N-3-05
Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp587-588

New types of resonant tunneling currents at Si-p/n junctions; Theoretical design

Sanghun Cho and Takashi Nakayama[1]

Department of Physics, Chiba University
1-33 Yayoi, Inage, Chiba 263-8522, Japan
Phone: +81-43-290-2762 E-mail: acda1899@chiba-u.jp

Abstract

It is well known that the co-doping of Al and N enhances the tunneling currents through Si-p/n junction due to the resonance of dopant states with conduction bands. In this work, we propose different types of two resonant tunnelings to enhance the ON currents of Si tunnel FET. One is to use the resonance between donor and acceptor dopant states, while the other is to use resonant states caused by the quantum-well-like hetero interface. The present results will help to design and realize Si-based tunnel FETs.

1. Introduction

Tunnel field-effect transistor (TFET) is one of promising candidates for next-generation energy-saving devices, due to its much steeper switching [1,2]. Although Si-TFET is fascinating because of the matching to developed Si technology, the tunneling ON current is still low owing to its indirect band-gap transitions. Recently, Mori and his coworkers succeeded in remarkably enhancing an ON current in Si-TFET utilizing a co-doping of Al and N atoms around the p/n junction [3,4]. Then, we showed by theoretical calculations that such enhancement occurs because the dopant states resonate with conduction bands and the transitions from valence to conduction bands markedly increase [5].

This result indicates that we can also enhance the ON current by designing other types of resonant tunneling. Resonance has a clear advantage because the OFF current is small at off-resonance state, while the ON current sharply increases at resonance. In this work, by changing the potential profile around p/n junctions, we demonstrate two new types of resonance tunneling currents at Si-p/n junctions.

2. Calculation Model and Method

Figures 1(a)-1(c) show the valence and conduction-band profiles at Si(100)-p/n junctions considered in this work. Fig. 1(a) shows the SD junction having a single donor type of dopant, corresponding to the co-doping by Mori et al. and already studied in our previous work [5]. Fig. 1(b) shows the DD junction having donor and acceptor types of double dopants, while Fig. 1(c) is the HI junction having hetero interface in the n-Si side.

To simulate these junctions, we employ the simple one-dimensional tight-binding models using the Wannier basis of valence and conduction bands. Dopant electronic states are produced by changing the on-site energy at the dopant site, while the hetero-interface is realized by arranging the abrupt change of on-site energy. The detailed parameters for Si-p/n junction are described in our previous publication [5]. The tunneling probability of electrons through the junction is calculated by the time-evolution of electron wave packets, following the Schrödinger equation, the details of which are also explained in the previous work [5].

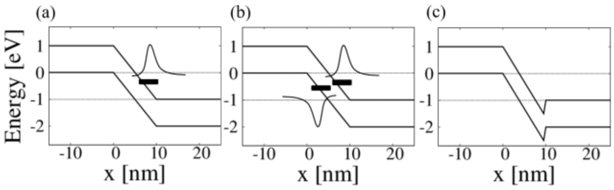

Fig.1 Schematic pictures of valence and conduction-band profiles at Si-p/n junctions; (a) a single dopant (SD) junction, (b) double dopant (DD) junction, and (c) hetero-interface (HI) junction.

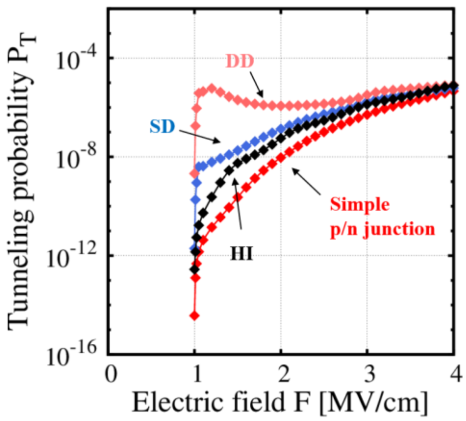

Fig.2 Calculated tunneling probabilities at SD, DD, and HI Si-p/n junctions as a function of electric-field strength. The result for simple Si-p/n junction is also shown for reference.

3. Results and Discussions

Figure 2 shows calculated tunneling probabilities of electrons through various junctions as a function of electric field. Compared to the simple junction, the tunneling probability is enhanced for all SD, DD, and HI junctions. To understand the origin of such enhancement, we show the local densities of electronic states (LDOS) around p/n junctions in Figs. 3(a)-3(c).

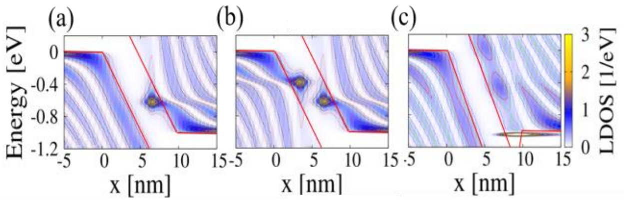

Fig.3 Local densities of electronic states around Si-p/n junctions; (a) SD, (b) DD, and (c) HI junctions. Red solid lines indicate edges of valence and conduction bands.

