity scattering. Ge/Si core-shell NWs were grown by a chemical vapor deposition (CVD) method. Raman and X-ray diffraction (XRD) measurements clarified the existence of compressive and tensile stress in the core and shell regions. The observation of the Fano effect by Raman measurements also clearly demonstrated that B atoms are selectively doped into the shell regions and electrically activated in the doped sites, showing the success of selective doping.

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[2], 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 high mobility transistor channels [3], since core-shell structures suppress impurity scattering by separating the carrier transport region from the impurity doped region. In this study, we grew Ge/Si and Si/Ge core-shell NWs and performed selective doping in the core and shell regions, respectively. The selective doping was investigated by Raman and XRD measurements. The results clearly showed the bonding states and the electrical activities of impurity atoms, demonstrating the selective doping.

2. Experimental

Ge/Si (Si/Ge) core-shell NWs structures were rationally grown on a Si substrate by CVD. Gold nanocolloid particles of 3 nm in diameter were used as seeds for vapor-liquid-solid (VLS) growth of core-GeNWs using 10 sccm GeH_4 (100%). After the growth of core-NWs, the shell layers were also formed by CVD. Doping with B was performed during the growth. Diborane (1% B_2H_6 in H_2) was used for the p-type dopant. Details of growth conditions have been reported elsewhere [4].

The structure of core-shell NWs were investigated by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Energy-dispersive X-ray analysis (EDX) measurements were also performed during TEM. Micro-Raman scattering and XRD measurements were performed to reveal the stress in the core and shell regions and the doping effects.

2. Results and discussion

The TEM and EDX images are shown in Fig. 1. The results clearly show the formation of i-Ge/p-Si (i: intrinsic, p: p-type) core-shell NWs. We also carefully checked the crystallinity of the shell in the core-shell NWs, and observed clear lattice fringes in the shell regions. The evidence of shell crystallinity was also shown by the results of the XRD and Raman measurements described below.

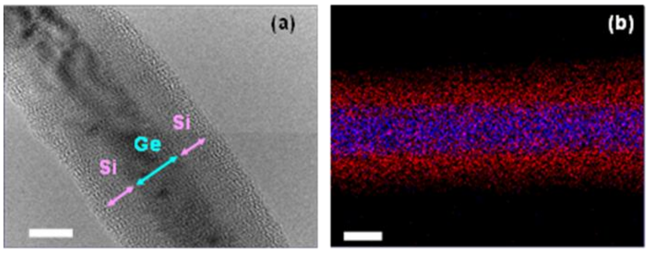

Fig.1 (a) TEM and (b) EDX images of i-Ge/p-Si core/shell nanowire. The scale bars are 10 nm.

We carefully investigated the dependence of diameters on the shell growth time and the flux of B_2H_6 gas by SEM. The SEM images demonstrated that the diameter is uniform along the length of the core-shell NWs. The diameter significantly increases with increasing the shell growth time and the flux of B_2H_6 gas as summarized in Fig. 2. The latter result shows that the introducing of B_2H_6 gas enhances the radial shell growth.

XRD measurements were performed to evaluate the stress which can be induced in the radial hetero core-shell structures. The results clearly revealed stress in the core and shell regions and characterized the compressive and shell regions and characterized the compressive and tensile stress present. We analyzed the data and plotted the lattice constant for Ge/Si core-shell NWs. The average lattice constant of the Ge core is smaller than bulk Ge, showing that

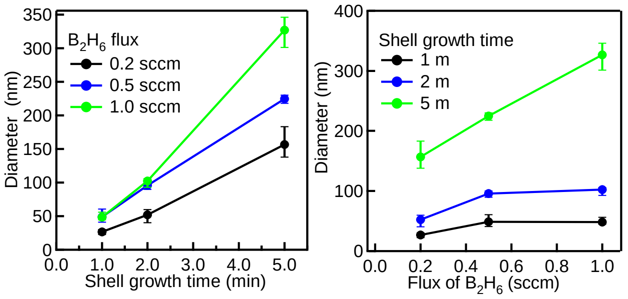

Fig.2 Dependences of the diameter of core-shell NWs on the shell growth time and the flux of B_2H_6 gas.

