Influence of the Geometry on the Coulomb Blockade in Silicon Nanostructures

Irina Ionica[(1)], Laurent Montès[(1)], Jacques Zimmermann[(1)],
Laurent Saminadayar[(2)] and Vincent Bouchiat[(2)].

(1) Institut de Microélectronique, Electromagnétisme et Photonique (IMEP),
UMR CNRS-INPG-UJF 5130, 23 Rue des Martyrs, BP257, 38016 Grenoble Cedex1, France.
(2) Centre de Recherche sur les Très Basses Températures (CRTBT),
UPR CNRS 5001, 25 Rue des Martyrs, BP166, 38042 Grenoble, France.
ionica@enserg.fr

Abstract:

In low dimension devices used in nanoelectronics, monoelectronic transport phenomena can dominate the electrical properties especially at low temperature. In this paper we are demonstrating a strong connection between the Coulomb blockade and the geometry of silicon nanostructures fabricated by atomic force microscopy on silicon on insulator. First, a study on a double-channel nanostructure is presented; depending on the bias voltage applied on the backgate we are able to electrically activate either the larger channel or both.
A comparative analysis between the stability diagrams for the double-channel nanostructure and a long nanowire showed differences in the electrical behavior that can be due to the different geometries. Simulations based on the orthodox theory of the Coulomb blockade prove that a model with two quantum dots in parallel is well adapted for the double-channel structure; meanwhile the appropriate model for long the nanowire is that of quantum dots in series.

1. Introduction

The interest in nanostructures has increased a lot nowadays because of the variety of their possible applications, such as Single Electron Transistor (SET) for logic circuits [1]. The sensitivity of these kind of devices for the charge detection is also well known [2]. Other applications concern the possible functionalization of the nanostructures in order to make them reactive to a certain chemical or biological element [3] and their use as detectors. For all these possible applications it is crucial to understand, control and predict the influence of the nanostructure geometry on the electrical properties and especially on the Coulomb blockade phenomenon.
In this paper we focus on the geometry of the nanostructures versus electrical properties.
Devices with different geometries are fabricated by a non-conventional top-down method: Atomic Force Microscopy (AFM) based lithography on Silicon-on-Insulator (SOI) substrates. An oxide mask is directly drawn on the top silicon layer of the SOI under low-energy electrons emitted by an AFM tip in the near-field of the substrate. A wet etching step is used to finalize the silicon nanostructures. The resolution is not affected by diffusion phenomena or proximity effects. Moreover, the main advantage of this technique is the easy-to-change geometry of the designed nanostructures. Double-channel and single long channel silicon nanostructures have been fabricated on a highly doped (Nd ~ 10^{19}cm^{-3}) ultra-thin (15nm) SOI between pre-processed contact pads. The fabrication technique is detailed elsewhere [4].
At room temperature these nanostructures act as field effect transistors due to the bias voltage applied on the backgate [5] while at low temperature single electron phenomena as the Coulomb blockade are dominating the electrical transport. In this paper we show that the geometry has a strong influence on the electrical transport. For a double-channel geometry the backgate voltage can activate only the larger channel or both.

2. Double-channel nanostructure

A double-channel silicon nanostructure having different channel widths is shown in Figure 1. It is a short structure of 40nm length (L); the width of the large channel is 20nm (w_1) and the width of the small channel is 10nm (w_2).

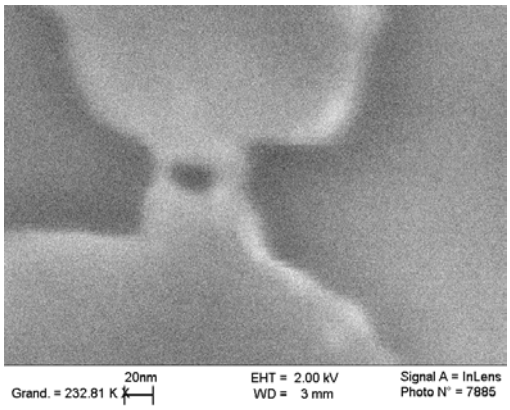

Figure 1: Scanning electron micrograph of a double-channel silicon nanostructure
(L=40nm; w_1=20nm; w_2=10nm).