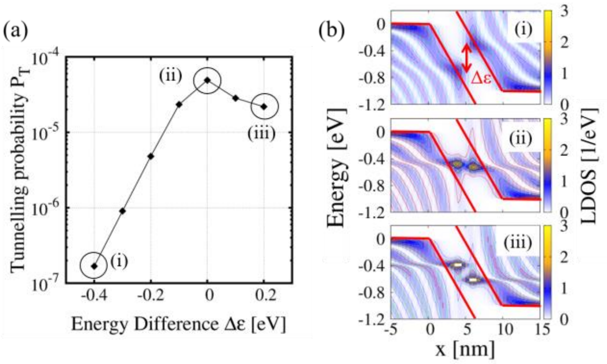

Fig.4 (a) Tunneling probability at the DD junction as a function of energy difference $\Delta\varepsilon$ between donor and acceptor dopant states. (b) Local densities of electronic states at the DD junction, corresponding to (i)-(iii) points in (a).

3.1 Junction with a single type of dopant

First, we shortly review why the tunneling is enhanced at the SD junction. As seen in Fig. 3(a), the dopant produces an electronic state that is resonating with the conduction band of n-Si. Such resonance effectively reduces the tunneling length between p-Si valence and n-Si conduction bands and markedly increases the tunneling probability.

3.2 Junction with donor & acceptor types of dopants

Next, we consider why the tunneling is enhanced at the DD junction. As seen in Fig. 3(b), both acceptor and donor produce electronic states in the band gap of Si. The resonance occurs between these states. In this case, since the tunneling length becomes much smaller than the case of Fig. 3(a), the probability is much larger than the case of the SD junction as seen in Fig. 2. To see the feature of resonance more clearly, we change the energy difference $\Delta\varepsilon$ between these states as shown in Fig. 4(b) and calculate the tunneling probability, the result being shown in Fig. 4(a). As the energy difference approaches zero, the probability remarkably increases, which definitely demonstrates that the origin of enhancement is the resonance. The resonance feature is also seen in Fig. 2, where the probability first increases and then a slightly decreases as the electric field increases.

3.3 Junction with hetero-semiconductor interface

Then, we consider why the tunneling is enhanced at the HI junction. As seen in Fig.3(c), when the quantum-well-like triangle potential is produced around the left edge of n-Si layers, there appear not only the bound states but also the resonant states embedded in the conduction bands. The latter states are localized around the edge of conduction band in the p/n-junction region, as schematically shown in Fig. 5(b). As a result, the tunneling length between valence band in p-Si and conduction band in n-Si decreases, which is the reason why the tunneling probability increases compared to the case of simple p/n junction as seen in Fig. 2.

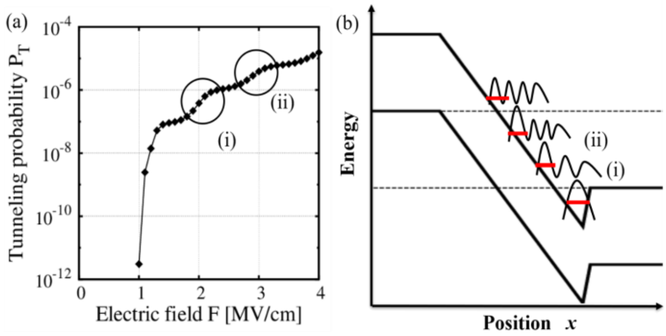

Fig.5 (a) Tunneling probability at the HI junction as a function of electric field. (b) Schematic picture to explain the appearance of resonance states that are embedded in conduction bands at the HI junction.

It is interesting to note that the tunneling probability shows several increases as shown in Fig. 5(a) in some cases of the HI junctions as the electric field increases. This is because, when there exist more than one resonance states as seen in Figs. 3(c) and 5(b), the number of resonance states that contribute to the current increases as the electric field increases. We found that this feature is sensitive to the many-body interaction between electrons when the bound states exist (not shown here).

4. Conclusions

In this work, we propose two new types of resonant tunneling to increase the ON currents of Si tunnel FET. One is to use the resonance between donor and acceptor dopant states, while the other is to use resonant states caused by the quantum-well-like hetero interface. We demonstrated that these resonance tunnelings not only enhance the current but also show the non-monotonous current-voltage characteristics at p/n junctions. We hope that the present result will help to design & realize Si-based tunnel FETs in near future.

Acknowledgements

This work is supported by MEXT KAKENHI (17K05488) and supercomputing centers of ISSP of Univ. Tokyo, Okazaki R. Center of NIMS, and Kyushu Univ.

References

[1] A. M. Ionescu et al., Nature **479**, 329 (2011).
[2] M. Noguchi et al., IEDM Tech. Dig., 28.1.1 (2013).
[3] T. Mori et al., VLSI Tech. Dig. 86 (2014).
[4] T. Mori et al., MRS Commun. **7**, 541 (2017).
[5] S. Cho et al., Jpn. J. Appl. Phys. (2019) in press.