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journal or publication title	Japanese Journal of Applied Physics
volume	50
number	8
page range	08LB10
year	2011-08-22
出版者	Japan Society of Applied Physics
権利	(C) 2011 The Japan Society of Applied Physics
URL	http://hdl.handle.net/10297/6175

doi: 10.1143/JJAP.50.08LB10

Single-Electron Charging in Phosphorus Donors in Si

Observed by Low-Temperature Kelvin Probe Force Microscope

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Abstract

Kelvin probe force microscopy (KFM) working at low temperatures (13 K) is used to study local electronic potential fluctuations induced by individual phosphorus donors. Electronic potential maps were measured at the surface of thin phosphorus-doped channel of silicon-on-insulator field-effect transistors for different values of backgate voltage. We observed local changes of the potential profile with increasing backgate voltage, indicating electron injection in the channel. Single-step changes in the depth of the fine potential wells, observed by changing backgate voltage, are ascribed to single-electron charging in individual donors. For clusters of donors, with overlapped potential wells, electron charging occurs gradually, without single-step behavior, as the backgate voltage becomes more positive.

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1. Introduction

Silicon field-effect transistors (FETs), with critical dimensions reduced into nanometer scale, are playing nowadays an increasing role in electronics. Modern fabrication techniques enable the definition of very fine structures and, in the case of transistors, the dimensions of the channel can reach, without special efforts, the order of several tens of nanometers. Since the size of devices is drastically reduced, the number of impurities necessary for device operation is also significantly lowered. Due to the discreteness of dopant distribution, even individual dopants can significantly alter the overall device performance.¹⁾ It has been shown, in fact, that individual dopants, either donors²⁻⁴⁾ or acceptors,⁵⁾ can work as quantum dots (QDs), controlling single-electron or single-hole tunneling currents in nanoscale FETs. In other words, it is possible to create single-electron transistors (SETs) with their operation governed by just one dopant. Theoretical works have also revealed recently the properties of individual dopants in gated nanostructures.⁶⁻⁸⁾ These developments open new fields of applications based on the properties of individual donors, such as quantum computing,⁹⁾ quantum cellular automata,¹⁰⁾ single-electron transfer,¹¹⁻¹³⁾ single-photon detection in dopant arrays¹⁴⁾ and dopant-based single-electron memory.¹⁵⁾ At the same time, advanced techniques for dopant implantation¹⁶⁻¹⁸⁾ and dopant mapping¹⁹⁻²¹⁾ have been already proposed, which will allow an improved controllability of dopant-based devices.

In the applications described above, single-electron transport via individual dopants is mainly analyzed from the electrical characteristics. It is, however, essential to precisely observe the channel potential profile created by randomly distributed dopants in order to understand the mechanisms of single-electron charging in individual dopants. For that purpose, it is reasonable to use Kelvin probe force microscopy (KFM),²²⁻²⁴⁾ in which long-range electrostatic forces

between a cantilever and a sample are detected and converted into surface potential. In our previous work, we observed by a low-temperature (13 K) KFM technique individual donor potentials in the channel of silicon-on-insulator field-effect transistors (SOI-FETs) under normal operation.²¹⁾ Low temperature operation is essential because it allows us to minimize the screening effects by free carriers in the channel, which hinder the observation of ionized donor potentials. At low temperature, the density of free carriers changes abruptly around Fermi level. Therefore, free carriers can be depleted from the channel even for small backgate voltages and, thus, the potential of fixed charges can be monitored. We have also previously demonstrated the capability of the KFM technique to detect the potential changes due to single-electron charging at the level of an individual donor.⁴⁾ This was done by comparing the surface potential changes with and without current flowing through the device channel, i.e., for zero and non-zero source-drain bias. However, in a randomly doped channel, donors can be also closely spaced, leading to the formation of donor clusters. Charging in separated donors, as well as in clusters of overlapped donors can play a key role in device operation. Therefore, in this paper, we study single-electron charging in donors, for separated and clustered configurations, by observing the surface potential changes of a doped SOI-FET channel when a backgate voltage is gradually changed.

