SINGLE-ELECTRON TRANSPORT CHARACTERISTICS IN QUANTUM DOT ARRAYS DUE TO IONIZED DOPANTS

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Abstract:

Single charge manipulation for useful electronic functionalities has become an exciting and fast-paced direction of research in recent years. In structures with dimensions below about 100 nm, the physics governing the device operation turn out to be strikingly different than in the case of larger devices. The presence of even a single charge may completely suppress current flow due to the basic electron-electron repulsion (so called Coulomb blockade effect) [1].

It is even more exciting to control this effect at the level of single-electron/single-atom interaction. The atomic entity can be one donor present in silicon lattice with a Coulombic potential well. In principle, it can accommodate basically a single electron. We study the electrical behavior of nanoscale-channel silicon-on-insulator field-effect transistors (SOI-FETs) that contain a discrete arrangement of donors. The donors can be utilized as "stepping stones" for the transfer of single charges. This ability opens the doors to a rich world of applications based on the simple interplay of single charges and single atoms, while still utilizing mostly conventional and well established fabrication techniques.

In this work, we distinguish the effects of single-electron transport mediated by one or few dopants only. Furthermore, we show how the single-electron/single-donor interaction can be tuned by using the external biases. We demonstrate then by simulation and experiment the feasibility of single-electron/bit transfer operation (single-electron turnstile).

Keywords: *single dopant, silicon nanowire, single-electron transport, single-electron transfer.*

1. Introduction

Single-electron tunneling and the Coulomb blockade effect have been observed in a variety of materials [1]. Silicon devices are, however, preferable due to the well-developed Si technology. Furthermore, utilizing naturally-formed Coulombic wells introduced by individual atoms (dopants) allows us to overcome present limitations of nanolithography. This extreme case of incorporating the physics of single-electron/single-atom interaction into useful electronic devices is the focus of this paper. In the following, we will briefly describe the basic physics of this interaction and the possibilities of controlling the device parameters for realizing applications such as single-electron turnstile [2].

2. Coulomb blockade in dopant-induced quantum dots

We fabricated and investigated doped-nanowire SOI-FETs containing a large number of dopants in the channel. The device structure is schematically shown in Fig. 1(a). The nanowire channel was patterned by an electron-beam lithography technique after doping with phosphorus by diffusion from a spin-coated silica film. The dimensions of the channel are estimated to be about 10 nm height, 50 nm width, and 100 nm length. Doping concentration is expected to be on the order of 1×10^{18} cm^{-3} which suggests that the number of dopants in the channel is very roughly about 50. Figure 1(b) shows the channel containing randomly distributed dopants (as a result of the uncontrollability in the doping process). Figure 1(c) shows a simulated possible potential landscape created by superposition of the Coulombic potentials of all the dopants in the channel. The fact that the interdopant distance is about 10 nm $[(N_d)^{-1/3}]$ and thus larger than Bohr radius for phosphorus in Si (~3 nm) is another hint that individual dopants may work as QDs. Due to the relatively large number of dopants and to the device geometry, it is plausible that a multiple-QD array will be formed between source and drain. This can be understood from typical source-drain current (I_{sd}) vs front gate voltage (V_{fg}) characteristics, as shown in Fig. 1(c), which contain strong oscillations of the current. These oscillations are due to the Coulomb blockade in the dopant-induced QDs.

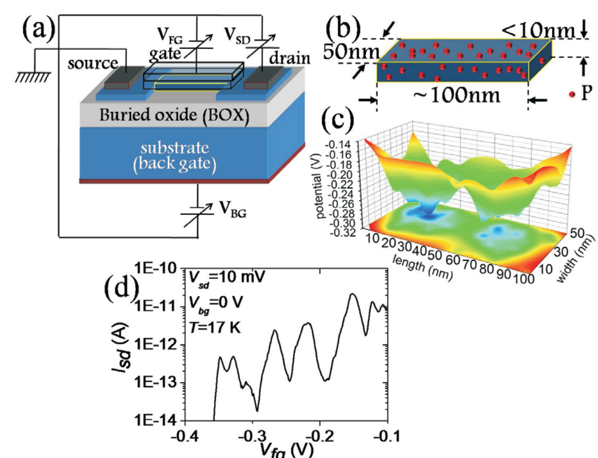

Fig. 1. (a) Device structure for doped-nanowire FETs investigated. (b) Nanoscale channel randomly doped with phosphorus. (c) Dopant-induced potential landscape simulated for one possible dopant arrangement. (d) Measured I_{sd}-V_{fg} characteristics exhibiting typical Coulomb oscillations.

