Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp919-920

Marked Suppression of the Fermi-level Pinning at Atomically Matched Fe_3Si/*p*-Ge(111) Contacts

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1. Introduction

It is well known that the Fermi-level pinning (FLP) effect at many metal/germanium (Ge) interfaces is very strong. For the metal/*n*-Ge interfaces, the electrical properties show Schottky behavior with a high Schottky barrier height (Φ_B) of ~0.6 eV, while for the metal/*p*-Ge interfaces Ohmic characteristics are frequently observed [1,2].

Recently, we found that using Fe_3Si/Ge(111) contacts can reduce the FLP effect [3]. In particular, the rectifying current-voltage (*I-V*) curves observed for the Fe_3Si/*p*-Ge(111) contacts were the first experimental demonstration of Schottky-like *I-V* behavior for directly connected metal/*p*-Ge contacts. In contrast, for the Fe_3Si/Ge(100) contacts, the electrical properties were dominated only by the strong FLP effect [3]. We consider that these differences between the Fe_3Si/Ge(111) and Fe_3Si/Ge(100) contacts are caused by the amount of the atomic matching at the interfaces between Fe_3Si and Ge. Figure 1(a) shows illustrations of the crystal structures for DO_3-ordered Fe_3Si and Ge. Here, we focus on the atomic arrangements looked at (111) and (100) planes for DO_3-ordered Fe_3Si and Ge [see Fig. 1(b)]. When we look at (111) plane, we find that the interface between Fe_3Si and Ge can completely match, having almost no dangling bond. In contrast, looking at (100) plane, we can find many atomic mismatches at the interface, giving rise to lots of dangling bonds.

If dangling bonds are major contributions to the strong FLP at metal/Ge interfaces, decreasing contact area (*A*) may obtain some information on the influence of the dangling bonds on the electrical properties for the atomically matched Fe_3Si/Ge(111) interface. In our previous work (Ref. 3), we used the Fe_3Si/Ge(111) diodes with a large *A* of ~10^6 μm^2. In this paper, we try to measure the *I-V* characteristics of the Fe_3Si/*p*-Ge(111) diodes with a small *A* of ~1 μm^2.

2. Experimental details

Fe_3Si/*p*-Ge(111) contacts were fabricated by low-temperature molecular beam epitaxy (LTMBE) [3], where *p*-Ge (111) substrates were used already on the market and their impurity densities were ~9.0 × 10^{-14} cm^{-3}. The chemical composition of the grown Fe_3Si layers was almost stoichiometric atomic composition [4]. After 25-nm-thick Fe_3Si layers were grown, a backside Al Ohmic contact was formed. And then, the Schottky diodes with *A* of ~1 μm^2 were fabricated using electron beam lithography and Ar^+ ion milling. Electrical properties of Fe_3Si/*p*-Ge(111)/Al diodes were measured by a standard dc method at various temperatures. As reference samples, we also fabricated the Fe_3Si/*p*-Ge(100)/Al diodes.

3. Results and Discussion

Figures 2(a) and (b) show the absolute value of the current (|*I*|) as a function of the bias voltage (*V*) at temperatures from 100 to 350 K for the two different diodes with *A* of ~1 μm^2

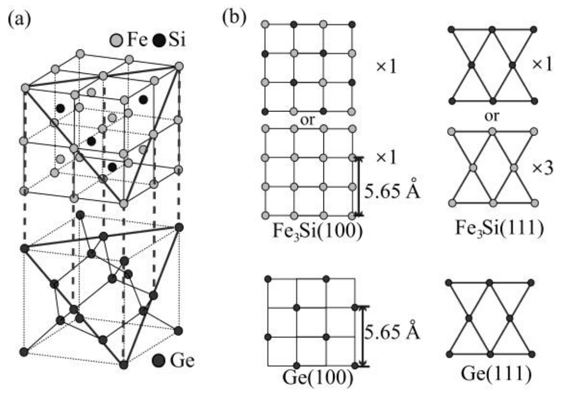

Fig. 1. (a) The illustration of the crystal structures of DO_3-ordered Fe_3Si and Ge. (b) The top and bottom figures are the atomic arrangements of Fe_3Si and Ge, respectively, which show (100) plane (left) and (111) plane (right).

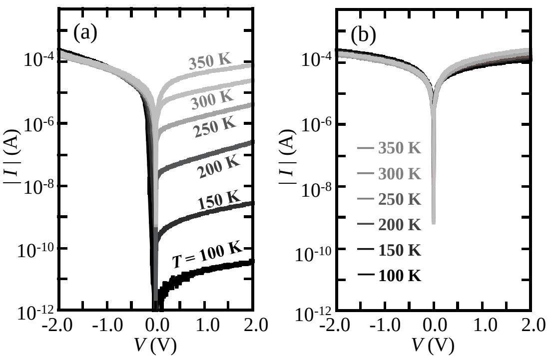

Fig. 2. (a) The significant rectifying *I-V* characteristics and (b) the symmetric *I-V* characteristics with respect to *V* polarity for the Fe_3Si/*p*-Ge(111) diodes at temperatures from 100 K to 350 K.

