

KFM Observation of Single-Electron Filling in Isolated and Clustered Dopants

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1. Introduction

The interplay between an individual dopant atom and a single electron has attracted a wide interest for future scaled-down electronics. Arrays of discrete dopants have also been considered for novel applications, such as quantum computing [1,2] and single-electron transfer [3,4]. Recently, single-electron transport through an isolated dopant has been characterized in field-effect transistors (FETs) by electrical measurements [5,6]. In light of these developments, it is essential to observe directly the potential of individual dopants and their charging mechanism.

One way to detect electrostatic potential with high accuracy is Kelvin Probe Force Microscopy (KFM) [7]. As shown in Fig. 1, in the KFM measurement, a conducting cantilever is scanned over the sample surface at constant height. At each measurement point, the electrostatic force between cantilever and sample is nullified by a dc voltage corresponding to the time-averaged electronic potential.

We have previously shown that individual dopants can be resolved even in devices under normal operating conditions using a low-temperature KFM (LT-KFM) technique [8,9]. In the present work, we study, with the LT-KFM, the charging of single electrons in dopants and observe successive and gradual electron filling, which are respectively ascribed to the charging of electrons into isolated and clustered dopants.

2. Electron filling in isolated and clustered dopants

We fabricated and studied silicon-on-insulator (SOI) FETs with a substrate back gate, as schematically shown in Fig. 1. The top 10-nm thick Si layer was doped with phosphorus ($N_d \approx 1 \times 10^{18} \text{ cm}^{-3}$, i.e., an average inter-dopant distance of 10 nm). A thin (2 nm) SiO_2 layer was grown by dry oxidation. The potential in the top Si layer can be controlled by a back gate. With grounded source and drain electrodes, negative back gate voltage (V_{BG}) can be used to deplete the channel of free carriers and allow the observation of bare dopant potentials. Each ionized dopant (P^+) should appear as a dark spot in the KFM electronic potential images. Figures 2(a) and 2(b) show two KFM maps (500 nm \times 500 nm) measured for negative V_{BG} 's. The number of dark spots is in good agreement with estimated number of dopants located within a few nanometers from the Si/SiO₂ top interface. Smallest dark spots have a radius of 4 ± 2 nm, comparable with the Bohr radius of P in Si [10,11]. This suggests that most dark spots are induced by individual ionized dopants.

We studied potential changes of the dopant atoms by

changing V_{BG} . We focused on areas that contain 2~3 dopants. Figure 3(a) shows a simple simulation of the resultant potential created by two dopants located at 10 nm from each other. Figures 3(b)-(d) show one series of potential maps for different V_{BG} 's in the range [-3V; 0 V]. The images have equal potential range (150 mV), with the average potential adjusted. It is expected that, by applying more positive V_{BG} , electron density in the channel will be increased and consequently dopant potentials will be screened by electrons. For this example, the dark spots are successively smeared out at different V_{BG} 's.

In a few areas, however, we observed dark spots of larger spatial extension and irregular shape that can be ascribed to a group of dopants in close proximity. Figure 4(a) shows an example of simulated potential and Figs. 4(b)-(d) are successive KFM potential images for different V_{BG} 's. For this case, gradual increase of potential with V_{BG} application was observed.

For better visualization of the charging effects, we took line profiles, as indicated by the dotted lines in Figs. 3 and 4. Figure 5(a) corresponds to Fig. 3 and illustrates the successive cancellation of the potential depressions when V_{BG} is increased, as indicated by the arrows. This is an evidence of single-electron filling in neighboring dopants, occurring independently. Figure 5(b) corresponds to Fig. 4 and shows gradual increase of potential. This is due to the fact that electrons are not localized in one dopant, but are shared by the entire group of more than two dopants.

To distinguish these two regimes (isolated and clustered dopants), we statistically analyzed the electron filling effect, focusing on the relation between projected inter-dopant distance (d_{xy}) and inter-dopant barrier ($\Delta\Phi$). The results are shown in Fig. 5(c). When d_{xy} is larger than 5 nm, observed $\Delta\Phi$ is higher than 5 mV and then we can expect that the electron filling occurs independently in each dopant. On the other hand, when the dopants are closer to each other (d_{xy} is smaller than 5 nm), $\Delta\Phi$ is decreased to zero. This can explain why the clustered dopants share the electrons.

3. Conclusions

We utilized LT-KFM to characterize charging effects in thin P-doped SOI-FETs. We observe single-electron filling, with changing V_{BG} , in isolated dopants and in clusters of dopants. This observation will provide support for design of electronic devices based on single-electron charging of individual dopants.

Acknowledgements

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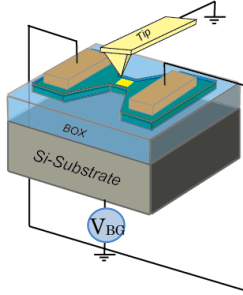


FIG. 1. SOI-FET under KFM measurement: schematic device structure and setup.

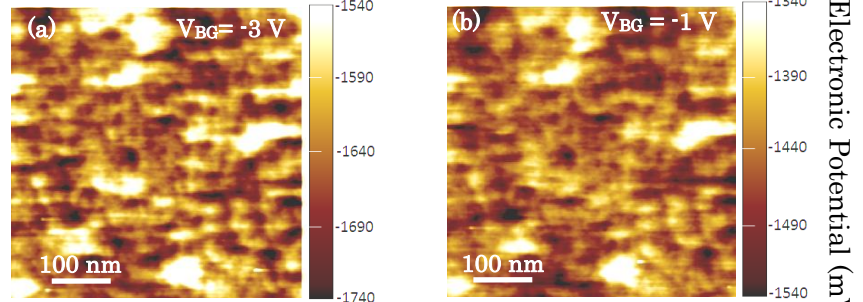


FIG. 2. Electronic potential maps measured by LT-KFM at the surface of SOI-FET for different V_{BG} : (a) -3 V, (b) -1 V.

