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

D. Moraru1,2, H. N. Tan1, R. Unno1, T. Mizuno1, M. Manoharan3, L. T. Anh1, R. Nuryadi4, H. Mizuta3,4, and M. Tabeda4
1Research Institute of Electronics, Shizuoka University 2E-mail: moraru.daniel@shizuoka.ac.jp
3Faculty of Engineering, Shizuoka University
4Japan Advanced Institute of Science and Technology (JAIST), Japan
5Agency for Assessment and Application of Technology, Indonesia

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.

Thin lateral pn and pin diodes
Figure 1 schematically shows the depletion region of a lateral pn diode formed in a 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 ~1.0x10^20 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.

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.