Low temperature (4.2K) electrical measurements were carried on this nanostructure for different backgate polarizations. Drain current versus backgate voltage

curves for four different values of the drain voltage are shown in Figure 2. The reproducible oscillations present on these curves are a signature of Coulomb blockade phenomenon. In highly doped silicon nanostructures the origin of the Coulomb blockade is linked to the potential fluctuations inside the structure due to the presence of the dopant atoms [6]. Small potential wells are formed around the ionized dopant atoms (Figure 3). Electrons can be spatially localized in these potential wells up to an energetic level fixed by the backgate voltage, as in quantum dots. Potential barriers are present between two dots and electrons may tunnel from one dot to the other. When the backgate voltage increases, the energy barriers between two doping atoms is smaller and also the tunnel barriers are smaller. As a result, new conductive paths through the nanostructure can be created, so the blocked regions are smaller for high backgate potentials.

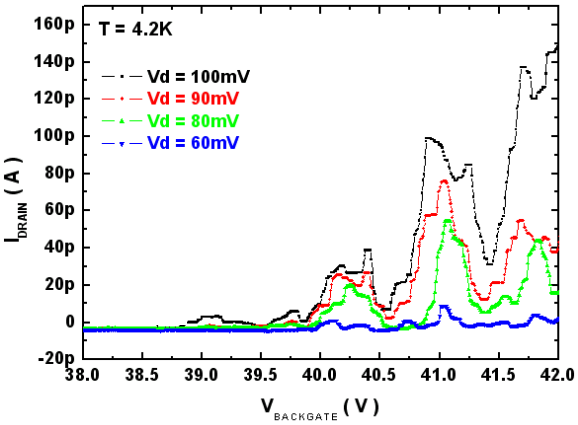

Figure 2: I_{DRAIN} versus $V_{BACKGATE}$ curves for some values of V_{DRAIN} are shown. Reproducible current peaks can be seen in all characteristics.

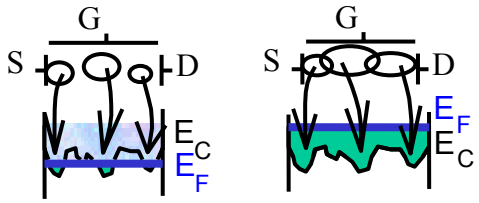

Figure 3: Potential fluctuations around the dopant atoms. The dimensions of these potential wells are controlled by the backgate voltage.

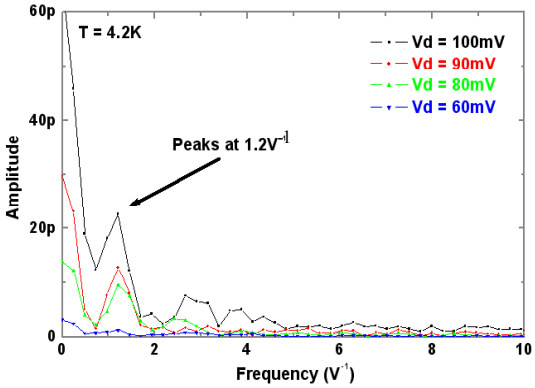

Figure 4: FFT of the I_{DRAIN} - $V_{BACKGATE}$ curves (Figure 2)

A periodicity of the current peaks in Figure 2 can be sensed in the fast Fourier transform (FFT) analysis, as shown in Figure 4.

A peak around $1.2V^{-1}$ in the FFT is evidencing a periodicity in the I_{DRAIN} versus $V_{BACKGATE}$ curve of about 0.83V, which corresponds well to Figure 2. We also note that this peak is at the same position for all the drain voltages. In a simple dot model, this peak to peak distance corresponds to the voltage that one needs to apply in order to charge a dot with one electron [7]. A gate capacitance can be estimated:

$$\Delta V = 0.83V \Rightarrow Cg = \frac{e}{\Delta V} = 0.19aF$$

A planar capacitance model between the dot and the backgate allows calculating the radius, r, of the dot where the Coulomb blockade takes place:

$$S = \frac{Cg \cdot tox}{\varepsilon ox} \Rightarrow r \approx 15nm$$

This result is coherent with the geometrical width of the larger channel. Each current peak is actually a double peak so we might have a small contribution due to the other channel. This contribution is not dominating and does not seem to affect the periodicity value of the electrical properties. We conclude that for these measurements the conduction is mainly insured by the large channel and the one-dot model seems to be well adapted to understand the electrical transport in the nanostructure.

The curves shown in Figure 5 represent measurements on the same sample but at a higher voltage bias. The peak structure and the FFT for this case are more complex (Figure 6). We can extract two frequency peaks at $0.5V^{-1}$ and at $0.9V^{-1}$. The second peak might just be the second harmonic of the first one. Nevertheless the FFT seems to have the same peak structure distribution around $2V^{-1}$ so, we assume that this is the second harmonic. In this case the double peak around $1V^{-1}$ has physical meanings.

