Electrical injection and detection of spin-polarized electrons in silicon through an Fe$_3$Si/Si Schottky tunnel barrier

Y. Ando, K. Hamaya, K. Kasahara, Y. Kishi, K. Ueda, K. Sawano, T. Sadoh and M. Miyao

1Department of Electronics, Kyushu University, 744 Motooka, Fukuoka 819-0395, Japan
2PRESTO, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi 332-0012, Japan
3Research Center for Silicon Nano-Science, Advanced Research Laboratories, Musashi Institute of Technology, 8-15-1 Todoroki, Tokyo 158-0082, Japan.

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We demonstrate electrical injection and detection of spin-polarized electrons in silicon (Si) using epitaxially grown Fe$_3$Si/Si Schottky-tunnel-barrier contacts. By an insertion of a δ-doped n$^+$-Si layer ($\sim 10^{19}$ cm$^{-3}$) near the interface between a ferromagnetic Fe$_3$Si contact and a Si channel ($\sim 10^{15}$ cm$^{-3}$), we achieve a marked enhancement in the tunnel conductance for reverse-bias characteristics of the Fe$_3$Si/Si Schottky diodes. Using laterally fabricated four-probe geometries with the modified Fe$_3$Si/Si contacts, we detect nonlocal output signals which originate from the spin accumulation in a Si channel at low temperatures.

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To solve critical issues caused by the scaling limit of complementary metal-oxide-semiconductor (CMOS) technologies, spin-based electronics (spintronics) has been studied. For semiconductor spintronic applications, an electrical spin injection from a ferromagnet (FM) into a semiconductor (SC) and its detection are crucial techniques. Recently, methods for spin injection and/or detection in Si were explored because Si has a long spin relaxation time and is compatible with the current industrial semiconductor technologies. Although electrical detections of spin transport in Si conduction channels were demonstrated by two research groups, an insulating Al$_2$O$_3$ tunnel barrier between FM and Si was utilized for efficient spin injection and/or detection. To realize gate-tunable spin devices, e.g., spin metal-oxide-semiconductor field effect transistors (spin MOSFET), demonstrations of electrical spin injection and detection in Si conduction channels using Schottky tunnel-barrier contacts will become considerably important.

By low-temperature molecular beam epitaxy (LTMBE), we recently demonstrated highly epitaxial growth of a binary Heusler alloy Fe$_3$Si on Si and obtained an atomically abrupt heterointerface. In this letter, inserting a heavily doped n$^+$-Si layer near the abrupt interface between Fe$_3$Si and n-Si, we achieve an effective Schottky tunnel barrier for spin injection into Si. Using nonlocal signal measurements, we demonstrate electrical injection and detection of spin-polarized electrons in Si conduction channels through the Schottky-tunnel-barrier contacts.

The n$^+$-Si layer was formed on n-Si(111) ($n \sim 4.5 \times 10^{15}$ cm$^{-3}$) by a combination of the Si solid-phase epitaxy with an Sb δ-doping process, where the carrier concentration of the n$^+$-Si layer was $\sim 2.3 \times 10^{19}$ cm$^{-3}$, determined by Hall effect measurements, and 10-nm-thick non-doped Si layer was grown on the Sb δ-doped layer. Ferromagnetic Fe$_3$Si layers with a thickness of $\sim 50$ nm were grown by LTMBE at 130 °C, as shown in our previous work. The interface between Fe$_3$Si and n$^+$-Si was comparable to that shown in Ref. 11. To evaluate electrical properties of the Fe$_3$Si/Si Schottky contacts, we firstly fabricated two different Schottky diodes (n$^+$-Si layer) with and without the n$^+$-Si layer between Fe$_3$Si and n-Si. Here, we define these Schottky diodes as Diode A (with the n$^+$-Si layer) and Diode B (without the n$^+$-Si layer). A schematic illustration of Diode A is shown in the inset of Fig. 1(a).

