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Individuality of Dopants in Silicon Nano-pn Junctions

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The reduced dimensionality of present electronic devices brings along changes in the dopant distribution in the device channel, in which only a small number of dopants exist. Recent studies demonstrated that individual dopants strongly affect the electrical characteristics of nanoscale transistors. On the other hand, nanoscale *pn* junctions, building unit of more complex devices, have not been sufficiently studied from this viewpoint. In this work, we report several experiments that we carried out on nano-*pn* junctions in which the individuality of dopants is prominently observed. In electrical characteristics, we report, under various conditions, random telegraph signals (RTS) related to dopants as traps. The dynamic behavior of the depletion region of nano-pn junctions is also characterized by Kelvin probe force microscopy.

Keywords: individual dopant, *pn* junction, nanoscale, silicon-on-insulator, random telegraph signal.

1. INTRODUCTION

In nanoscale transistors, individuality of dopant atoms plays a key role in the electrical characteristics [1, 2], which becomes more critical since the position and number of dopants in the channel cannot be well controlled with usual doping techniques. This is a significant issue for conventional electronic devices, such as transistors, functioning based on classical transport mechanisms. On the other hand, this impact of individual dopants appears as an opportunity to develop devices with single dopants, for instance phosphorus donors, working as single-electron quantum dots (QDs) [3 – 5]. This opens a fundamentally different field of research for dopant-atom devices, i. e., devices which are established on the basis of silicon technology, but have the possibility of achieving atomic-level functionality [6].

Nanoscale *pn* junctions have not received as much study as transistors from the point of view of the individuality of dopants. Small-scale *pn* junctions have been analyzed theoretically and experimentally to reveal mainly their macroscopic or low-dimensional fundamental properties [7]. However, due to the importance of the *pn* junctions as building blocks of complex electronic device, specific study must be dedicated to these structures in terms of the impact of individual dopants on their behavior.

In this work, we outline our recent results of electrical characteristics, supported by Kelvin probe force microscopy (KFM) measurements, which reveal that the individuality of dopants plays a dominant role in the definition of the potential and, implicitly, significantly affects the current flowing through the depletion region of nanoscale *pn* junctions.

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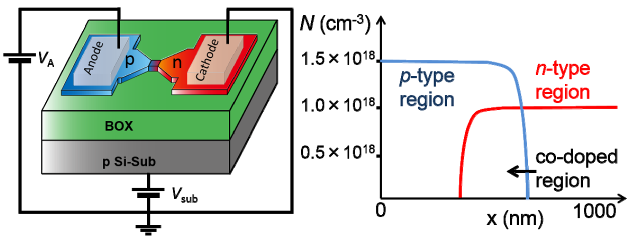
2. DEVICE STRUCTURE AND SETUP

The devices under investigation are *pn* junctions fabricated with a lateral layout within the thin (< 10 nm) top Si layer of silicon-on-insulator substrates. As reference devices, *pin* junctions have also been fabricated, with an insulator (*i*) layer purposely maintained between the *n*- and *p*-type regions. The fabrication processes are all carried out in clean-room environment, using only CMOS-compatible processes.



a b

Fig. 1. Bird's eye view of silicon-on-insulator lateral *pn* junctions, as reported in this work, along with the measurement circuit (a). Doping concentration (*N*) profiles for the *p*-type region (doped with B) and the *n*-type region (doped with P) (b)

A schematic device structure is shown in Fig. 1, a, together with a usual doping concentration profile for the *n*-type and *p*-type regions of the devices. Doping was carried out by thermal diffusion from spin-coated films, using oxide masks patterned by an electron-beam lithography technique. For typical devices, the *n*-type region is doped with phosphorus (P) to a concentration, $N_D \cong 1 \times 10^{18}$ cm^{-3}, while the *p*-type region is doped with boron (B) with usually higher doping concentration, $N_A > 1.5 \times 10^{18}$ cm^{-3} (as illustrated in Fig. 1, b). The depletion region is, thus, expected to be form around the position where the P and B concentrations are balanced. The schematic circuit for the measurements of the electrical characteristics is also shown;

for the KFM measurements, the main difference is that a metallic tip was approached to the sample surface in order to map the electronic potential profile due to the dopants in the top Si layer.