One possible interpretation would be that by increasing the backgate voltage the second channel is activated.

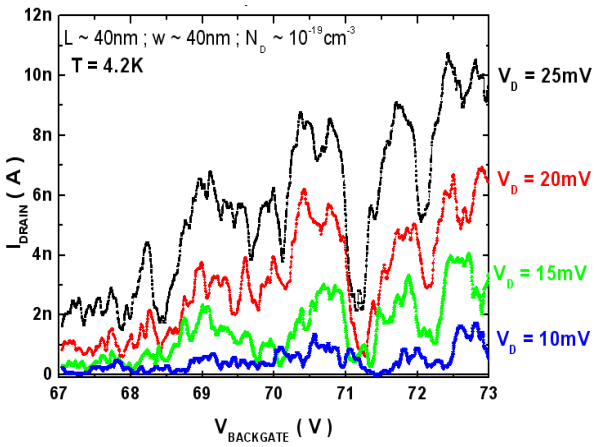

Figure 5: I_{DRAIN} versus $V_{BACKGATE}$ curves for different values of V_{DRAIN} at higher backgate voltages (around 70V). Reproducible but more complex current peaks can be seen in all characteristics.

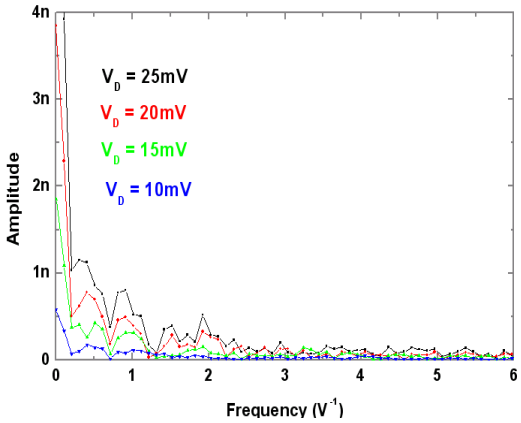

Figure 6: FFT of the I_{DRAIN} - $V_{BACKGATE}$ curves shown in Figure 5. A double peak around $1V^{-1}$ and its second harmonics around $2V^{-1}$ are clearly evidenced.

Another way to interpret this result is based on the fact that a second dot in the same channel became electrically active due to the increase of the backgate voltage. Moreover, we will demonstrate in the next section that the structure is well modeled with a parallel double-dot model.

3. Geometry versus electrical properties

In this section a comparative electrical analysis of two structures with different geometries is realized. One of the nanostructures used for this comparative test is the short double-channel wire presented in the previous section and polarized at high backgate voltages. The other nanostructure used is a long single channel nanowire (see Figure 7).
One way to represent the low temperature measurements is to make a drain current mapping versus the backgate voltage and the drain voltage, also called stability diagram. For a simple dot this mapping evidences zero conduction regions having a repeating pattern in shape of rhombus or Coulomb diamonds. For devices with more than one dot, the stability diagram is more complex [8].

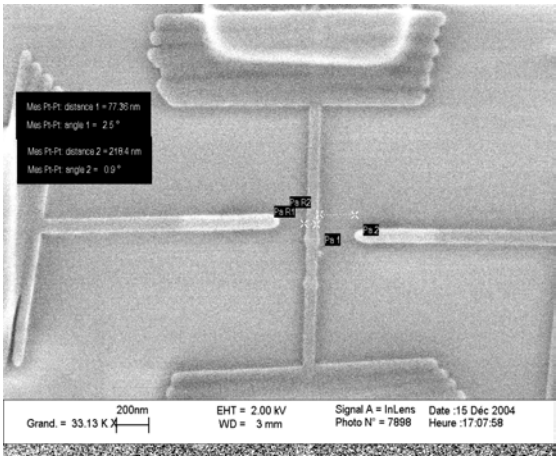

Figure 7: Scanning electron micrograph of a simple long channel nanowire. The dimensions of this nanowire are: L=1.2µm, w=40nm, h=15nm, which corresponds to a cross-section of $600nm^2$.

The stability diagram for the long nanowire is evidencing Coulomb diamonds (see Figure 8). The diagram has quite a simple structure even though the diamonds are not regular. The nanowire is in a regime where the Coulomb blockade is superposed with the field effect. We have added two white lines on the diagram to show the impact of the electrical field effect.