the compressive stress is applied by the radial growth of p-Si shell. It also decreases with increasing shell growth time. This is probably attributable to relaxation caused by the radial growth of Ge/Si core-shell NWs at a higher temperature (700°C). The average lattice constant of the p-Si shell is greater than that for bulk Si. This is due to the tensile stress from the Ge core. In addition to this, the lattice constant decreases with increasing the flux of B_2H_6 gas, demonstrating that the lattice contraction of the p-Si shell results from the substitution of smaller B atoms into the Si lattice and indicating B-doping in the Si shell.

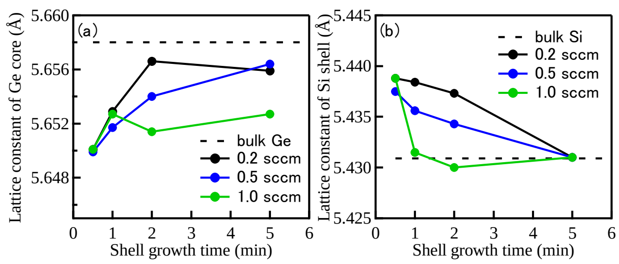

Fig.3 The lattice constant of (a) the Ge core and (b) the Si shell in the i-Ge/p-Si core-shell NWs.

To further confirm the selective B-doping in the shell region, we performed Raman measurements. The electrical activity of B atoms can be clarified by the Fano effect [5], which is due to coupling between discrete optical phonons and the continuum of interband electron excitations in degenerately doped p-type Si. The representative results of Raman measurements are shown in Fig. 4. The Si optical phonon peaks observed for i-Ge/p-Si NWs shows an asymmetric broadening toward higher wavenumber, while no asymmetric broadening was observed for the i-Si shell. This asymmetric broadening is due to the Fano effect, showing that B toms are electrical activated in the Si shell, resulting in the formation of p-Si shell. The electrical active B concentration can be estimated by fitting the Si optical phonon peaks using the Fano equation. The asymmetric phonon shape is given by

$$I(\omega) = I_0 \frac{(q+\varepsilon)^2}{(1+\varepsilon^2)}, \qquad (1)$$

where ω is the wavenumber, I_0 the prefactor, q the asymmetry parameter, and ε is given by $\varepsilon = (\omega-\omega_p)/\Gamma$, where ω_p is the phonon wavenumber and Γ is the linewidth parameter. The electrically active B concentration was roughly estimated to be in the order of 10^{18} cm^{-3}.

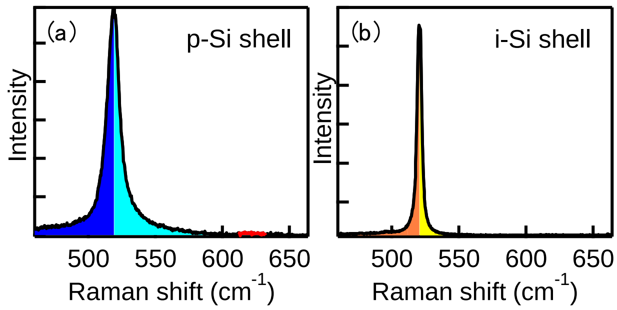

Fig.4 Raman spectra observed for (a) i-Ge/p-Si and (b) n-Ge/i-Si core-shell NWs. The shell growth times are (a) 5 min and (b) 15 min, respectively.

3. Conclusions

The growth of Ge-Si core-shell NWs was carried out by CVD. The thickness and doping levels were controlled by the shell growth time and B_2H_6 gas flux. The existence of stress in the core-shell NWs and the doping effects were evaluated by XRD and Raman measurements. The electrical activity of B atoms in the shell region was investigated by the Fano effect. The results clearly demonstrated that the B atoms are selectively doped into the shell and electrically activated in the shell, showing the success of site-selective doping in i-Ge/p-Si core-shell NWs.

Acknowledgements

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