3. CAPTURE AND EMISSION OF SINGLE CARRIERS IN THE DEPLETION REGION

The current-voltage (*I-V*) characteristics were typically measured starting from low temperatures (~20 K) up to room temperature (T = 300 K). In Fig. 2, *I-V* characteristics are shown for *pn* junctions, under visible light illumination at low temperature (Fig. 2, a) and in dark conditions at room temperature (Fig. 2, b). *I*-time measurements in Figs. 2, c and d, respectively, show typically observed random telegraph signals (RTS). The results appropriately reflect the representative trend of the majority of data, i. e., that noisy features (RTS) are usually observed for a large number of *pn* junctions (albeit still for only a fraction of all *pn* junctions measured), under various conditions. On the other hand, *pin* junctions do not exhibit such noisy features except for a single exceptional device. This suggests that *pn* junctions contain favorable conditions for the appearance of the RTS features. In other words, it seems to be important to have opposite types of dopants interacting in the same location within the *pn* junction to induce measurable effects of charge trapping and detrapping. The predominant observation of RTS mostly in the *pn* junctions suggests, furthermore, that the trap is not an interface trap,

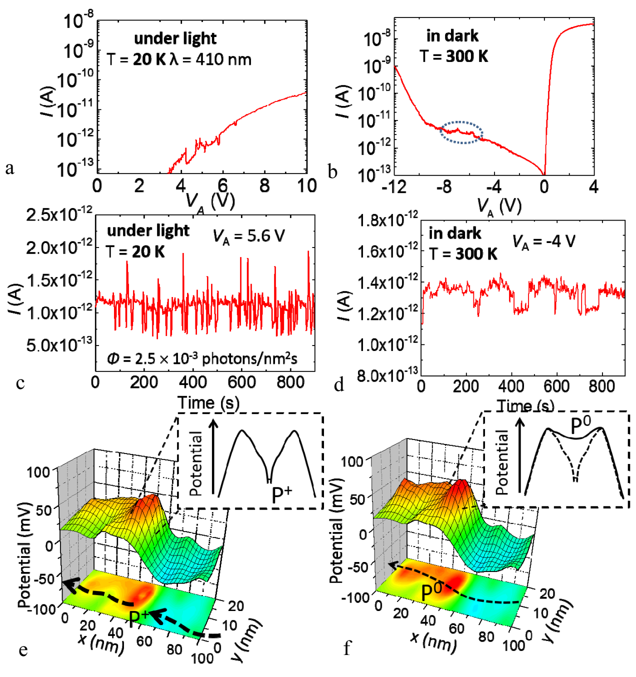


Fig. 2. (a) *I-V* characteristics measured at low temperature (T = 20 K) and under visible light illumination. (b) *I-V* characteristics measured at room temperature, in the absence of light. Under reverse bias, noisy features can be seen, as indicated on the graph. (c) *I*-time dependence with the bias set in the noisy region in (a). Multiple-level RTS can be seen. (d) *I*-time measurements in the noisy region of (b), exhibiting double-level RTS. Such RTS can be ascribed to the impact of individual dopants working as traps. As an example, (e) and (f) show the impact of a P dopant in different charge states (ionized and neutral) on the potential landscapes and, implicitly, on the current

which should play a dominant role in the *pin* junctions, as well.

In the case of light illumination, high-energy carriers can be generated by the absorption of photons in the depletion region. These high-energy carriers may be captured by dopant traps even having relatively higher energy levels. Such a trap, with raised potential, is most likely a P donor flanked by B acceptors [8]. Considering the relatively higher B doping concentration, such a P-B complex can be expected with high probability in our devices. In the simplest form of a P-B pair, such a trap system is expected to have multiple (more than two) available charge states, which can also explain the observation of RTS with multiple distinct current levels, as shown in Fig. 2, c. Further analysis, based on experimental and theoretical considerations, provides information on the fundamental interaction between photons and dopants in nanoscale *pn* junctions [8].