The main panel of Fig. 1(a) shows absolute values of the current density, $|I|$, as a function of bias voltage ($V_{\text{bias}}$) for both Diode A and B. These characteristics were reproduced for ten devices. A typical rectifying behavior of a conventional Schottky diode is seen for Diode B (blue), while we find almost symmetric behavior with respect to $V_{\text{bias}}$ polarity for Diode A (red). For spin injection from Fe$_3$Si directly into Si, the $I - V_{\text{bias}}$ characteristic in the reverse bias regime ($V_{\text{bias}} < 0$) is important. We note that the reverse-bias $|I|$ ($|I_{\text{rev.}}|$) for Diode A is extremely large more than three orders of magnitude compared to that for Diode B. For both diodes, the temperature-dependent $|I_{\text{rev.}}|$ measured at $V_{\text{bias}} = -0.3$ V is representatively shown in Fig. 1(b) in order to discuss transport mechanisms in $V_{\text{bias}} < 0$. For Diode B (blue), $|I_{\text{rev.}}|$ ($V_{\text{bias}} = -0.3$ V) is significantly reduced (more than six orders of magnitude) with decreasing temperature. By an analysis of the Arrhenius plot shown in the inset, the thermionic emission electron transport over a Schottky barrier is indicated, in which the Schottky barrier height is estimated to be $\Phi_B$ = 0.61 eV, consistent with our previous study. Using such contacts (without the n$^+$-Si layer), we can not detect spin-polarized carriers electrically due to additional resistance originating from a wide width of the depletion re-
duction electrons between the Fe and the conductance. This may mean that the tunnel barrier sees the weak insulator-like temperature dependence of the conductance, indicating that the tunnel probability across the barrier is dominated by the Fermi-Dirac distribution of the conduction electron’s energy in the Fe and AlGaAs. In a preliminary study, we also observed the similar weak insulator-like features of the conductance for FeSi/Si Schottky barriers with a highly-doped (~10^18 cm^-3) interface. On the other hand, for the present FeSi/Si Schottky barriers with a δ-doped n^+ Si layer (~10^19 cm^-3), we could not see the weak insulator-like temperature dependence of the conductance. This may mean that the tunnel barrier becomes very thin and the wave functions of the conduction electrons between the FeSi and Si are nearly overlapped. As a consequence, there is almost no influence of temperature on the tunnel probability. Thus, under the reverse-bias conditions, we can expect to achieve spin injection via a Schottky tunnel barrier consisting of the epitaxially grown FeSi/Si interface, as schematically shown in the left inset of Fig. 1(a).

Using the FeSi/Si Schottky-tunnel-barrier contacts, we fabricated four-probe lateral spin devices, as shown in Fig. 2(a), where the lateral geometries have been utilized by lots of researchers for the detection of spin transport in semiconductor channels. The fabrication processes were also developed for the FeSi/Si system. First, an FeSi/Si mesa structure (800 × 200 μm^2) including a Si conduction channel was defined by Ar ion milling. Second, four FeSi/Si contacts were formed by reactive ion etching. To form bonding pads, a 200-nm-thick SiO_2 thin film was deposited by rf magnetron sputtering at room temperature, and then the contact holes were formed by reactive ion etching. Finally, Au/Ti pads were fabricated by electron beam evaporation and lift-off methods.

Figures 2(c) and 2(d) display representative nonlocal spin signals (∆V/I) as a function of magnetic field (B) for two different samples with the n^+ Si layers. The nonlocal voltage measurements, being reliable methods for detecting spin accumulation in a nonmagnetic
channel.[3, 17, 18, 19] were performed by a conventional dc method for the current-voltage geometry shown in Fig. 2(a). External magnetic fields \( B \) were applied parallel to the long axis of the \( \text{Fe}_3\text{Si} \) contacts in the film plane. Here, we define the two samples presented here as Sample 1 and Sample 2, and the lateral geometry of Sample 1 is almost identical to that of Sample 2. For Sample 1, hysteretic behavior is clearly obtained but the curve feature is somewhat different from that of the previous lateral spin valves.\[17, 18, 19\] It should be noted that very large \( \Delta V/I \) (\( \sim 400 \, \text{mO} \)) can be detected at 20 K. On the other hand, for Sample 2, we can see a spin-valve-like \( \Delta V/I - B \) curve at 2 K, but \( \Delta V/I \) is extremely small compared to Sample 1. For other samples without the \( n^{+} \)-Si layer, such hysteretic features could not be obtained because of the limitation of the current flow.\[2, 14\] The hysteretic nonlocal signals (\( \Delta V/I \)) shown in Figs. 2(c) and 2(d) indisputably exhibit the experimental demonstrations of electrical spin injection and detection in Si-based devices via a Schottky tunnel barrier.

