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Effect of Insertion Layers on Schottky Barrier Height of Fe/*n*-type Ge Junctions

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Abstract

We investigated the effect of thin insertion layers of GeO_2 and MgO on the Schottky barrier height (ϕ_{SBH}) of the Fe/*n*-type Ge junctions where the Ge has a non-degenerate character. Current-voltage (*I-V*) characteristics of the Fe/GeO_2/Ge devices showed a significant suppression of the ϕ_{SBH} whereas the *I-V* curves hardly depended on thickness of the MgO layer. We report a large reduction of the ϕ_{SBH} from 0.60 eV down to about 0.25 eV by inserting the GeO_2 layer.

1. Introduction

Technologies for electrical spin injection in practical semiconductors (SCs) using a ferromagnetic (FM) tunnel contact have recently made remarkable progress [1]. For Si and Ge, the spin injection/detection experiments have been mainly done in degenerately doping SCs. From an application point of view, however, a non-degenerate SC should be more important because it is utilized as the core part of the practical SC devices such as a channel layer of metal-oxide-semiconductor field-effect-transistor (MOSFET). For a metal/non-degenerate SC junction, one of the major obstructs for developing a practical device should be a formation of wide depletion region due to the Schottky barrier potential. This causes a high resistance-area-product (*RA*), thereby a degradation of the device performance in a high-speed operation.

Ge is a promising candidate as a channel layer material of next-generation high-speed MOSFET. The Fermi-level (E_F) at a metal/Ge interface is strongly pinned at around the top of the valence band of Ge, resulting in high Schottky barrier height (ϕ_{SBH}) of 0.5 ~ 0.6 eV for *n*-type Ge irregardless of the work function of the metal electrode [2]. Nishimura *et al*. has recently reported that GeO_2 is one of the most effective insulating materials to alleviate the E_F-pinning and reduce the ϕ_{SBH} for the non-magnetic metal (Al and Au)/*n*-Ge junctions [3].

In this study, we demonstrate that the GeO_2 insertion layer is quite effective to reduce the ϕ_{SBH} for the FM metal (Fe)/non-degenerate *n*-type Ge junction.

2. Experiments

Films were grown by molecular beam epitaxy on non-degenerate phosphorous-doped Ge(001) substrates with a carrier concentration of ~ 5 × 10^{16} cm^{-3} at room temperature (RT). Tunnel contacts consisting of a Au(10 nm)/Fe(3 nm)/GeO_2(d_{GeO} nm) were deposited by electron-beam evaporation at RT. As reference samples, epitaxial Fe(001)/MgO(001) tunnel contacts were also grown on the substrate at RT, where the MgO is a canonical tunnel barrier [1,4]. The junctions with several different sizes of active area (*A*) between 25×12.5 and 600×300 μm were prepared with standard micro-fabrication techniques.

3. Results and discussion

Figures 1(a) and 1(b) show the current-voltage (*I-V*) characteristics of the devices with the GeO_2 and MgO insertion layers at RT. The current dramatically increases by inserting GeO_2 layers up to d_{GeO} = 1.0 nm, indicating the alleviation of the E_F-pinning and a large reduction of the ϕ_{SBH}. The current starts to decrease with further increasing d_{GeO}. In contrast to the GeO_2-based device, no noticeable change was observed in the *I-V* characteristics of the Fe/MgO/Ge devices, suggesting that the ϕ_{SBH} is hardly

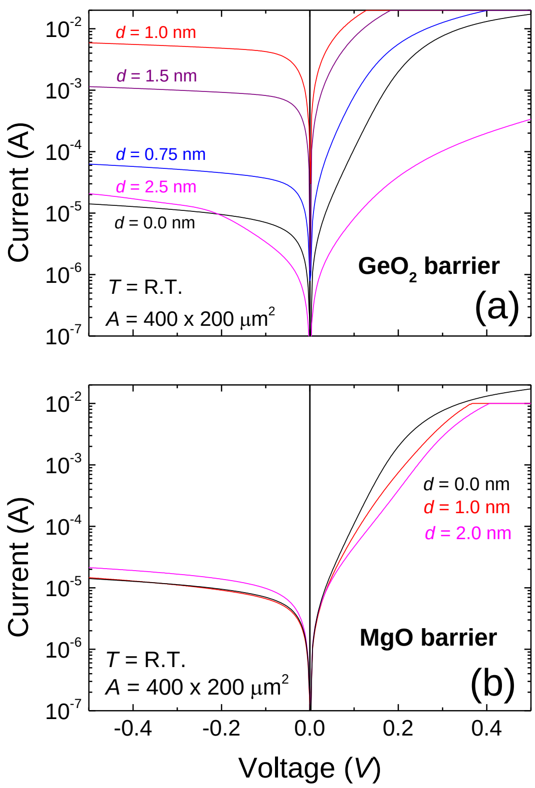

Fig. 1 *I-V* characteristics of the devices with (a) GeO_2 and (b) MgO insertion layers at RT, respectively.

suppressed by inserting the MgO layer. This is consistent with our previous results showing an absent of Schottky potential in the Fe/MgO/*p*-type Ge junctions [5, 6].