In the absence of light, only carriers contributing to the diffusion current can be captured in dopant-traps, even if having lower potential. In fact, RTS observed in dark conditions contains, in most cases, two levels, as the examples shown in Fig. 2, d. In such situation, RTS can be ascribed to an individual dopant working as a charge trap, as illustrated by the simple potential landscapes shown in Figs. 2, e and f. It is important to note that these characteristics were obtained under reverse bias conditions, for room temperature, which suggests that the dopants have relatively deep ground-state energy levels, which could ensure sufficiently long capture times even at such elevated temperature. A full analysis of the impact of individual dopants on the electrical characteristics of *pn* junctions in dark conditions will be presented in more details in an upcoming work.

The results introduced so far reflect the impact of individual dopants on the electrical characteristics of nanoscale *pn* junctions. From a different approach, the properties of nanoscale *pn* junctions have also been investigated by KFM measurements (with the measurement setup shown in Fig. 3, a), both at low temperatures and at room temperature [9, 10]. The KFM system used is designed to work in a wide range of temperatures and to allow for measurements of devices under normal operating conditions, biased from an external circuit [11]. Using this technique, we have directly observed the electronic potential signatures of individual dopants (donors and acceptors) located in the channels of nano-transistors [11], as well as single-electron injection in single P donors controlled by gate voltage [12].

These previous studies demonstrated the capability of the KFM technique to reveal the dopant individuality in nanoscale devices, which suggests it as a suitable method for characterizing *pn* junctions as well.

Figure 3, b, shows the *pn* junction area measured by KFM, with the electronic potential map (at 15 K) shown in Fig. 3, c. Between flat-potential *p*-type and *n*-type pads, a localized area with sharp potential fluctuations can be observed. Detailed studies, both in dark conditions [9] and under light illumination [10], revealed that this localized noisy area can be identified as the depletion region of the *pn* junction. The noisy features are induced by continuous events of charging and discharging of carriers by the ensemble of dopants present in this area. At this low temperature, shallow-energy dopants work prominently in inducing the noisy features because P and B dopants with deeper energy levels are strongly affected by the freeze-out effect and are practically neutral [13]. However, room temperature results (not shown) are likely dominated by the capture/emission into/from conventional dopants, but with deeper ground-state energy levels [9]. Such deepening of the ground-state level for dopants located in nanostructured-channel devices has been predicted theoretically [14] and supported by experiments, including our recent findings for nano-patterned transistors [5, 15].

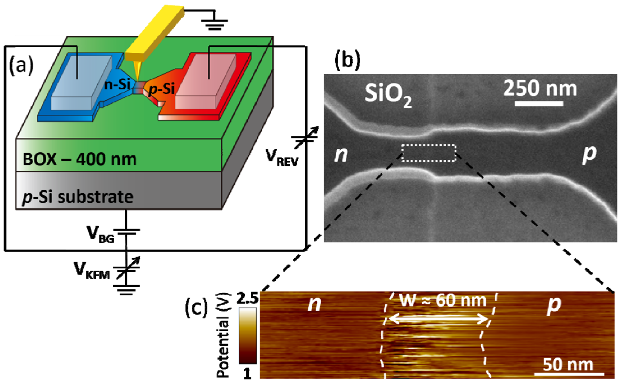


Fig. 3. KFM measurement setup for *pn* junctions (a). SEM image of the measured nano-*pn* junction (scan area is marked) (b). Low-temperature (15 K) KFM electronic potential image around the depletion region (c)

The results described in this paper reflect the impact of the individuality of dopant atoms on electrical characteristics and potential landscape of nanoscale *pn* junctions. Additional information has been presented about the behavior of the nano-*pn* junction in dark and under light, at low and high temperatures and from the dynamic and static aspects of the devices.

4. CONCLUSIONS

We showed the impact of dopant individuality on the properties and behavior of nanoscale *pn* junctions. We demonstrated that individual dopants affect the electrical characteristics as random telegraph signals. These current fluctuations arise from capture and emission of carriers in the dopants located in the depletion region which leads to the modulation of the potential landscape in critical locations. Potential fluctuations have also been observed by KFM, providing direct information about the dynamics of dopants in nano-*pn* junctions. All results accumulated here indicate the significant effect of individual dopant atoms on the functionality of the *pn* junctions. Based on these points, it is worth considering the possibility of utilizing dopant individuality for developing fundamental applications relying upon the nanoscale *pn* junction.

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