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Epitaxial Growth of Sb-doped Ge Layers on Ferromagnetic Fe_3Si for Vertical Semiconductor Spintronic Devices

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Abstract

By combining solid phase epitaxy (SPE) and molecular beam epitaxy (MBE) with Sb doping, we develop an epitaxial growth technique for n-type Ge layers on one of the ferromagnetic Heusler alloys, Fe_3Si. The Sb-doped Ge layers can be grown epitaxially on the Si-terminated Fe_3Si surface at 175 ºC. Electrical properties of the Au-Ti/Sb-doped Ge/Fe_3Si/p-Ge/Al vertical devices indicate that the grown Sb-doped Ge layers are n-type conduction. We also demonstrate a high-quality CoFe/n-Ge/Fe_3Si trilayer structures for vertical semiconductor spintronic devices.

1. Introduction

Semiconductor (SC) spintronic devices based on the electrical spin injection and detection have been proposed for low power consumption in logic and memory devices [1,2]. Up to now, vertically stacked ferromagnet (FM)/SC/FM trilayer structures have been explored for demonstrating spin-dependent transport through the SC channels [3,4]. Recently, we developed heteroepitaxial growth techniques of vertically stacked FM/Ge/FM trilayer structures [5,6]. Since these techniques can be utilized on Si, vertical Ge spintronic devices can be formed even on the Si platform. Using CoFe/Ge/Fe_3Si vertically stacked structures on Si, we have already observed the spin-dependent transport through p-type Ge from low temperatures to room temperature [7]. Since the spin diffusion length of p-Ge was extremely small [7,8], the spin signals decayed rapidly with increasing temperature.

On the other hand, we have clarified that the spin diffusion length of n-Ge is one order of magnitude larger than that of p-Ge even at room temperature [9,10]. If we grow n-Ge layers on Fe_3Si, the spin signals in the CoFe/Ge/Fe_3Si structures can be enhanced. In general, because the p-type conduction was induced by the formation of point defects in epitaxial Ge layers on Fe_3Si, we have to reduce the formation of such point defects and to add n-type dopant into the epitaxial Ge layer during the low-temperature growth.

In this paper, we have explored the epitaxial growth of Sb-doped Ge layers on Fe_3Si for vertically stacked FM/n-Ge/Fe_3Si trilayer structures. By measuring current-voltage characteristics of the Au-Ti/Sb-doped Ge/Fe_3Si/p-Ge/Al vertical devices, we confirmed that the grown Sb-doped Ge layers are n-type conduction. We also demonstrated that an ideal magnetization reversal process of the CoFe/n-Ge/Fe_3Si trilayer is achieved. This CoFe/n-Ge/Fe_3Si structure has great potentialities to be utilized as vertical-type Ge channel spintronic devices.

2. Growth of Sb-doped Ge on Fe_3Si

First, a 50-nm-thick Fe_3Si layer was grown directly on a Ge(111) substrate below 130 ºC [11]. Next, the Fe_3Si surface was terminated with 2 ML of Si [12,13] and a good flat surface was confirmed by *in-situ* reflection high energy electron diffraction (RHEED) observation [Fig. 1(a)]. On top of the Si-terminated Fe_3Si, we grew a Ge layer by combing solid phase epitaxy (SPE) and molecular beam epitaxy (MBE) [6]. After the deposition of a 2-nm-thick amorphous Ge (a-Ge) layer at room temperature, the substrate temperature was raised from RT up to ~125 ºC at a rate of 5 ºC/min and was kept at ~125 ºC for 30 minutes to induce SPE growth. *In-situ* RHEED pattern was gradually changed to the streak pattern, indicating the crystallization

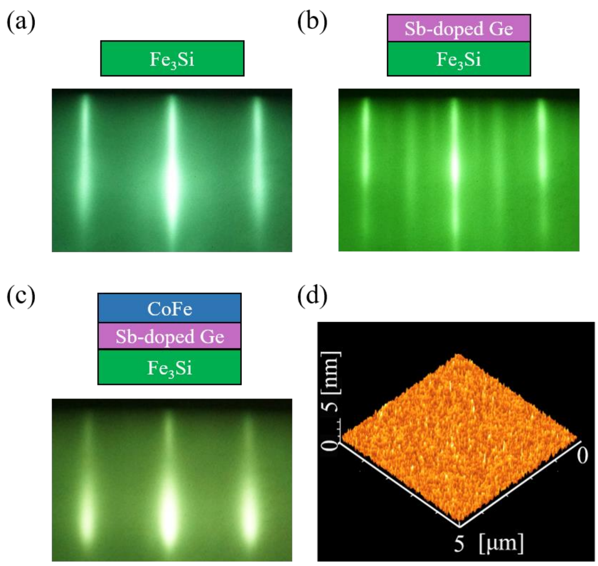

Fig. 1 RHEED patterns of (a) Si-terminated Fe_3Si, (b) Sb-doped Ge and (c) CoFe layers. (d) AFM image of the surface of Sb-doped Ge layers.

