Study of Quantized-Energy Effects in Si Nanoscale Lateral *pn* Junction Diodes

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Abstract — **In this work, we study SOI nanoscale *pn* junctions and find that transport characteristics are strongly affected by states of individual dopants and by quantized energy states. For *pn* diodes with lower doping concentration, we find that individual dopant atoms work as electron traps, inducing RTS in the diode current. On the other hand, for highly-doped *pn* diodes, quantization effects play critical roles in transport characteristics for both forward and reverse bias regimes.**

I. Introduction

The *pn* junctions are fundamental building blocks for electronic devices and, therefore, it becomes critical to study their properties when they are reduced into nanoscale. Nanoscale *pn* junctions have been studied, in recent years, from various viewpoints, such as for photonics applications [1,2], tunneling functionality [3,4], and impact of low dimensionality on the electronic properties [5,6]. More recently, we have demonstrated the influence of individual dopants in the depletion region of silicon-on-insulator (SOI) *pn* junctions on the I-V characteristics [7,8] and on the potential landscape, measured by low-temperature Kelvin probe force microscopy (LT-KPFM) [9,10]. New insights can be obtained by studying transport mechanisms as a function of doping concentration.

Here, we show the behavior of nanoscale *pn* junctions for samples with relatively low doping concentration (lower *N*), versus samples with high doping concentration (higher *N*). We find that, for lower *N*, the impact of individual dopants can be often resolved as random telegraph signal (RTS). For higher *N*, for which band-to-band tunneling is a dominant mechanism, quantization effects become critical.

II. Structure of Nanoscale PN Diodes

Lateral *pn* junctions are fabricated in SOI substrates, with a common structure as shown in Fig. 1. Selective doping was used to define the *n*-type (doped with P) and *p*-type (doped with B) regions. Doping concentration was changed, from $\sim 1.0 \times 10^{18}$ cm^{-3} (for the lower-*N* sample) to $>5.0 \times 10^{19}$ cm^{-3} (for the higher-*N* sample). In all devices, the *pn* junction is formed in a constriction region defined by EB lithography, with width on the order of ~100 nm and thickness <10 nm. Due to the low-dimensionality of these systems, it is expected that individual dopants and quantum effects play prominent roles in the electrical characteristics. Next, we treat the impact of doping concentration on *pn* junction behavior.

III. Low Concentration: Impact of Individual Dopants as Traps

I-V characteristics for the devices with lower doping concentration are shown in Fig. 2(a) as a function of temperature. In particular at low temperature ($T < 30$ K), these devices exhibit RTS in forward-bias regime, as shown in Fig. 2(b) for different biases.

This is ascribed to the impact of individual dopant potentials in the depletion region, as illustrated in Fig. 3. Such dopant-induced potential fluctuations, observed also by LT-KPFM [9], modulate the current through the depletion region, in particular at its boundaries [8].

IV. High Concentration: Energy Quantization

In the *pn* junctions with higher doping concentration, band-to-band tunneling transport mechanism is expected to be observable, not only in reverse-bias regime, but also in forward bias. For such conditions, it has been predicted that sub-band alignment in the *p* and *n* regions can lead to steps in current, but this should be observed only in reverse-bias condition [11]. On the other hand, quantization effects in both *p* and *n* electrodes revealed significant impact on forward-bias tunneling regime [6]. In fact, our *ab initio* simulations, with basic results shown in Fig. 4, suggest that, in Si nanostructures containing P and, respectively, B atoms, energy spectra have strongly quantized levels, with dopant states mixed with Si quantized states.

Figure 5(a) shows I-V characteristics at low temperatures. Figs. 5(b) and 5(c) show the reverse-bias and forward-bias ranges, respectively. Fine current steps, marked by arrows, can be observed. Since these steps are found for both bias polarities, in band-to-band tunneling regimes, they are most likely ascribed to the quantized energy levels in down-scaled structures. Such states may work in interplay with the individuality of dopants and their discrete energy spectrum.

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V. Conclusions

Downscaled Si *pn* junctions have been studied for different doping concentrations. We found that these systems are strongly affected by individual dopant atoms (dominantly for low doping concentration) and by the quantization of energy states (for higher doping concentration). These findings provide insights into the interplay of donor and acceptor atoms in nanostructures.

Acknowledgements

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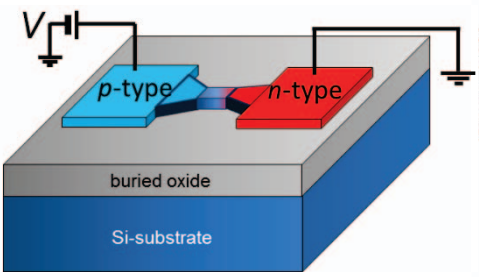

Fig. 1. Device structure and I-V bias setup for SOI lateral *pn* junction measurements.

