Effects of phonons and discrete dopants on band-to-band tunneling in two-dimensional Si *pn* junction diodes

°D. Moraru[1,2,*], H. N. Tan[1], R. Unno[1], T. Mizuno[1], M. Manoharan[3], L. T. Anh[3], R. Nuryadi[4], H. Mizuta[3,5], and M. Tabe[1]
[1]Research Institute of Electronics, Shizuoka University *E-mail: moraru.daniel@shizuoka.ac.jp
[2]Faculty of Engineering, Shizuoka University
[3]Japan Advanced Institute of Science and Technology (JAIST), Japan
[4]Agency for Assessment and Application of Technology, Indonesia [5]Univ. of Southampton, UK

Introduction

Si *pn* junction diodes are fundamental devices for electronics, and their miniaturization into nanoscale is expected to reveal new physics related to the low-dimensionality and dopant individuality [1]. In previous reports, we identified the role of discrete dopants working as traps in downscaled *pn* diodes doped with moderate doping concentrations [2-4]. Here, we characterize high-concentration *pn* diodes (Esaki tunnel diodes), with band-to-band tunneling transport significantly affected by two factors: (i) discrete dopants; (ii) phonon assistance.

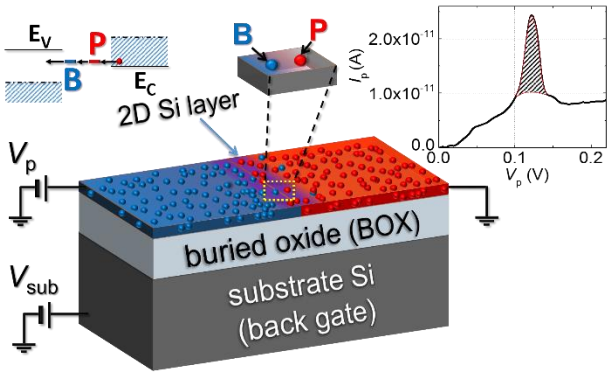

Fig. 1. Schematic depletion region of a 2D highly-doped *pn* diode, with a P-B pair giving rise to resonance-assisted tunnel current enhancement.

Thin lateral *pn* and *pin* diodes

Figure 1 show schematically the depletion region of a lateral *pn* diode formed in an SOI layer (*pin* diodes were also fabricated by introducing an *i*-layer between *p* and *n* leads). Si thickness in the co-doped region is evaluated to ~9.0 nm, while doping concentration is on the order of ~1.0×10^{20} cm^{-3}. Under these conditions, *p* and *n* sides are degenerate and band-to-band tunneling occurs in reverse- and forward-bias regions.

Band-to-band tunneling in thin-Si with phonon assistance

Figure 2(a) shows an example of I_p-V_p characteristics at low temperature (5.5 K) for a *pn* junction diode. In some devices, as reported before [5], we observed tunnel-current enhancement due to pairs formed by a P-donor and a B-acceptor (see Fig. 1, insets). Such behavior was not observed in *pin* junction diodes. However, in all devices (*pn* and *pin*), we can observe clear current modulations (i.e., peaks in conductance, dI_p/dV_p) suggesting that tunneling involves discrete energy levels. The origin of these modulations is discussed in details in this report.

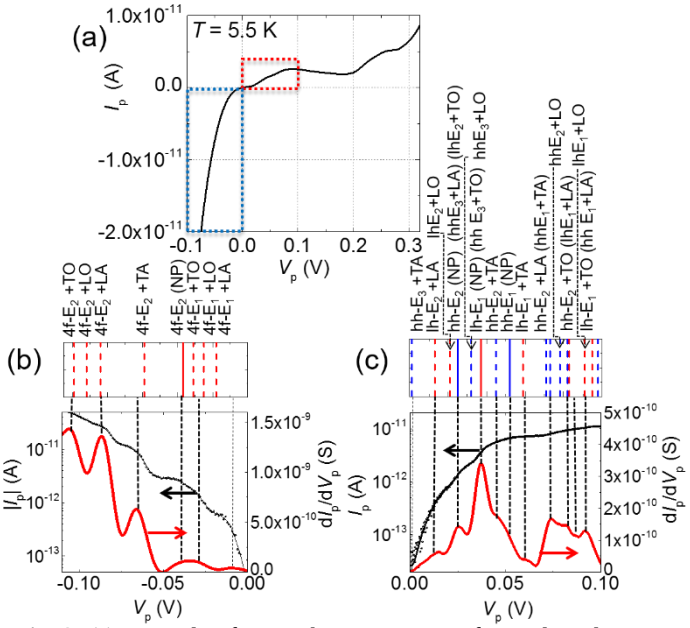

Fig. 2. (a) Example of I_p-V_p characteristics in forward- and reverse-bias regimes at 5.5 K. (b)-(c) I_p and dI_p/dV_p curves, with features correlated with 2D-quantized energy levels, with phonon assistance (TA, TO, LA, LO) for 4-fold valley electrons and light/heavy holes.

By analyzing the simple 2D quantization of energy levels, the fine features cannot be reproduced. A good match can only be attained by considering assistance by phonon emission, as shown in Figs. 2(b)-(c). Phonon-assisted tunneling appears, thus, prominently in the 2D *pn* and *pin* diodes. This suggests that phonons play a key enhanced role in the function of downscaled Si *pn* and *pin* diodes. Additional analysis of the two types of devices and their evolution with temperature can clarify this enhanced impact in nanoscale diodes.

References [1] M. Tabe *et al.*, ECS Trans. **69**, 189 (2015). [2] A. Udhiarto *et al.*, Appl. Phys. Express **5**, 112201 (2012). [3] R. Nowak *et al.*, Appl. Phys. Lett. **102**, 083109 (2013). [4] S. Purwiyanti *et al.*, Appl. Phys. Lett. **103**, 243102 (2013). [5] H. N. Tan *et al.*, Proc. Silicon Nanoelectronics Workshop (2015).