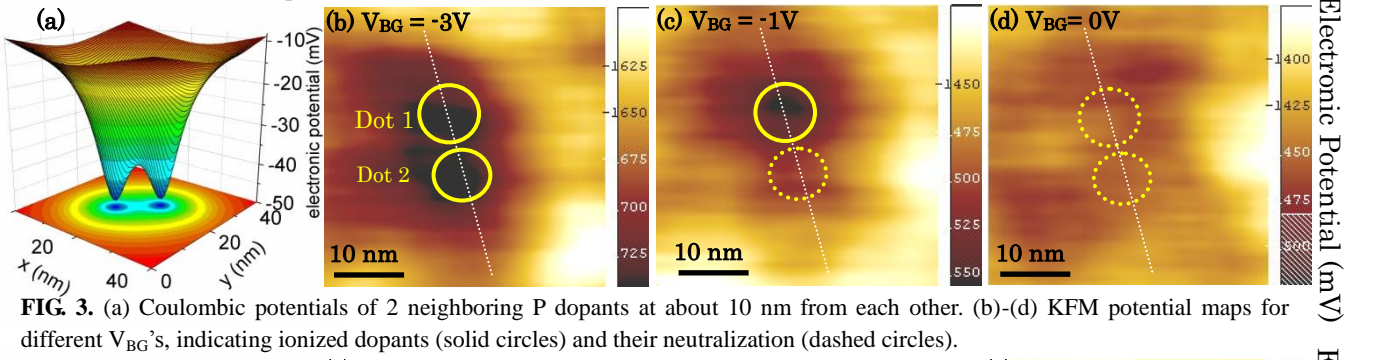


FIG. 3. (a) Coulombic potentials of 2 neighboring P dopants at about 10 nm from each other. (b)-(d) KFM potential maps for different V_{BG} 's, indicating ionized dopants (solid circles) and their neutralization (dashed circles).

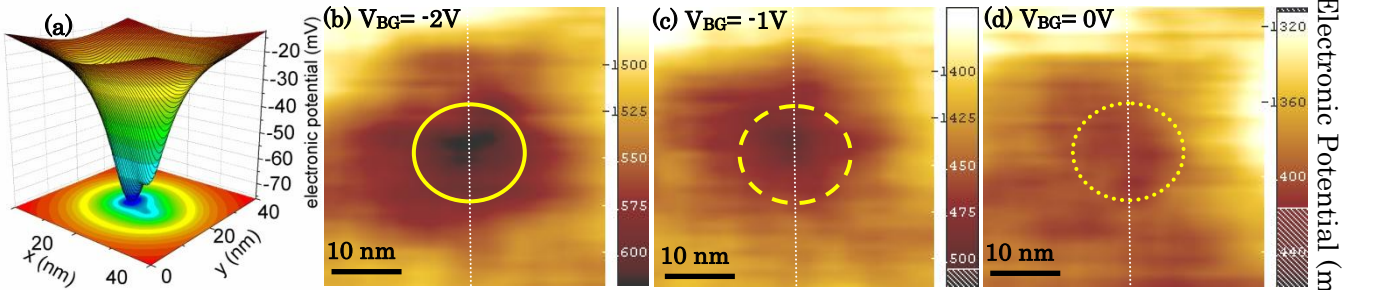


FIG. 4. (a) Coulombic potentials of several dopants close to each other. (b)-(d) KFM potential maps for different V_{BG} 's, indicating gradual screening of the deep larger dot.

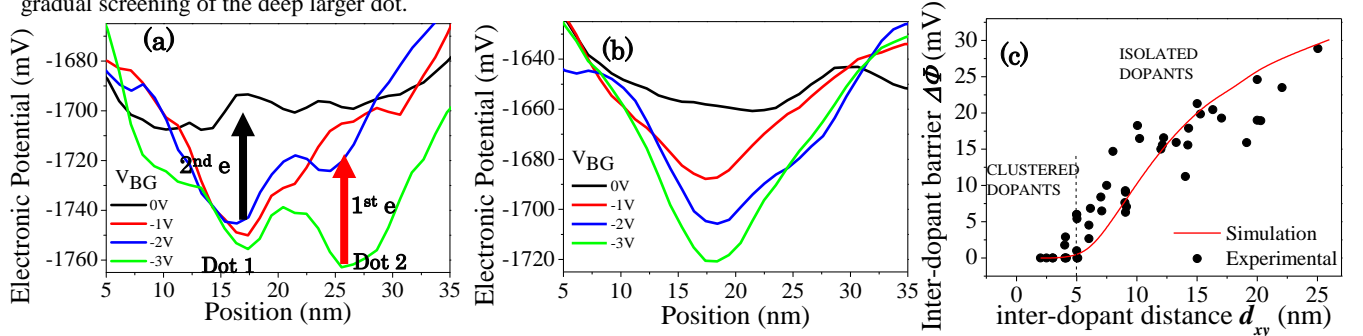


FIG. 5. (a) Line profiles with V_{BG} dependence along dot 1 and dot 2 of Fig. 3. Abrupt increases of potential due to single-electron filling are indicated by arrows. (b) Line profiles of a group of closely-packed dopants, indicating that potential is increased gradually by increasing V_{BG} . (c) Relation between inter-dopant distance (projected in the measurement plane) and inter-dopant barrier height. Black dots are experimental result of barrier height for different double-dopant areas measured for $V_{BG} = -3V$. Red line corresponds to a simulation for two dopants located at 1 nm below the surface.