We first briefly describe the device structure and measurement setup. Then, we present experimental results as surface electronic potential maps measured by LT-KFM for different backgate voltages (V_{BG}). Examples will illustrate charging in separated donors, as well as in clusters containing several donors. A statistical analysis indicates the general properties of isolated and clustered donors in terms of electron charging.

2. Device structure and measurement setup

Figure 1(a) shows the schematic structure of the fabricated SOI-FETs and the measurement setup. Channel is defined by an electron-beam lithography technique as a constriction between larger Si pads working as source and drain. Channel thickness is about 15 nm, with length and width of more than 500 nm, respectively. Top Si layer was doped with phosphorus, diffused from a spin-coated silica film containing P_2O_3 . Doping concentration, evaluated from room temperature four-point probe measurements, is about $1 \times 10^{18} \text{ cm}^{-3}$, which corresponds to an average inter-donor distance of less than 10 nm. Channel surface was covered by 2-nm-thick SiO_2 layer. The main purposes of the SiO_2 layer are to passivate Si surface and to prevent it from contamination. Therefore, SiO_2 layer was thermally grown by dry oxidation in purified oxygen gas in a quartz tube furnace located in the clean room. On the other hand, in order to optimize the detection capability of dopants by KFM, SiO_2 should be grown as thin as possible (in our device, SiO_2 thickness is 2 nm).

For the KFM measurement, the sample was inserted in the low-temperature (13 K) and ultrahigh vacuum chamber (base pressure $< 5 \times 10^{-9}$ Torr), with the electrodes connected to external voltage sources. Source and drain electrodes were grounded, while the p-type substrate ($N_A \cong 1 \times 10^{15} \text{ cm}^{-3}$) works as a backgate. The KFM measurements were done with a gold-coated cantilever, with resonant frequency $f = \sim 250 \text{ kHz}$, resistance $R = 650\text{-}700 \text{ }\Omega$, and spring constant $k = 30\text{-}40 \text{ N/m}$. An ac KFM bias is applied with amplitude of 2.5 V and a frequency of 2 kHz. In a typical measurement setup, the tip-surface distance is around 5 nm.

We measured the KFM surface potential images in an area of $500 \times 500 \text{ nm}^2$, centered in the channel of the device. By keeping both source and drain electrodes grounded, we ensured that no current flows in the device channel, which allows us to study the static charge

distribution in the channel. At the low temperatures used in our study (13 K) and without electric field in the channel, it is expected that the freeze-out effect will be significant and most donors are neutral.²⁵⁾ For our measurement, however, negative backgate voltage (V_{BG}) is applied to deplete the channel of free carriers. The internal electric field existing along the channel is probably sufficient to ionize the donor electrons,²⁵⁾ which will be collected at the grounded source and drain electrodes. Hence, during the KFM scan time, the channel potential is mostly given by the immobile fixed charges of ionized dopants (donors). In fact, in our previous studies we have shown that the observed potential fluctuations are due to the ionized donors.^{21,26)} Figure 1(b) shows the potential landscape induced by a single isolated donor, calculated based on a simplified description of the donor potential.²⁷⁾

3. Results and discussion

Figure 2(a) shows the surface electronic potential map measured for $V_{BG} = -3$ V. Several dark spots, visible in the images, can be ascribed to positive charge centers located within the Si channel. It is reasonable to assume that most dark spots are created by the ionized donors, randomly distributed within the device channel. Some of the dark spots have a roughly circular symmetry, a size of about 5~10 nm (in agreement with the Bohr diameter for phosphorus in silicon, $d_B \cong 6$ nm),²⁸⁾ and a potential depth of a few tens of mV. These features are consistent with the characteristics of separated ionized donors.²¹⁾ However, larger dark spots, with irregular shapes and deeper potentials, can also be observed. Such features are most likely due to clusters of donors, for which the superimposed potentials of several closely spaced donors can lead to the formation of deeper potential wells.

In order to observe charging in the channel, we changed the backgate voltage, V_{BG} , from -3 V to 0 V in steps of 1 V. This procedure allows gradual injection of electrons, which are supplied from source and drain electrodes, in the initially depleted channel. For the measured device, the overall potential landscape is only weakly affected by the applied backgate voltage, as it can be seen from the series of KFM images in Figs. 2(a)-(d). In fact, most features (dark spots) are identical in all images. We have found, however, in several locations, significant modifications, as the measured potential becomes flatter by applying more positive V_{BG} , indicating electron filling into donor sites, as will be described in details below.

