Extended Abstracts of the 2017 International Conference on Solid State Devices and Materials, Sendai, 2017, pp983-984

PS-12-08

Inverse spin-valve effect in MBE-grown nanoscale Si spin-valve devices

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Abstract

We investigated the spin-valve effect in nano-scale silicon (Si)-based spin-valve devices with a 2 nm-thick MgO / 1 nm-thick Ge double layer tunnel barrier inserted between Fe electrodes and a 20 nm-long Si channel. Here, the Fe/MgO/Ge layerd were deposited on a Si substrate by molecular beam epitaxy. We observed clear magnetoresistance (MR) up to 3 % at low temperature when a magnetic field was applied in the film plane along the Si channel transport direction. A large spin-dependent output voltage of 20 mV was observed at a bias voltage of 0.9 V at 15 K, which is the highest value in lateral spin-valve devices reported so far. Furthermore, we observed that the sign of the spin-valve effect is reserved at low temperatures, suggesting the possibility of a spin-blockade effect of defect states in the MgO/Ge tunneling barrier.

1. Introduction

The conventional electron device technology based on the electron charge is facing a serious problem of high idling power consumption due to leaky off-currents as the device size is decreased. Hence, it is necessary to find alternative low-power solutions to overcome the problem in the beyond-CMOS era. The silicon (Si) based spin-MOSFET [1] is considered to be one of the most promising candidates because of its high compatibility with the well-established CMOS technology [1] and long spin lifetime in Si [2]. In fact, spin injection into microns of Si channels by using the three terminal Hanle effect [3] or the four-terminal spin-valve effect [4] has been demonstrated up to 150 K with a spin-dependent output voltage below 1 mV. Recently, we have fabricated nano-scale Si-based spin-valve devices with a Fe/MgO/Ge spin injector / detector and a 20 nm-long Si channel by using electron beam (EB) evaporation and nanolithography. In those spin-valve devices, we observed a clear spin-valve effect up to 0.8% and spin-dependent output voltage ~ 13 mV [5], which is important for the realization of nano-scale spin-MOSFETs. In this work, by using molecular beam epitaxy (MBE) to grow the Fe/MgO/Ge spin injector / detector, we have significantly improved the spin-valve effect up to 3% and the spin output voltage up to ~ 20 mV, which are the highest values reported so far in lateral spin-valve devices. Importantly, we observed that the sign of the spin-valve effect is reserved at low temperatures, suggesting the possibility of spin-blockade effect of defect states in the MgO/Ge tunneling barrier.

2. Experiments

Device fabrication

The devices in this study were fabricated on a highly doped n-type Si (100) substrate with an electron density $n = 1\times10^{18}$ cm^{-3}. The Si substrates were cleaned by the standard cleaning with H_2SO_4/H_2O_2 solution, dipped into diluted hydrofluoric acid solution to remove the native oxide layer, and then rinsed in de-ionized water. After that, the samples were introduced into a MBE chamber with the base pressure of 1×10^{-9} Pa. We grew successively a 1 nm-thick Ge layer, 1 nm-thick MgO layer, and a 10 nm-thick Fe layer. Here, a double layer of MgO(2 nm)/Ge(1 nm) was inserted between the Fe electrodes and 20 nm-long Si channel (Figure 1) to enhance the spin injection efficiency to the Si channel.

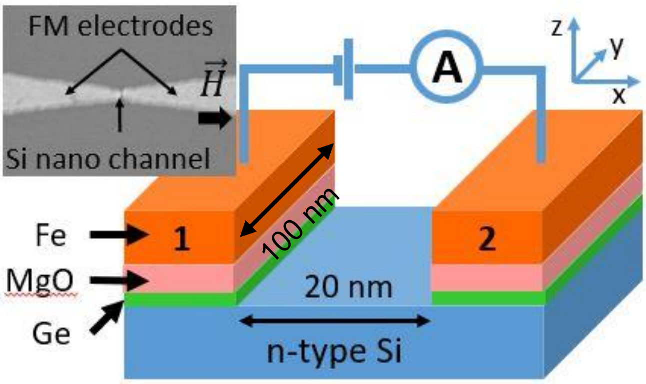

Fig. 1. Schematic structure of device with MgO / Ge tunnel barriers and the set-up of local spin-valve measurement. Inset shows a top-view image of the device by scanning electron microscopy.

After depositing the tunnel barrier and the FM layer, we used the e-beam lithography (EBL) and Ar ion-milling technique to fabricate the nano-scale Si spin-valve devices. First, we used the EBL and EB evaporation to pattern a 30 nm Au hard-mask layer on these samples. Then, we used Ar ion milling to define the 20 nm Si channels. Finally, we fabricated pad electrodes of Au (40 nm) / Cr (5 nm) by e-beam evaporation and standard photolithography.

