Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp804-805

Impact of Dopant-Induced States on Interband Tunneling in Nanoscale *pn* Junctions

H. N. Tan[1], S. Purwiyanti[1,2], D. Moraru[1], L. T. Anh[3], M. Manoharan[3], T. Mizuno[1], H. Mizuta[3,4], D. Hartanto[2], and M. Tabe[1]

[1]Research Institute of Electronics, Shizuoka University, Japan
[2]Department of Electrical Engineering, University of Indonesia, Indonesia
[3]School of Materials Science, Japan Advanced Institute of Science and Technology, Japan
[4]Nano Group, Faculty of Physics and Applied Sciences, University of Southampton, United Kingdom
Email: f0330299@ipc.shizuoka.ac.jp

Abstract

We report on an interband tunneling nanoscale Si pn junction with high doping concentration of ~5.0×10^{19} cm^{-3}. We find that transport characteristics show step-like structure, indicating that interband tunneling is strongly influenced by dopant-induced states of the depletion region. Also, we find a current peak observed in reverse bias condition at low temperatures, indicating that the dopant states can directly contribute to interband tunneling current. This is different from pn junctions with low doping concentration of ~1.0×10^{18} cm^{-3}, in which individual dopant atoms work as electron traps.

1. Introduction

The pn junctions are fundamental building blocks for electronic devices. Therefore, study about nanoscale pn junctions has an important role in clarifying the operation of nano-devices like tunnel field-effect transistors (TFETs) or downscaled metal-oxide-semiconductor FETs. Recently, nanoscale pn junctions have been studied from different approaches, such as tunneling functionality [1-3], or impact of low-dimension on electrical characteristics [4].

Our main target is to clarify the influence of individual dopants on transport characteristics. Previously, we demonstrated the influence of individual dopants in the depletion layer of Si pn junctions on potential landscape, by using low-temperature Kelvin probe force microscopy [5,6]. We also reported that individual dopant atoms work as electron traps, inducing RTS in current at temperature under 30 K in devices with low doping concentration of ~1.0×10^{18} cm^{-3} [7].

Here, we show I-V characteristics of nanoscale interband tunneling pn junction devices, for which doping concentration is relatively high. We find that dopant-induced states of the depletion region and dopant states located in the depletion region play a key role in interband tunneling mechanism.

2. Structure of nanoscale tunneling pn diodes

Nanoscale tunneling pn diodes are fabricated in silicon-on-insulator (SOI) substrates, with a constriction structure, as shown in Fig. 1(a). We utilized thermal diffusion technique for selective-doping process to define region of n-type (doped with phosphorus) and p-type (doped with boron). The atomic force microscope (AFM) image of the device, including the junction, is shown in Fig. 1(b). Doping concentrations in both p-type and n-type regions are ~5.0×10^{19} cm^{-3}. The top-Si thickness is ~10 nm, and width of the constriction region of pn diode is on the order of ~100 nm. For electrical measurements, we applied two types of bias, i.e., bias between p and the n type (V_A), and bias from the substrate (V_{sub}). The measurements have been done using low-temperature measurement system, under high vacuum conditions.

3. Impact of dopant-induced states on interband tunneling

First, I-V characteristics as a function of temperature for pn junctions with low doping concentration (1.5×10^{18} cm^{-3}) are shown in Fig. 2(a). These devices exhibit rectifying characteristics, even though the pn junction region is in nanoscale, in the whole temperature range [7].

On the other hand, in highly-doped devices, we observed I-V characteristic exhibiting step-like behavior in both forward and reverse bias conditions at low temperatures, as shown in Fig. 3(a). The absence of negative differential conductance (NDC), as a common feature of tunneling current on pn junction under forward bias [8], indicates that some energy states exist in the band gap, causing higher excess current [9]. By first principle simulation, as it will be explain below, we also observed the existence of band tailing caused by dopant-induced density of states (DOS) in nanoscale Si devices. In our devices, this band tailing in the depletion region mediates the interband tunneling, correspondingly producing current step behavior, as indicated in Fig. 3(b).

Figure 4 shows ab initio simulations of nanostructured Si doped with single donor or acceptor. It is seen that the DOS spectra are quantized, especially near the band edge, with dopant states mixed with Si quantized states.

Furthermore, in some devices, we obtained fine current peaks in I-V characteristic at low temperature. Figure 5 shows I-V characteristics under reverse bias for several substrate biases (V_{sub}). For some V_{sub} values, current steps behavior can also be observed, similarly to the forward bias behavior. However, for small range of V_{sub}, we observed current peak feature, as marked in Fig. 5(e) by the dashed box. It most likely that there are some additional energy states in the band gap of depletion layer region. By changing gate voltage, when one of these states is aligned with electron energy states in source, resonant tunneling current is enhanced, inducing a peak in drain current, as indicated in Fig. 5(f). The origin of these states can be either dopants or point defects, but further study is needed to fully clarify this issue.

4. Conclusions

In this work, we found that, in nanoscale interband tunneling pn junctions, dopant-induced states of depletion region and dopant states in the depletion region play a critical role in interband tunneling mechanism. This finding provides a different way to monitor individual dopant levels in depletion layer region of nanoscale pn junction devices. Furthermore, this can be extended to the study of dopant-atom devices, with properties dominantly governed by dopants.

Acknowledgements

This work was supported by MEXT Grants-in-Aid for Scientific Research (23226009, 25630144, and 22310085). We thank Y. Kuzuya and S. Miki for their support.