At the low temperature used in this study and in the absence of source-drain bias, it is expected that electrons will be trapped in the donor potentials. Figure 3 shows an example of two dark spots (marked by circles) that can be ascribed to two different donors. The dependence on V_{BG} (-3, -2, -1, and 0 V) can be monitored in Figs. 3(a)-(d). Figure 3(e) shows line profiles through the dark spots, in which the curves have been offset to align all profiles to a reference potential level and to account thus for the overall potential changes induced by V_{BG} application. At $V_{BG} = -3$ V, each dark spot, corresponding to each donor, can be identified distinctly. At $V_{BG} = -2$ V, the lower dark spot vanishes, indicating neutralization of the donor. The second dark spot remains, suggesting that the second donor is still kept ionized, and only vanishes for $V_{BG} = 0$ V. The potential changes can be evaluated from the line profiles to be around 40 mV, which is close to the value of the charging energy of a single electron in a donor-induced QD.³⁾ It is worth to mention that, when V_{BG} is increased from -2 V to -1 V, the potential landscape does not change significantly, indicating that no charging occurred between these two voltages. Such lack of changes as backgate voltage is increased indicates a non-linear effect of V_{BG} in terms of electron charging. Although the ideal potential of a neutralized donor should become perfectly

flat, in our observations shallow potential contrast sometimes remains even after charging. We believe this can be basically ascribed to the effects of other surrounding charges.

The case of a cluster of dopants is more complex, since the resultant potential is due to the superposition of several closely spaced donors. It strongly depends then on the number of donors and also on their spatial configuration, i.e., inter-donor distance. The exact interaction between donors in a cluster is still unsolved. However, we expect to observe an asymmetric shape of the potential well. Furthermore, the electron wavefunction is expected to be distributed within the entire cluster area, which should be observed as a less-localized potential increase by the addition of electrons.

In Fig. 4, an example of a cluster of donors (marked by a circle) is presented. Figures 4(a) to 4(d) show the KFM images of the electronic potential obtained by changing V_{BG} from -3 V to 0 V in steps of 1 V. Line profiles are also shown in Fig. 4(e) aligned to a reference level. Here, similarly to the case of separated donors, the potential well becomes flatter by applying more positive V_{BG} . However, unlike the case of separated donors, the potential changes of the well are more gradual, in agreement with our expectation that electrons are not localized around just one donor, but are shared by all the donors incorporated in the cluster. Also, several other differences can be pointed out. Firstly, for $V_{BG} = -3$ V, the potential depth is around 180 mV, which strongly indicates local donor agglomeration. Secondly, the size of the well is much larger than 20 nm, so it cannot be ascribed to an isolated donor. These differences allow us to distinguish in the observed cases the configurations of isolated donors from those of clustered donors.

Figure 5 shows the statistical results obtained for individual charge traps (13 cases) and clusters (6 cases). At first, we describe the case of single isolated charge centers in Fig. 5(a). Horizontal axis is the applied backgate voltage, V_{BG} , while vertical axis represents the potential

depth, measured at the location of the potential minimum (observed for $V_{BG} = -3$ V) relative to a common reference level, as indicated in Fig. 3(e). For the majority of the cases, we can see only one significant step-like change within the range of V_{BG} investigated. This indicates a single charging event, most likely a single-electron trapping. In order to extract the general behavior, all the potential changes have been plotted in the histogram shown in Fig. 5(b). The x -axis gives the values of the potential change $\Delta \phi$ (with a bin size of 3 mV), while the y -axis gives the count of cases within each bin. In most cases, the potential variations are small, around 10 mV, and can be ascribed to the effect of background charging. Typical potential jumps are grouped in the range of 20~40 mV, which suggests single-electron trapping in individual donors. The distribution of these potential jumps has a certain broadening, which can be most likely ascribed to the different depths of the monitored donors.²¹⁾ It is reasonable to assume that, for donors closer to the top surface, a larger potential change can be observed by the addition of one electron, as compared to donors located deeper in the Si channel. Additionally, we observe a tail of the distribution at values larger than about 50 mV. The origin of these larger potential variations is most likely single-electron interface traps with deeper energy levels. Such traps may be either defects formed during fabrication or donors located very close to interfaces, for which it was found that the ionization energies can be significantly enhanced compared to bulk-like donors.^{29,30)} In order to fully clarify these points, further studies are necessary.

