

Molecular Beam Epitaxy of Ferromagnetic Silicide for Spin-Transistors with Ge Channel

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Introduction

Research and development for new semiconductor devices which enable ultrahigh speed operation, ultralow power dissipation, and/or multi-functional operation are strongly required to overcome a scaling limit of CMOS (complementary metal-oxide-semiconductor) performance. In line with this, Si-based heterostructure technologies have been widely developed in a quarter century [1]. Among them, development of the SiGe heteroepitaxy technique on Si substrates enabled strained growth, modulation doping, and formation of quantum well structures, which achieved significant enhancement of carrier mobility and resonant tunneling transport. What is the next jump? New functions created by spin injection from ferromagnetic electrodes into semiconductor channels or quantum dots are big candidates to be used for this purpose [2-4]. To combine such spintronics with Si-based heterostructure technologies, we have been developing atomically controlled heteroepitaxy of ferromagnetic silicide Fe_3Si on the group-IV semiconductor platform [5-6]. This paper reports our recent progress in novel epitaxial growth of Fe_3Si (Curie temperature: 840K, Spin polarization: 43%) on Ge for the application of group IV-based spin-transistors, which is schematic illustrated in Fig.1.

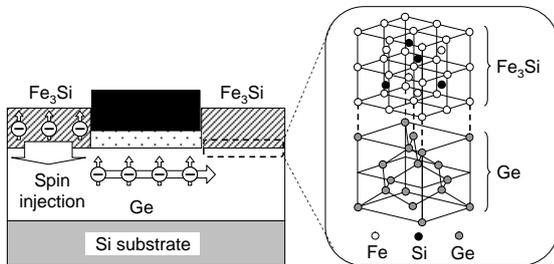


Figure 1. Schematic illustration of spin transistor, i.e., Ge channel with high mobility and Fe_3Si source/drain for spin-injection.

Experimental

In the experiment, Fe and Si were co-evaporated

(60-200 °C) on Ge substrates with (100), (110), and (111) orientations by using MBE (Molecular Beam Epitaxy) system. The crystal structures and of grown layers were evaluated with TEM (Transmission Electron Microscopy), and RBS (Rutherford back scattering) measurements. In addition, magnetic and electrical properties were evaluated by using vibrating sample magnetometry and current-voltage measurements, respectively

Results and Discussion

From RBS axial-channeling measurements, large values of the minimum yield (χ_{\min}) exceeding 65 % were obtained for (100) and (110) substrates. These values were drastically decreased to less than 7 % by substituting (111) substrates. Detailed experiments indicated that both Fe/Si ratio and growth temperature were key factors to improve interface quality of $\text{Fe}_3\text{Si}/\text{Ge}$ (111). Very low χ_{\min} of 2.2 % was achieved by tuning Fe/Si ratio exactly to 3/1 and optimizing growth temperature (130 °C), as shown in Fig.2.

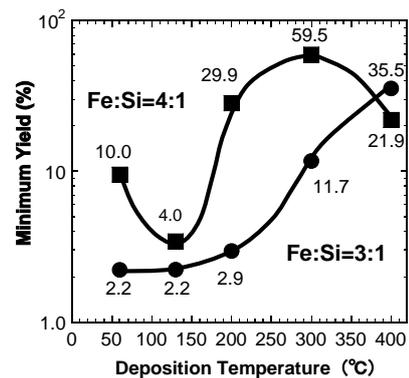


Figure 2. χ_{\min} of Fe_3Si evaluated from RBS spectra as a function of Fe/Si ratio and growth temperature.

Cross-sectional TEM observation demonstrated the atomically flat interface of $\text{Fe}_3\text{Si}/\text{Ge}$ (111). In addition, its electron diffraction pattern indicated strong super-lattice reflection spots, which confirmed the formation of ordered DO_3 -type Fe_3Si layers, as shown in Fig.3.

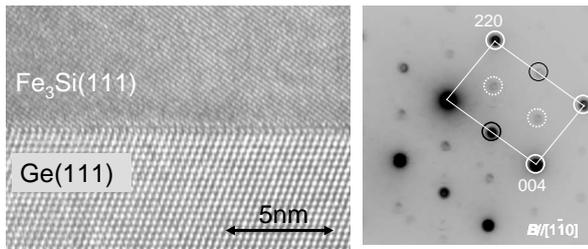


Figure 3. Cross-sectional TEM image and electron diffraction pattern of Fe₃Si/Ge (111) grown at 130 °C under stoichiometric condition.

Magnetic properties were evaluated by using the vibrating sample magnetometry, which showed the growth-temperature dependent coercivities. A smallest value (0.8 Oe) was obtained from the sample with highest crystal quality (χ_{\min} : 2.2 %), as shown in Fig.4. Weak uniaxial anisotropy supposed to originate from a uniaxial lattice strain was observed, where the anisotropy field was very small (7 Oe). Consequently, formation of source/drain electrodes with uniform magnetic properties is expected to be realized by using the shape anisotropy.

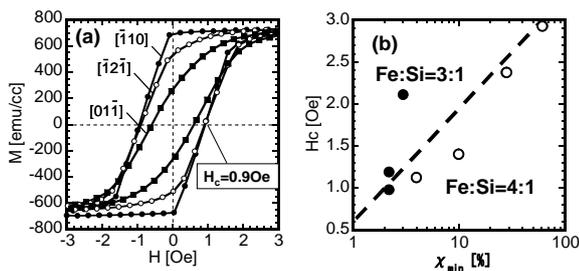


Figure 4. Magnetic hysteresis loop of Fe₃Si layer (Fe:Si=3:1, 130 °C growth) for various field directions (a), and crystal quality (χ_{\min}) dependent coercivities (b).

Electrical properties were also evaluated by using current-voltage and capacitance-voltage measurements, which indicated good Schottky characteristics with the barrier height of 0.56 eV. The ratio of the on-current to the off-current was the order of 10^3 , as shown in Fig.5.

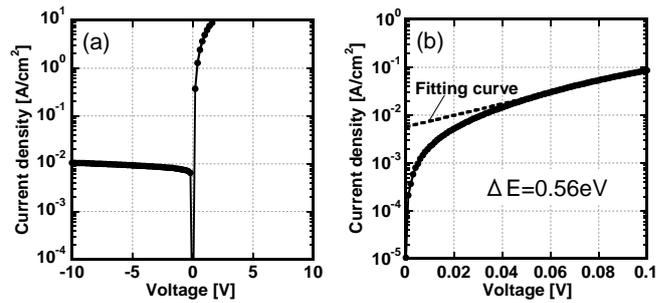


Figure 5. Diode characteristics of Fe₃Si/Ge Schottky contact (a) and magnified forward characteristics (b).

These results will be a powerful tool to realize new-type group IV-based spin-transistors, i.e., Ge channel with high mobility and Fe₃Si source/drain for spin-injection.

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References

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