Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp1276-1277

Charge transfer by multiple donors in a Si nanowire

G. P. Lansbergen*, Y. Ono and A. Fujiwara
NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa, 243-0198, Japan

I. Introduction

Single electron pumps [1] are the ultimate limit in scaling of current sources. Their ability to generate single electrons on demands is useful in a variety of quantum information schemes and as a meteorological current standard. Ideally, these devices would generate electrons with high frequency and accuracy; a property especially stringent for potential use as a current standard. Several routes to fabricate such devices are currently perceived [2].

In this paper we investigate a novel device concept; single electron pumping via multiple donors in a (selectively doped) silicon nanowire. Recently, much progress has been made in the fabrication- and operation -of single donor devices of various nature [3]. Utilizing single donors as active components in charge transfer devices [4] would have several advantages regarding speed and acuracy. First of all, donor atoms form a very reproducible potential in the silicon lattice that do not require tuning by external gates. Secondly, by charging- and decharging -multiple donors with a single electron each, the device would be capable of generating high currents in a fashion analogues of parallel single electron transfer devices. Thirdly, gigahertz operation should be possible as both capture of electrons by donors and tunneling emission from the donors [5] is fast enough.

II. Experiments and Results

Our devices consist of Si-wire MOSFETs in series fabricated on a silicon-on-insulator wafer, see Fig. 1a. A stacked gate layer structure is employed: the lower layer consist of three fine gates (LG, MG and RG) defined by electron beam lithography and the top layer consist of a large single upper gate (UG). The fine gates are used to induce and control local electron barriers in the silicon nanowire. In some samples donor atoms (As) are introduced by ion implantation between MG and RG through a 60 nm wide aperture in a pre-designed E-beam mask. The top gate layer is used to control the electron density; application of a positive voltage leads to electron inversion in the undoped SOI layer beneath. The wide UG layer furthermore serves as a mask during an ion implantation step that forms the n^+-type contact areas. The SOI substrate is used as a back gate electrode (BG).

The concept of operation of our donor based electron pump devices is depicted in Fig. 1b. For charge transfer operation, we apply an AC signal to the middle of the three fine gates (MG). The rightmost of the fine gates (RG) is tuned such that it induces a small barrier in the Si nanowire beneath it. The leftmost fine gate (LG) does not play a role in the experiment. When the barrier formed by V_{MG} is in its low state (I), electrons from the source region are captured on the donor sites (and for large V_{UG} also in the electrically induced inversion layer at the SiO_2 interface). When the barrier is subsequently ramped up (II) to its high state by V_{MG}, it generates an electric field large enough to ionize the donors and evacuate their associated electrons to the drain region (III).

Figure 2a shows the source/drain current I_{SD} (in units of electron charge per pump cycle) as a function of V_{UG} for several different doping concentrations. Here, we set V_{RG} to -0.5 V, V_{LG} to +1 V, and cycle V_{MG} between +1 V (low state) and -3 V (high state). We observe that the normalized current is virtually the same for 2.5 MHz and 5 MHz, showing that

*e-mail: gabriel.lansbergen@lab.ntt.co.jp, tel: +81 46 240 3407, fax: +81 46 240 4317

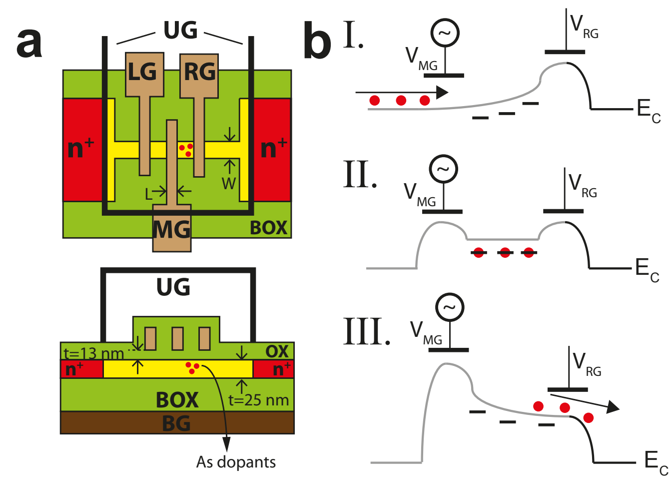

Fig. 1. **(a)** Schematic top- and side -view of the device. The Si nanowire has a thickness (t) of 25 nm and a width (W) of 80 nm, the fine gates (brown) have a length (L) of 100 nm and are spaced 60 nm apart. **(b)** Schematic diagrams of operation of charge transfer during a pumping cycle ($I - III$). Electron flow from the source into the island region when the barrier formed by V_{MG} is low (I), are captured by multiple donors (II) and emitted when the potential barrier is high (III).