The theory of Coulomb blockade is well established nowadays for metallic QDs. In ultrasmall (nanometer-scale) QDs coupled to the environment through tunnel junctions, the presence of even one electron in the QD significantly raises the dot potential blocking further transport. This increase is related to the charging energy $E_{ch}=e^2/2C$, where e is the elementary charge and C is the dot capacitance.

For a donor-induced QD, the situation is roughly similar. However, donors can in principle accommodate only one electron (which will practically neutralize the donor). [3] This reasoning can be extended further to arrays of dopants, which have been acknowledged as more attractive for various applications. Roughly speaking, when a nanowire contains many dopants, electrons "looking" into the channel from the source Fermi level will first see the lowest-energy potential valleys (most probably serially arranged). It is important to note that these lowest-energy valleys are expected to be the result of the strong confinement potential due to individual dopants. As gate voltage is increased, the channel potential is continuously lowered. Current will flow by successive single-electron tunneling events and then electrons will become "trapped" inside the dopant-QDs and transport will be blocked. This will give rise to a current peak, from which we can extract information about the structure of the QD array itself. As gate voltage is even further increased, it is expected that conduction path will change so that it incorporates other dopants located in the next lowest potential valleys. This mechanism suggests the possibility of characterizing and utilizing doped nanowires still based on single-electron/single-dopant interaction. One of many possible applications consists of single-electron turnstile mediated by few-dopant arrays.

3. Finding the optimal structure for single-electron turnstile - statistical simulations

Single-electron turnstile is defined as the ability of a device to shift one electron between two electrodes during every cycle of an ac gate voltage. The conditions required to achieve this operation can be understood from the charge stability diagram of the device (i.e., contour map of source-drain current (I_{sd}) as a function of source-drain bias (V_{sd}) and front gate voltage (V_{fg})). Such a stability diagram is shown in Fig. 2(a) for a 3-QD system with uniform parameters. It contains zero-I_{sd} rhomboidal regions (so-called Coulomb diamonds) inside which a fixed number of elementary charges reside in the QD array. Consecutive Coulomb diamonds correspond to charge configurations that differ only by one electron. For single-electron turnstile, the basic requirement is an overlap between two such consecutive stable regions. An ac gate voltage crossing this overlap periodically may lead to single-electron/cycle transfer from source to drain as follows. During the high level of the pulse, one electron is injected into the channel from one electrode (e.g., source – the source-side arm of the "turnstile" is open while the drain-side one is still closed). Then, during the low level, the electron is removed towards the opposite electrode (e.g., drain - the drain-side arm is opened this time).

We found that the required overlap is strongly dependent on the array parameters. Figure 2(b) shows, as example, few Isd-Vsd characteristics simulated under ac-V_{fg} bias for different inter-dot coupling (inter-dot capacitances). The other parameters are all fixed. We can see that by adjusting the inter-dot coupling we find a current plateau aligned at $e\times f$ (where f is the ac frequency). This is a clear mark of single-electron turnstile. Controlling this parameter is a key aspect of our experimental results, as shown in Section 4.

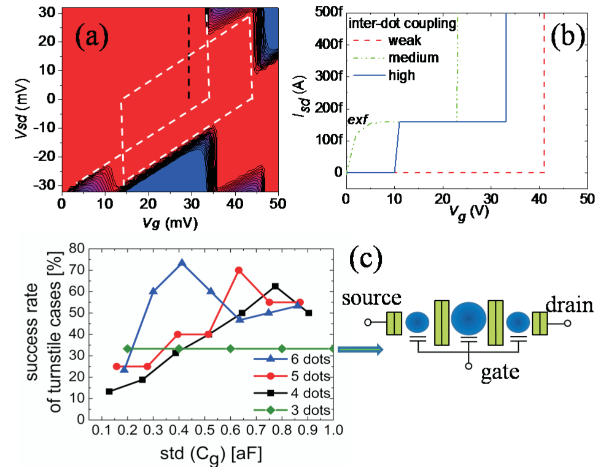

Fig. 2. (a) Simulated stability diagram for a 3-QD array (first two stable regions are marked). (b) Simulated I_{sd}-V_{sd} characteristics under ac-gate operation for different inter-dot coupling (inter-dot junction capacitances). (c) Statistical results of single-electron turnstile operation for a large number of QD arrangements. 3-QD arrays (particularly with larger central dot and/or larger inter-dot capacitances) are found to be stable turnstile devices.