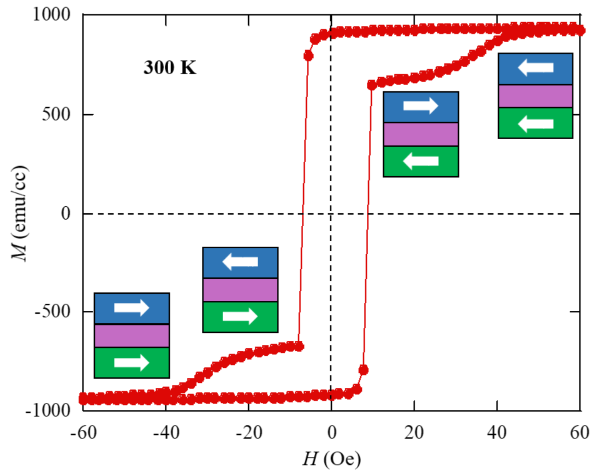

Fig. 2 *M-H* curve of the CoFe/n-Ge/Fe_3Si trilayer measured at 300 K.

of the a-Ge layer even at ~125 ºC. After the SPE growth, the substrate temperature was raised up to ~175 ºC at a rate of ~10 ºC/min for MBE. Subsequently, we grew a 18-nm-thick Ge layer at ~175 ºC by MBE with Sb doping (cell temperature: 280 ºC) on top of the SPE-grown Ge. We confirmed the RHEED pattern maintains the streak pattern, indicating a suppression of Sb surface segregation [Fig. 1(b)]. At this time, we also confirmed good flatness of Sb-doped Ge layers (root-mean-squire roughness R_{rms}: ~0.4 nm, measured area: 5 x 5 μm^2) by atomic force microscopy (AFM) measurements [Fig. 1(d)]. After cooling the substrate temperature down to RT for half a day, we grew a 10-nm-thick CoFe layer. The RHEED pattern indicates the 2D epitaxial growth of the top CoFe layers [Fig. 1(c)]. From these results, we concluded that an all-epitaxial CoFe/Sb-doped Ge/Fe_3Si trilayer structure is demonstrated.

3. Characterizations of Sb-doped Ge layers on Fe_3Si

To examine whether Sb atoms in the Ge layers work as donor or not, we fabricated Au-Ti/Sb-doped Ge/Fe_3Si/p-Ge/Al vertical devices by electron beam lithography and Ar ion milling and measured *I-V* characteristics of the devices at 10-300 K. Nonlinear *I-V* curves were observed and the magnitude of *I* was decreased with decreasing the measurement temperature. In general, because of the strong Fermi level pinning (FLP) at metal/Ge interfaces, electrical properties of metal/p-Ge junctions show Ohmic characteristics while those of metal/n-Ge ones show Schottky characteristics [14,15]. The observed nonlinear *I-V* curves mean that the Au-Ti/Sb-doped Ge and/or Sb-doped Ge/Fe_3Si interfaces behave like metal/n-Ge junctions. Thus, we can judge that the grown Sb-doped Ge layers are n-type semiconductors.

Figure 2 shows an *M-H* curve of the CoFe/Sb-doped Ge/Fe_3Si trilayer at 300 K. A clear spin-valve-like magnetization reversal process is observed, indicating that the top CoFe layers and the bottom Fe_3Si layers are magnetically decoupled by the intermediate Ge layer. The magnetization switching field of several Oe is almost equivalent to that of Fe_3Si/Ge(111) while that of 35 Oe is slightly larger than that of CoFe/Ge(111) [11,16]. Although a slight diffusion of Ge atoms into the top CoFe layers might still remain [6], we can fabricate the spin-valve structures to observe the spin transport. From now on, we will try to perform magnetoresistance measurements of the CoFe/n-Ge/Fe_3Si vertical spin valve devices for applications to vertical-type Ge channel spintronic devices.

4. Conclusions

We developed an epitaxial growth technique for n-type Ge layers on a ferromagnetic Heusler alloy, Fe_3Si by combining SPE and MBE with Sb doping. Electrical properties of a Au-Ti/Sb-doped Ge/Fe_3Si/p-Ge(111)/Al vertical device indicated that the grown Sb-doped Ge layers are n-type conduction even at the growth temperature of 175 ºC. We also demonstrated two-dimensional epitaxial growth of a CoFe layer on top of the Sb-doped Ge epilayer, enabling us to achieve an all-epitaxial CoFe/n-Ge/Fe_3Si trilayer. We believe that this trilayer has great potentialities to be utilized as novel vertical-type Ge channel spintronic devices.

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