Results and discussions

Because the Hanle effect cannot be measured in such a device with a nano-scale Si channel, we employed the two-terminal (local) spin-valve effect to detect the spin transport properties. Figure 2(a) shows representative MR curves of a device measured at 15 K with a magnetic field applied along the Si channel (along the *x*-direction in Fig. 1) and a bias voltage of 300 mV. We observed inverse magnetoresistance with a large change of resistance ΔR of 57 kΩ, corresponding to $\Delta R/R$ = 3%. We then systematically investigated the bias dependence, temperature dependence, and magnetic field direction dependence of the MR, and confirmed that that the observed signal is not caused by the anisotropy magnetoresistance (AMR) of the Fe ferromagnetic electrodes, or the tunneling anisotropy magnetoresistance (TAMR) at the Fe/MgO interface, but it is caused by the spin transport through the nano-scale Si channel.

Figure 2(b) shows the evolution of the MR ratio (=$\Delta R/R$) with increasing temperature. The MR decreases as temperature increases, but changes its sign at temperatures higher than 200 K. From the temperature dependence of the device resistance, we found that the tunneling process is unlikely due to the direct tunneling through the MgO/Ge barrier, but it is likely due to the thermally activated tunneling process through defect sites inside the barrier. Therefore, the inverse MR may be explained by the spin-blockade effect of defect sites in the tunnel barrier layer at low temperatures.

Figure 2(c) shows the spin-dependent output voltage $(\Delta R/R)V$ of the device as a function of bias voltage, measured at 15 K. The inset shows the bias voltage dependence of the MR ratio. We achieved the spin-dependent output voltage of 20 mV at the bias voltage of 0.9 V at 15 K, which is among the highest values reported so far in lateral spin-valve devices.

3. Conclusion

We have investigated the spin transport in the nano-scale Si spin-valve devices fabricated by the MBE method. We observed a large spin-valve effect with ΔR up to 57 kΩ, corresponding to $\Delta R/R$ = 3%. We observed that the sign of the spin-valve effect is reversed at low temperatures, suggesting the possibility of the spin-blockade effect of defect states in the MgO/Ge tunneling barrier. The highest spin-dependent output voltage is 20 mV at the bias voltage of 0.9V at 15 K, which is the highest values reported so far in lateral spin-valve devices. Our result is an important step towards the realization of nano-scale spin-MOSFETs.

Acknowledgements

This work is supported by the Tokyo Tech Nanofab Platform and the Center for Spintronics Research Network at the University of Tokyo.

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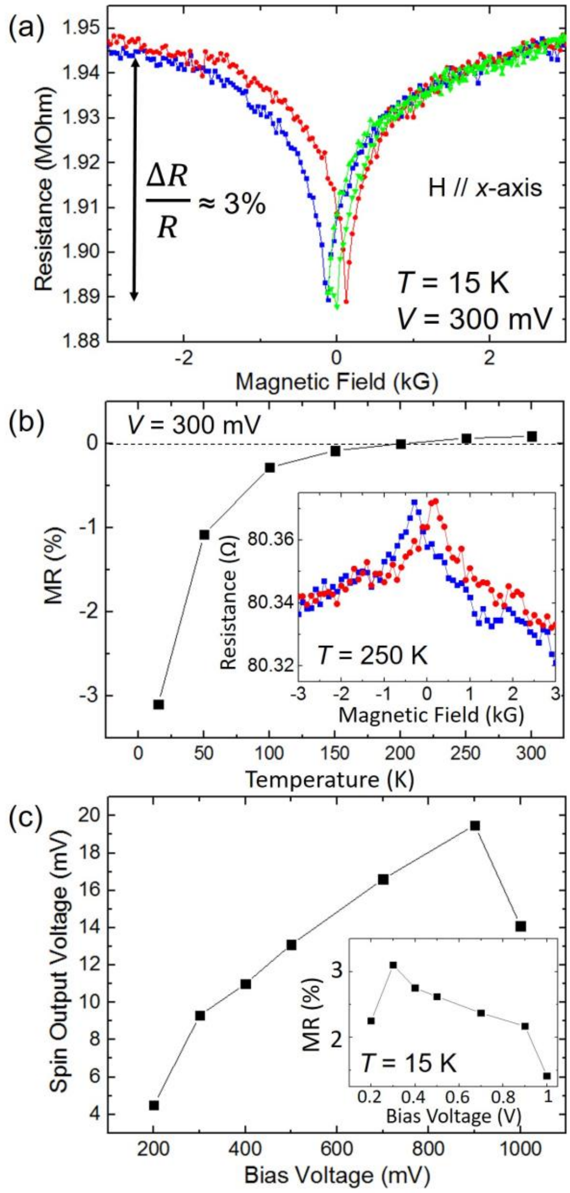

Fig. 2. (a) MR characteristics of a device measured at 15 K with a bias voltage of 300 mV. The red and the blue curves are the major loops, while the green curve is the minor loop. (b) Temperature dependence of MR(=$\Delta R/R$). Inset shows the MR curve at 250 K. (c) Bias voltage dependence of the spin-dependent output voltage $(\Delta R/R)$V at 15 K. The highest output voltage ΔV of 20 mV was achieved at the bias voltage of 0.9 V. Inset shows the bias voltage dependence of the MR.