When dopants are utilized as QDs, it is important to consider their positions as random (following basically a Poisson distribution). Therefore, it is necessary to understand the effect of parameter dispersion on the ac behavior of multiple-QD arrays. Our statistical analysis [4] of a variety of configurations suggests that single-electron turnstile is achievable in devices containing more than 3 QDs with a fairly high chance (as shown in Fig. 3(c)). It is even more important though that we were able to find an optimal structure which would be very stable against parameter fluctuations. This consists of a 3-QD array commonly coupled to a gate. When the central dot is made larger than the outer ones, the probability of realizing single-electron turnstile is practically 100%. These findings are promising for developing very stable single-electron turnstile devices based on single-electron/single-dopant interplay.

4. Electrical characterization and tuning of dopant arrays

Simulation results suggest the importance of controlling the device parameters for single-electron turnstile. This is consistent with our previous experimental observations of single-electron turnstile operation in few-dopant nanowire SOI-FETs [5]. In this paper, we attempt to control the QD array parameters based on the specific properties of our SOI-FET structure. The advantage of the SOI-FET is that it allows the characterization of the transport through the nanoscale channel with four external

biases: source and drain, front gate, and back gate (metalized substrate). We focus on identifying at first the necessary conditions for single-electron turnstile, i.e., an overlap between adjacent Coulomb diamonds in the charge stability diagram. Figure 3(a) shows the stability diagram for one device measured at 17 K with zero back gate voltage (V_{bg}). Coulomb diamonds can be observed and it is expected that the number of electrons inside the QD array changes one by one as V_{fg} is increased. However, the necessary overlap cannot be clearly identified. It can be concluded that the device parameters are not optimal for single-electron turnstile operation.

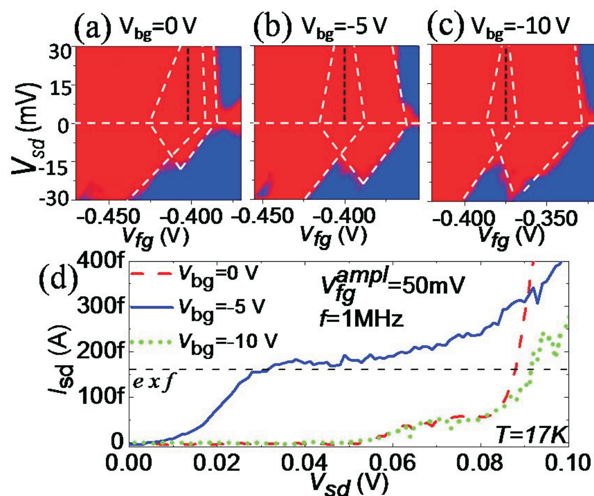

Fig. 3. (a)-(c) First stable charge regions as a function of V_{bg}. (d) I_{sd}-V_{sd} characteristics under ac-V_{fg} pulses. The ef plateau is observed only for the "optimal" case of V_{bg}=-5 V.

We suggest that back gate voltage (V_{bg}) can be utilized to tune the stability diagrams appropriately. Figures 3(a)-3(c) show the influence of V_{bg} on the stability diagrams. The structure of the stable regions is significantly changed by changing V_{bg}. Most importantly, it becomes now possible to identify an optimal overlap between the first and second observable Coulomb diamonds. This adjustment is due to the strong electric field vertically across the channel created by the large V_{bg}. The V_{bg}-induced field is felt differently by dopants located at different depths in the channel. Although not very straightforward, this means that in fact the inter-dopant coupling can be modulated by V_{bg} [6].

After tuning the charge stability diagrams using V_{bg}, we apply ac V_{fg} pulses to the front gate. The high and low levels of the V_{fg} pulse were set as described above inside the first and the second observable stable regions. The device is actually operated inside the zero-dc-current areas (inside the Coulomb diamonds). However, as shown in Fig. 3(d), under ac-V_{fg} operation, we found that I_{sd} is in fact not zero and, more strikingly, for V_{bg}=-5 V it is very close to $e \times f$ (where f is the ac frequency). This means that during each V_{fg} cycles precisely one electron is transferred between source and drain. Single-electron transfer is thus achieved by modulating the inter-dopant coupling with V_{bg} [6]. Furthermore, this operation takes place by single-electron tunneling in single-dopant-QD arrays. This ability is very promising for developing a new class of electronics based on single-electron/single-atom interaction.

5. Conclusions

We have shown that single-electron/single-dopant interplay can be controlled electrically in doped-nanowire FETs. This allowed the adjustment of the device charge stability diagrams for operation as single-electron turnstile. Further insight can be provided by the ability of directly monitoring the dopant arrangement. This has been also recently demonstrated by our group utilizing a low-temperature Kelvin probe force microscope [7]. The combination of these techniques can become an essential frame for development of single dopant electronics field [8].

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