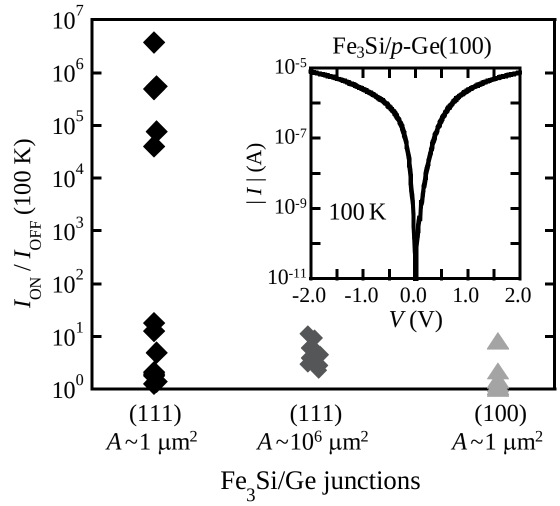

Fig. 3. The ratio of the forward-bias current I_{ON} (V < 0) to the reverse-bias current I_{OFF} (V > 0) at 100 K for the Fe_3Si/*p*-Ge(111) diodes with A ~1 mm^2 and ~10^6 mm^2, and the Fe_3Si/*p*-Ge(100) diodes with A ~1 mm^2 . The inset shows the *I-V* characteristic for the Fe_3Si/*p*-Ge(100) diode at 100 K.

fabricated from an atomically matched Fe_3Si/*p*-Ge(111) junction. In Fig. 2(a) we can see clear rectifying characteristics at all temperatures, i.e., the Schottky behavior can be seen. These results mean that the FLP effect is suppressed markedly. In contrast, the almost symmetric *I-V* characteristics with respect to *V* polarity are also observed for all temperatures in Fig. 2(b). Thus, this diode has Ohmic *I-V* characteristics due to the strong FLP effect. We emphasize that Fe_3Si/*p*-Ge(111) diodes with A of ~ 1 μm^2 show both characteristics, i.e., Schottky and Ohmic behavior.

In Fig. 3 we plot the ratio of the forward-bias I_{ON} (V < 0) to the reverse-bias current I_{OFF} (V > 0), i.e., I_{ON}/I_{OFF} at 100 K. In addition to the Fe_3Si/*p*-Ge(111) diodes with A of ~1 μm^2, we also show I_{ON}/I_{OFF} (100 K) for the Fe_3Si/*p*-Ge(111) diodes with A of ~10^6 μm^2 and the Fe_3Si/*p*-Ge(100) diodes with A of ~1 μm^2. It should be noted that the I_{ON}/I_{OFF} (100 K) values split between 10^0 ~ 10^1 and 10^4 ~ 10^7 for the Fe_3Si/*p*-Ge(111) diodes with A of ~1 μm^2. On the other hand, for the Fe_3Si/*p*-Ge(111) diodes with A of ~10^6 μm^2 and the Fe_3Si/*p*-Ge(100) diodes with A of ~1 μm^2, the I_{ON}/I_{OFF} (100 K) values are almost constant, i.e., I_{ON}/I_{OFF} = ~ 10^1 and = ~10^0, respectively.

Judging from the data for the Fe_3Si/*p*-Ge(100) diodes, we can understand that I_{ON}/I_{OFF} (100 K) = ~10^0 is caused by the Ohmic characteristic, as shown in the inset of Fig. 3, due to the strong FLP. Though small rectifications with I_{ON}/I_{OFF} (100 K) = 10^1 were seen in all the Fe_3Si/*p*-Ge(111) diodes with A of ~10^6 μm^2, we can speculate that these features are attributed to the mixed contributions of the FLP and its suppression to the *I-V* characteristics [3]. On the other hand, the discreteness of the I_{ON}/I_{OFF} (100 K) values for the Fe_3Si/*p*-Ge(111) diodes with A of ~1 μm^2 is attributed to the two different situations, i.e., almost no or a strong contribution of the FLP to the *I-V* characteristics. These features can be interpreted by the model based on the influence of the interfacial defects at the metal/Ge interface on the hole transport properties.

4. Conclusions

Decreasing the diode's contact aria A of the atomically matched Fe_3Si/*p*-Ge(111) to ~1 μm^2, we clearly identified two different *I-V* characteristics, i.e., Schottky and Ohmic behavior, for the hole transport properties. These results indicate that there is an influence of extrinsic factors such as dangling bonds on the FLP effect at metal/Ge interfaces.

5. Acknowledgements

This work was partly supported by Industrial Technology Research Grant Program from NEDO.

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