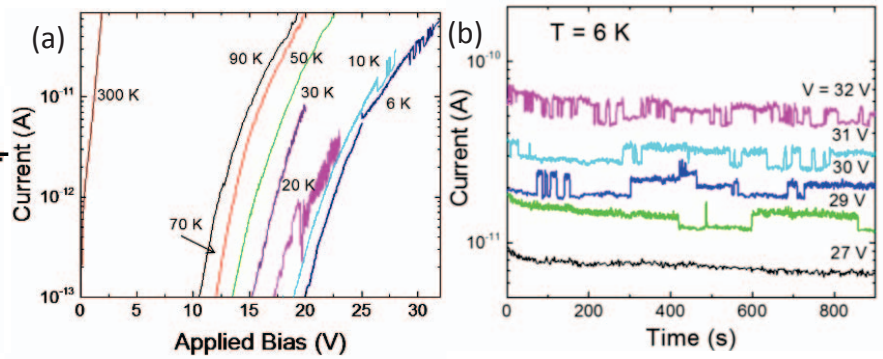

Fig. 2. (a) Low temperature (T<100 K) forward-bias I-V characteristics for nano-*pn* junctions with **lower** ***N***. (b) RTS as a function of time at low T, for different forward-biases (after Ref. 8).

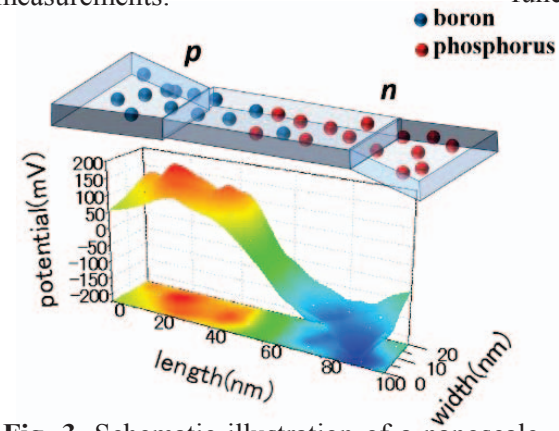

Fig. 3. Schematic illustration of a nanoscale *pn* junction around the depletion region. Potential landscape is strongly modulated by discrete dopants.

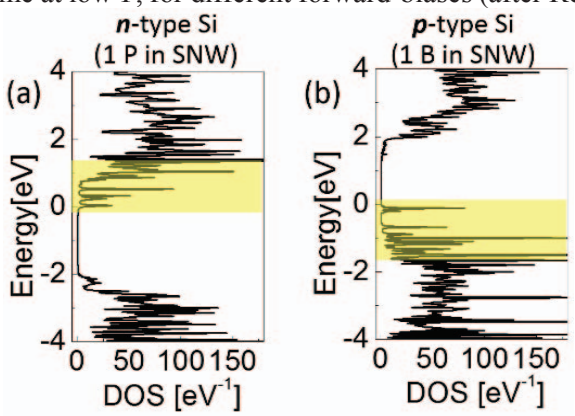

Fig. 4. Density-of-states spectra by *ab initio* simulations for Si nanostructures doped with individual P [(a)] and B [(b)] dopants. Dopant discrete energy states appear near the corresponding band edge (Fermi level is set as E= 0 eV).

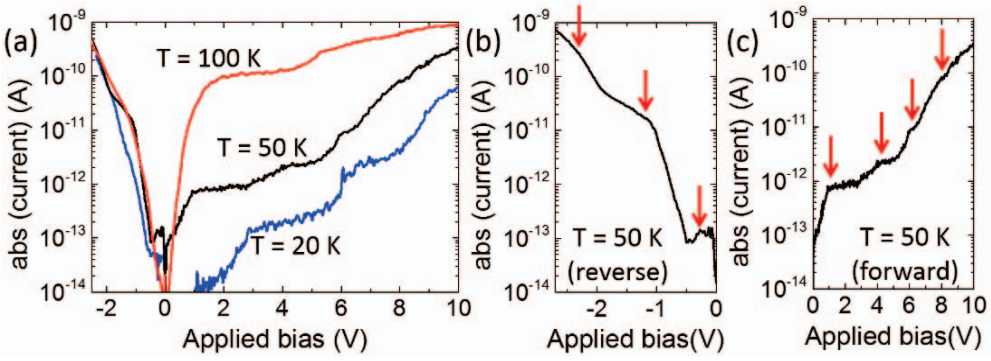

Fig. 5. (a) Low-T I-V characteristics measured in forward and reverse bias for nano-*pn* junctions with **higher** ***N***. (b)-(c) Zoom-in on the voltage ranges for reverse and, respectively, forward bias (T = 50 K). Arrows mark the observed current steps.