Several cases of larger dark spots, with more gradual potential modifications, are shown in Fig. 5(c). For these, it is difficult to distinguish step-like behavior of the potential changes, as also understood from the example shown in Fig. 4(e). All the potential changes are plotted as a histogram in Fig. 5(d), using the same procedure as described above. It can be observed that, although the distribution is not clearly defined, most potential changes are grouped in the range

of 10~30 mV, which is smaller than for the case of isolated donors. This can be ascribed to the fact that the spatial extension of the potential well is larger, leading to a reduced charging energy when an electron is added. This result suggests that several electrons are successively filling the potential wells at different V_{BG} 's. This can only indicate that the origin of the potential wells is a cluster of donors, since such structures can accommodate more than one electron.

4. Conclusions

We presented results of low-temperature KFM measurements on phosphorus-doped SOI-FETs as a function of backgate voltage. We observed that, by increasing V_{BG} , electrons are filling the potential wells created by the donors located in the channel. Two behaviors can be distinguished: step-like single-event charging, which can be in most cases ascribed to single-electron trapping in an individual donor, and gradual successive charging, which can be ascribed to consecutive electron trapping in clusters of donors. These results demonstrate the capability of KFM to resolve single-electron charging events in devices under operation. Thus, we believe that KFM can serve as a useful method for the study of single-dopant effects in nanoscale devices.

Acknowledgements

The authors thank M. Ligowski for valuable contribution in device fabrication and for fruitful discussions. This work was partially supported by KAKENHI Grants-in-Aid (20246060 and 22656082).

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Figure captions

FIG. 1. (Color online) (a) SOI-FET device structure and schematic KFM measurement setup. (b) Electronic potential created by a single ionized phosphorus donor at the surface of the Si channel.

FIG. 2. (Color online) Electronic surface potential maps measured by LT-KFM for different values of applied backgate voltage (V_{BG}): (a) - 3 V, (b) - 2 V, (c) - 1 V, and (d) 0 V. The scan area ($500 \times 500 \text{ nm}^2$) was centered on the channel of an SOI-FET device. Scale bars show electronic potential in mV, with the same width (200 mV) for all figures. Dark spots indicate regions of positive fixed charges, such as ionized donors.

FIG. 3. (Color online) Example of single-electron charging in individual separated donors: (a)-(d) KFM electronic potential images measured for different V_{BG} 's (-3, -2, -1, and 0 V, respectively). Scale bars show electronic potential in mV, with the same width (150 mV) for all figures. Circles mark the location of donor potential wells. (e) Line profiles through the dark spots, aligned to a common reference potential level for comparison. Arrows indicate local potential changes.

FIG. 4. (Color online) Example of electron charging in a cluster of donors: (a)-(d) KFM electronic potential images measured for different V_{BG} 's (-3, -2, -1, and 0 V, respectively). Scale bars show electronic potential in mV, with the same width (170 mV) for all figures. The circle marks the location of the potential well induced by the cluster of donors. (e) Line profiles through the dark spots, aligned to a common reference potential level for comparison.

FIG. 5. (Color online) Statistical analysis of the potential changes induced by increasing V_{BG} , shown as examples at different locations in the scan area (upper graphs) and histograms illustrating the statistical distribution of the values of the potential changes (lower graphs). Two distinct cases are presented: (a)-(b) small-size dark spots exhibiting step-like single-electron

charging behavior and (c)-(d) larger-size dark spots with gradual reduction of the potential depth with increasing V_{BG} . Curves in (b) are guides for the eyes to indicate a possible distribution of cases.

FIG. 1. M. Anwar *et al.*, Jpn. J. Appl. Phys. 2011

FIG. 2. M. Anwar *et al.*, Jpn. J. Appl. Phys. 2011

FIG. 3. M. Anwar *et al.*, Jpn. J. Appl. Phys. 2011

FIG. 4. M. Anwar *et al.*, Jpn. J. Appl. Phys. 2011

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