The *RA* as a function of d_{GeO} is given in Fig. 2, where the *RA* is obtained from a linear part of *I-V* characteristics at a low *V* range of ± 10 mV. For $d_{GeO} \geq 1.5$ nm, a good linear relation in the ln(*RA*)-d_{GeO} plot appeared, which is characteristics in a tunnel junction [7]. This indicates that tunneling is a dominant transport process and the *RA* is governed by the GeO_2 layer for $d_{GeO} \geq 1.5$ nm.

For a conventional metal/SC Schottky diode, the thermionic emission is a dominant transport process. Then, the value of ϕ_{SBH} can be estimated from the slope of the $\ln(I_S/T^2)$- T^{-1} plot (thermal-activation method) without considering the tunneling transport [7], where the I_S is the saturation current. In a case of the present Fe/GeO_2/Ge devices, however, this method is no longer valid to evaluate an accurate value of the ϕ_{SBH} because the tunneling is a major transport mechanism, especially for $d_{GeO} \geq 1.5$ nm. Here, we estimate the ϕ_{SBH} of the Fe/GeO_2/*n*-Ge devices by taking the tunneling probability of the GeO_2 layer into account. For a metal/insulator/non-degenerate SC junction, *RA* [≡ $(dJ/dV)^{-1}$] at low *V* is expressed by [7]

$$RA \approx \frac{\eta k}{A^{*}Tq}\exp(\varsigma^{1/2}d)\exp\left(\frac{q\phi_{SBH}}{kT}\right) \qquad (1),$$

where η is the ideality factor, *k* is the Boltzmann constant, A^* is the effective Richardson constant, *T* is the temperature, *q* is the electron charge. The $\exp(-\zeta^{1/2}d)$ represents the tunneling probability due to the insulating layer. Here, ζ (in eV) and *d* (in angstrom) are the effective barrier height and thickness of the insulating layer, respectively (A constant of 1.01 $eV^{-1/2}$/angstrom is omitted). Following the equation (1), a relative change in the ϕ_{SBH} from that of the device with d = 0.0 nm ($\Delta\phi_{SBH}$) can be given by

$$\Delta\phi_{SBH} \approx \frac{kT}{q}\left[\ln\left(\frac{A^{*}(0)}{A^{*}(d)}\cdot\frac{\eta(d)}{\eta(0)}\cdot\frac{RA(0)}{RA(d)}\right)+\varsigma^{1/2}d\right] \qquad (2).$$

The value of ζ is estimated to be 0.35 eV from the slope of linear part in the ln(*RA*)-d_{GeO} plot. We obtained the ϕ_{SBH} (= 0.60 - $\Delta\phi_{SBH}$, where 0.60 eV is the ϕ_{SBH} of Fe(001)/*n*-Ge(001) junction [8]) as a function of d_{GeO} by assuming that the A^* does not depend on d_{GeO} (Fig. 2). The ϕ_{SBH} decreases and reaches to be ~ 0.25 eV (corresponding to $\Delta\phi_{SBH}$ ~ 0.35 eV) for $d_{GeO} \geq 1.5$ nm. Further reduction of the ϕ_{SBH} would be expected by optimizing growth conditions, post-annealing or using lower work-function FM electrode such as Gd [9].

4. Conclusion

In this study, we present a systematic investigation on the effect of the GeO_2 and MgO insertion layers on the ϕ_{SBH} and *RA* for the Fe/non-degenerate *n*-type Ge junctions. The

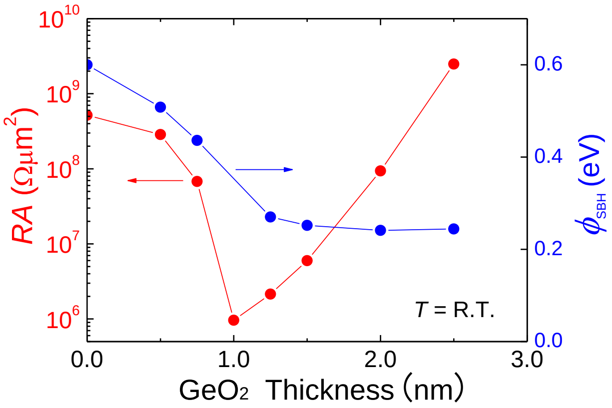

Fig. 2 *RA* and ϕ_{SBH} of the Fe/GeO_2/*n*-Ge devices as a function of the GeO_2 thickness.

data on *I-V* characteristics show a large suppression of the ϕ_{SBH} by inserting the GeO_2 layer. A good linear relation was observed in the ln(*RA*)-d_{GeO} for $d_{GeO} \geq 1.5$ nm, indicating that the *RA* is determined by the FM tunnel contact. For the device with $d_{GeO} \geq 1.5$ nm, the values of ϕ_{SBH} were estimated to be about 0.25 eV by taking the tunneling probability of the GeO_2 into account. This result offers that the GeO insertion layer is a promising candidate for the tunnel barrier of the FM contact for Ge-based spintronic device.

Acknowledgements

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