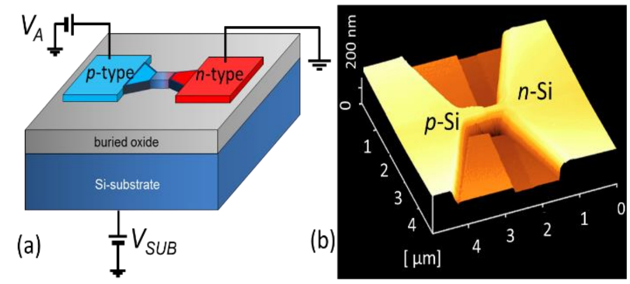

Fig. 1 (a) Schematic structure of nanoscale lateral *pn* junctions and *I-V* measurement setup. (b) AFM measurement result of constriction region.

References

[1] H. Schmid *et al.*, Nano Lett. **12,** (2012) 699.
[2] C. Aydin *et al.*, Appl. Phys. Lett. **84**, (2004)1708.
[3] A.L. Vallerr *et al.*, Nano Lett. **10**, (2010) 4813.
[4] Y. Omura, Jpn. J. Appl. Phys. **39**, (2000) 1579.
[5] R. Nowak *et al.*, Appl. Phys. Lett. **102**, (2013) 083109.
[6] R. Nowak et al., Thin Sold Films **557**, (2014) 249
[7] S. Purwiyanti *et al*., Appl. Phys. Lett. **103**, (2013) 243102.
[8] L. Esaki *et al*., Phys. Rev. **109**, (1958) 603.
[9] A.G. Chynoweth *el al.*, Phys. Rev. **121,** (1961)3.

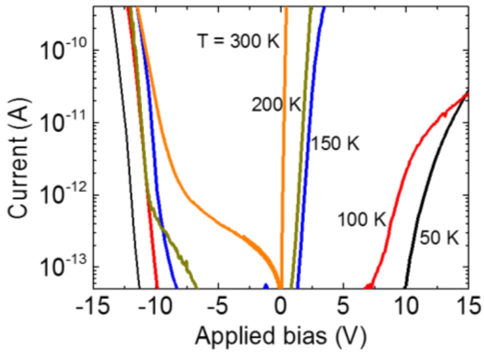

Fig. 2 I-V characteristics in forward and reverse bias at several temperatures (T = 50~300K) for devices with low doping concentration [7].

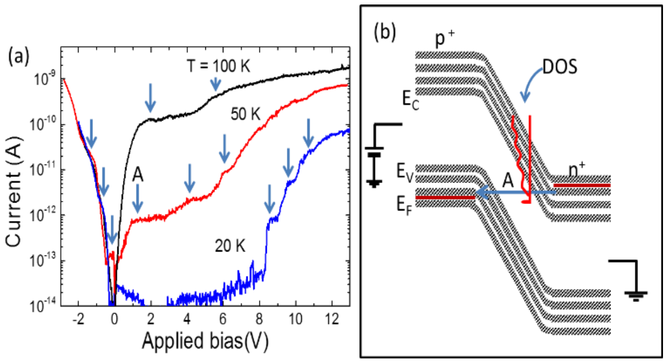

Fig. 3 (a) I-V characteristics exhibiting current steps in forward and reverse bias at low temperature. Arrows mark the observed steps at 50 K. (b) Band diagram of corresponding to current step marked arrow A. The arrow shows interband tunneling via quantized energy states in band gap.

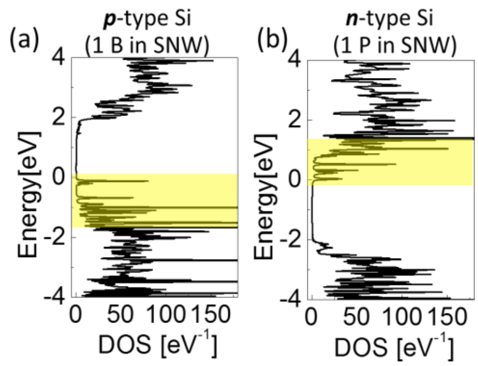

Fig. 4. First principle simulation results of DOS spectra for Si nanostructures doped with individual (a) B and (b) P dopants. Dopant discrete energy states appear near the corresponding band edge.

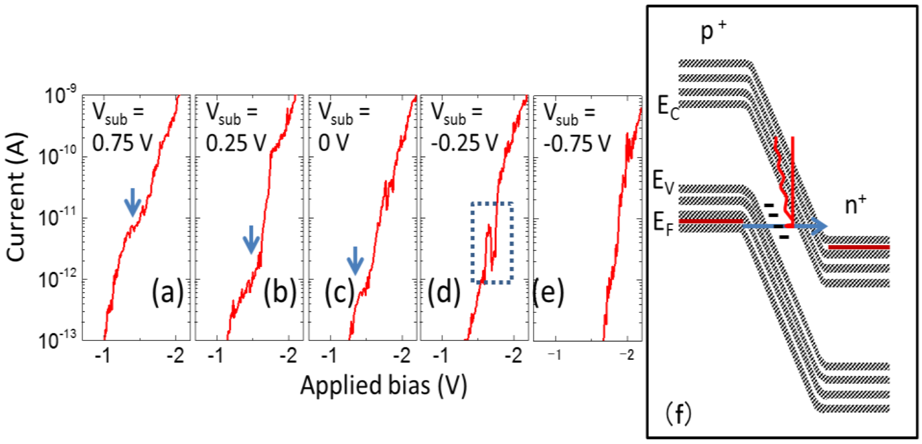

Fig. 5. (a) – (e) Substrate bias dependence of interband tunneling current in reverse bias condition at 10 K. Current steps can be observed at several V_{SUB} as indicates by blue arrows. Current peak appears only for V_{sub} = -0.25 V.
(f) Band diagram for interband tunneling via dopant state in band gap, corresponding to peak in (d).