We now infer that the shape of the \( \Delta V/I - B \) curve is affected by in-plane magnetic anisotropies for the \( \text{Fe}_3\text{Si}/\text{Si}(111) \) epilayers. For epitaxially grown \( \text{Fe}_3\text{Si}/\text{Ge}(111) \) layers, we found that there is a strong in-plane uniaxial magnetic anisotropy with a random-oriented easy axis.\[20\] In addition, it is well known that such complicated in-plane anisotropies can affect in-plane magnetic configurations for epitaxially grown ferromagnetic thin films in various external magnetic fields.\[21, 22\] Namely, if the applied field direction, which is nearly parallel to the long axis of the wire-shaped \( \text{Fe}_3\text{Si} \) injector and detector, is deviated from its magnetic easy axis, we could not get precise parallel and anti-parallel configurations at zero field and at a magnetization switching field, respectively. These influences are probably related to the shape of the \( \Delta V/I - B \) curve for Sample 1. As we can accidentally obtain a sample with the wire-shaped \( \text{Fe}_3\text{Si} \) oriented along the in-plane easy axis, we can see a spin-valve-like \( \Delta V/I - B \) curve,\[22\] as shown in Fig. 2(d) (Sample 2).

Next, we focus on uneven characteristics of the \( \Delta V/I \) magnitude. The \( \Delta V/I \) magnitude is known to decrease with decreasing the interface resistance between ferromagnets and nonmagnets. According to a simple one-dimensional spin-diffusion model,[24] the spin accumulation voltage is roughly proportional to the square of the interface resistance when the interface resistance is much smaller than the spin resistance of the nonmagnets.\[25\] We confirmed that the interface resistance for Sample 2 is quite low more than two orders of magnitude compared to that for Sample 1. Therefore, the reduction of the \( \Delta V/I \) magnitude for Sample 2 is probably caused by the low interface resistance, resulting in a low efficiency of the spin injection. The precise origin of the dispersion of the interface resistance is still unclear, but the local inhomogeneity of the doped Sb ionization near the \( \text{Fe}_3\text{Si}/\text{Si} \) interface and the damage due to the device fabrication processes may influence crucially for each sample. Because of such local and slight inhomogeneous carrier concentration, we can speculate a small change in the temperature dependence of the interface resistance. This sensitive change has already been confirmed by a comparison of characteristics for diode structures (\( \sim 1 \, \text{mm} \) in diameter) with a highly-doped (\( \sim 10^{18} \, \text{cm}^{-3} \)) interface and a \( \delta \)-doped \( n^{+} \)-Si (\( \sim 10^{19} \, \text{cm}^{-3} \)) interface, as described above.

Figures 3(a) and 3(b) show temperature dependence of the \( \Delta V/I - B \) curve and \( \Delta V/I \), respectively, for Sample 1. The \( \Delta V/I - B \) hysteresis and \( \Delta V/I \) are significantly decayed with increasing temperature, and disappear completely at 50 K. We also explored the \( \Delta V/I \) signal for various temperatures for Sample 2, but the hysteretic \( \Delta V/I - B \) feature disappeared at 4 \( \sim 10 \, \text{K} \) unfortunately (not shown here). If the highly efficient spin injection into Si is realized, we can see spin transport at higher temperatures because Si has a long spin-diffusion length. However, the laterally fabricated spin devices include some problems such as the dispersion of the interface resistance, as stated in previous paragraph. We infer that the decays of the \( \Delta V/I - B \) curve and \( \Delta V/I \) are probably caused by a slight decrease in the interface resistance to rising temperature unfortunately, in which the decrease in the interface resistance reduces the efficiencies of the spin injection and detection. Thus, it is still insufficient that the efficiency of the spin injection and detection at the \( \text{Fe}_3\text{Si}/\text{Si} \) interface of the present devices. Further optimization of the \( \delta \)-doping technique, device fabrication processes, and the device geometry, is required to observe the spin transport in Si at higher temperatures.

In summary, we have demonstrated electrical injection and detection of spin-polarized electrons in silicon using epitaxially grown \( \text{Fe}_3\text{Si}/\text{Si} \) Schottky-tunnel-barrier contacts, where a \( \delta \)-doped \( n^{+} \)-Si layer (\( \sim 10^{19} \, \text{cm}^{-3} \)) is inserted near the interface between a ferromagnetic \( \text{Fe}_3\text{Si} \) contact and a Si channel (\( \sim 10^{15} \, \text{cm}^{-3} \)). By fabricating lateral four-probe geometries with the modified \( \text{Fe}_3\text{Si}/\text{Si} \) contacts, we detected nonlocal output signals which originate from the spin accumulation in a Si chan-

![Figure 3: (Color online) (a) The \( \Delta V/I - B \) curves recorded at various temperatures for Sample 1. (b) \( \Delta V/I \) as a function of temperature.](image-url)
nel at low temperatures. To get a spin device with high-temperature operation, we need further optimizations of the $\delta$-doping technique, device fabrication processes, and the device geometry.

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