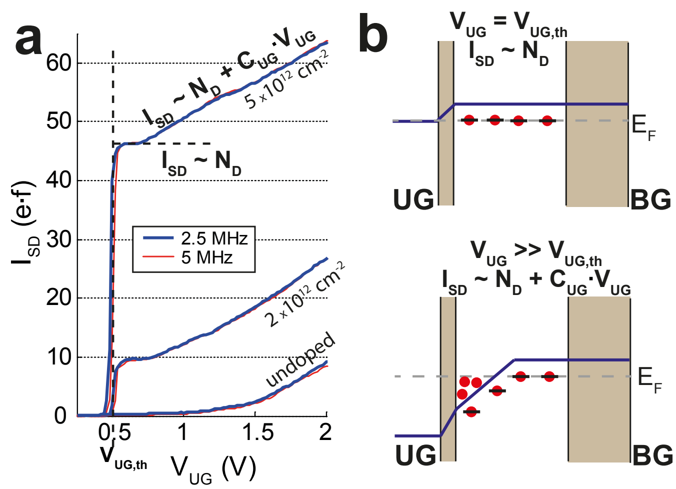

Fig. 2. **(a)** Source drain current (I_{SD}) in units of ef as a function of upper gate voltage (V_{UG}) for several donor implantations doses. Here, $V_{BG} = 0$ V. **(b)** Band diagram in the island region between UG and BG for $V_{UG} = V_{UG,th}$ (upper panel) and $V_{UG} >> V_{UG,th}$ (lower panel).

I_{SD} originates from charge pumped by the AC signal on MG. The current onset marked by $V_{UG,th}$ is the threshold voltage of the parasitic undoped region below the upper gate, indicated in yellow in Fig. 1a, (as it is also present when all fine gates are open; $V_{LG} = V_{MG} = V_{RG}$ =+1 V).

The source drain current I_{SD} is equal to the amount of charge captured in the island region multiplied by the pumping frequency. For the undoped sample, charge capture in the island starts when the conduction band in the island region (between MG and RG) is pushed below the Fermi energy (E_F). The upper gate voltage required for inversion in the island region ($V_{UG,is}$) is actually higher than for the parasitic region $V_{UG,th}$ due to screening of the upper gate field by MG and LG. After inversion in the island region ($V_{UG} \geq V_{UG,is}$), the current scales with $I_{SD} \sim C_{UG}V_{UG}$, with C_{UG} being island capacitance to the upper gate.

Implantation of donors in the island region of our devices introduces positive charge and has two effects on the characteristics. Firstly the positive charge shifts down $V_{UG,is}$ close to the level of $V_{UG,th}$. Secondly the donors are able to bind electrons and thus increases the charge transfer per cycle. Since $V_{UG,is}$ will still be slightly higher than $V_{UG,th}$ (on the order of the donor binding energy), at $V_{UG} = V_{UG,th}$ there is *no* inversion layer yet, all the charge transfer takes place via donor sites (see Fig. 2b). As a result, we observe a small flat region at $V_{UG} \sim V_{UG,th}$. The height of the plateau is in reasonable agreement with the expected number of implanted donors (N_D).

The small plateau is only present when the conduction band is in flatband conditions, as we will show next. Figure 3a-b shows the charge transfer characteristics as a function of back gate voltage (V_{BG}) for the two doped samples. We observe a shift in the threshold as a function of V_{BG}, associated *only* with a shift in $V_{UG,th}$, the threshold voltage of the parasitic regions. Inside the island region the negative potential applied to V_{BG} leads to a depletion layer that screens the back gate field, causing the potential in the island region $V_{UG,is}$ to shift lower than the potential in the parasitic region $V_{UG,th}$ (Fig. 3c-d). For $V_{BG} << 0$, starting at $V_{UG} = V_{UG,th} >> V_{UG,is}$ electron start to fill the inversion layer in the island and the source drain current directly scales with $I_{SD} \sim C_{UG}V_{UG}$. We can thus no more observe a donor plateau at $V_{UG} = V_{UG,th}$. The observed characteristics are compatible with our simple model of the device behavior and supports the notion that in flatband conditions, $V_{UG} \sim V_{BG}$, charge transfer is exclusively carried by isolated donors.

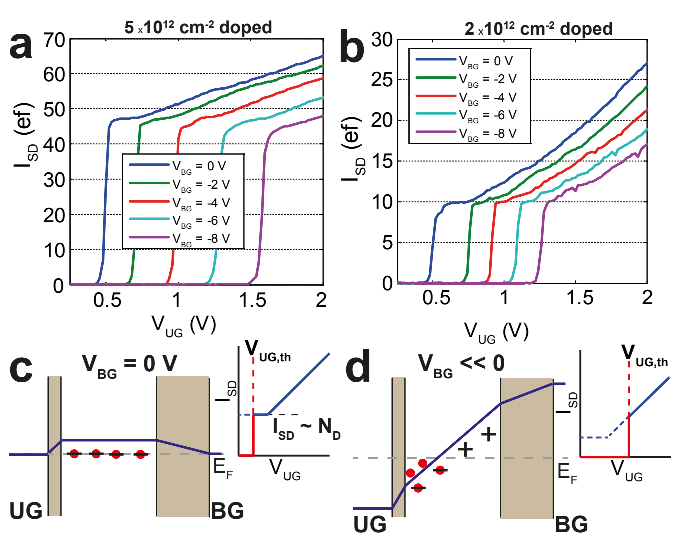

Fig. 3. **(a-b)** Device characteristics $I_{SD} - V_{UG}$ as a function of V_{BG} for the 5×10^{12} cm^{-2} and 2×10^{12} cm^{-2} respectively. **(c-d)** Band diagram between UG and BG across the island region and schematic $I_{SD} - V_{UG}$ curves for V_{BG} = 0 V and $V_{BG} << 0$ V respectively.

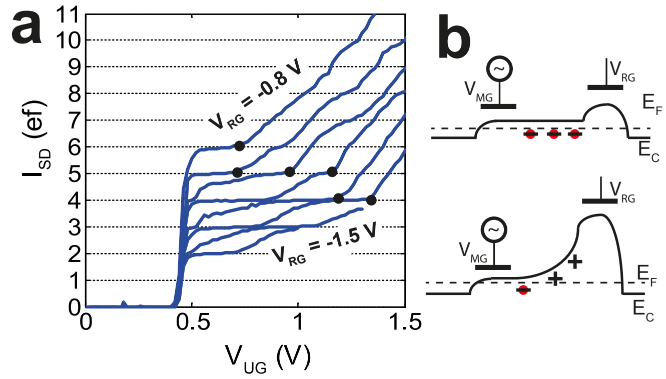

Fig. 4. **(a)** Device characteristics $I_{SD} - V_{UG}$ as a function of V_{RG}, showing integer charge transfer up to I_{SD} =6 ef. The black dots (roughly) indicate $V_{UG,is}$ **(b)** Schematic diagram of operation of charge transfer as a function of V_{RG}; for increasingly negative V_{RG} a depletion layer in the channel is formed, reducing the number of donors participating in the transport.

Next, we show that the donor-based charge transfer region can be extended by tuning the fine gate voltages. Figure 4a shows the charge transfer characteristics I_{SD} versus V_{UG} for increasingly negative right fine gate voltage (V_{RG}). We observe a decreases in I_{SD} for more negative V_{RG} combined with clear integer steps developing as a function of V_{UG}. When a negative potential is applied to V_{RG} (at fixed V_{UG}) it induces a depletion region extending well into the island region, making less donors available for charge transfer (see Fig. 4b). When we subsequently *increase* V_{UG} to higher positive values, in some cases donor are neutralize again, shifting the potential where inversion occurs to higher positive values. The threshold voltage of the island region $V_{UG,is}$ is (roughly) indicated by the black dots. The right fine gate voltages can thus be employed to tune the number of donors participating in the transport.

III. Conclusion

In this paper we demonstrated single electron charge transfer by multiple donors, implanted in the island region of a charge transfer devices. The voltage condition of the devices can be tuned such that electrons are exclusively transferred via donor atoms. Furthermore, the donor atoms give rise to clear integer steps in the source drain current, underlining the discrete nature of the charge transfer.

This work was partly supported by KAKENHI 20241036, 22310062 and the Funding Program for Next Generation World-Leading Researchers of JSPS.

References

[1] H. Pothier *et al.*, *Europhys. Lett.* **17**, 249 (1992)
[2] In the following and references therein: M. D. Blumenthal *et al.*, *Nat. Phys.* **3**, 343 (2007); A. Fujiwara *et al.*, *Appl. Phys. Lett.* **92**, 042102 (2008) ;V. F. Maisi *et al.*, *New Jour. Phys.* **11**, 113057 (2009)
[3] P. M. Koenraad and M. E. Flatté, *Nature Materials* **10**, 91 (2011)
[4] D. Moraru *et al.*, *Phys. Rev. B* **76**, 075332 (2007)
[5] E. Rosencher *et al.*, *Phys. Rev. B* **29**, 1135 (1984)