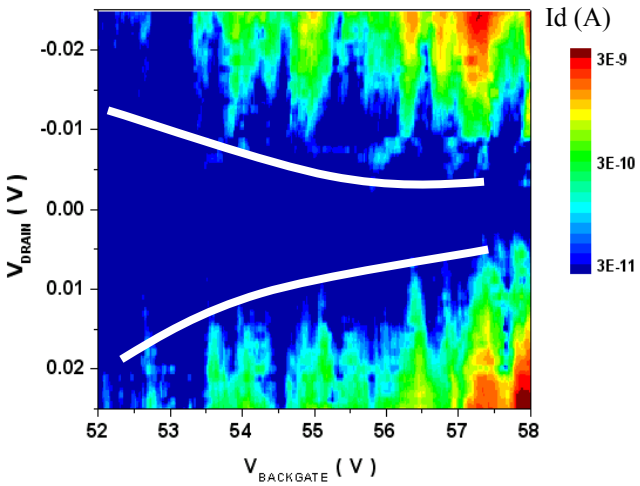

Figure 8: Drain current mapping (in logarithmic representation) versus backgate voltage and drain voltage for the long nanowire shown in Figure 7.

The stability diagram in Figure 9 presents the electrical properties of the double-channel structure, at high backgate voltages. The field effect is reduced compared to the previous nanostructure. The transport is dominated by the Coulomb blockade. The diamonds are also less regular: series of large diamonds are followed by series of narrow diamonds. In this case the backgate voltage does not have a clear influence on the diamonds shape.
In order to understand the different electrical behavior of the two nanostructures models are needed.

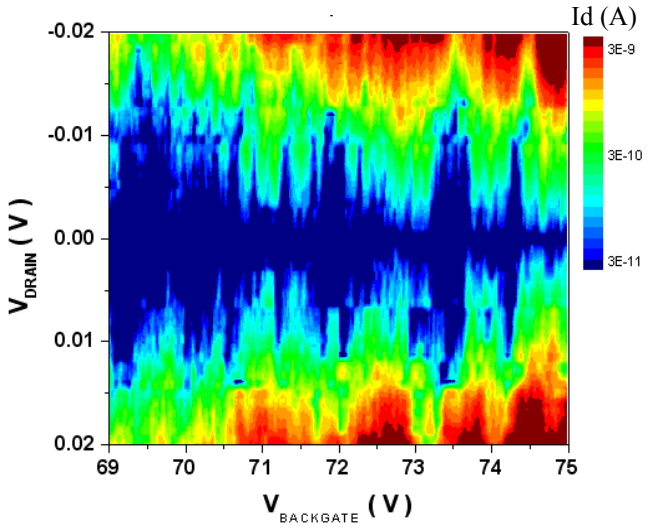

Figure 9: Drain current mapping (in logarithmic representation) versus backgate voltage and drain voltage for the double-channel nanostructure.

We have simulated the stability diagram for two cases: two dots in series (Figure 10a) and two dots in parallel (Figure 10b). Each dot has a different geometry, so their capacitance is different. The field effect is not included in the model.

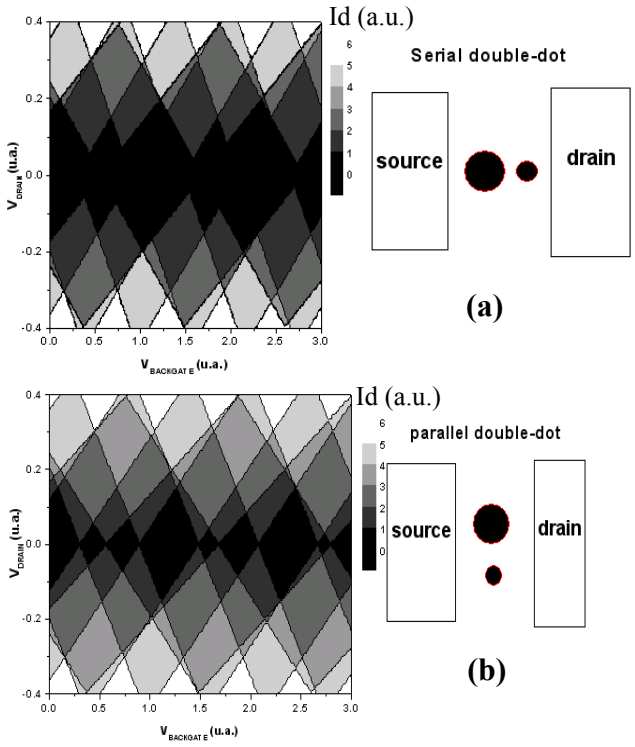

Figure 10: Simulation of the stability diagrams for a system with two dots in series (a) and in parallel (b).

For the serial double dot the diamonds have very small variations in height and the Coulomb gap (zero conductance region) in drain voltage is always larger than zero because there is no perfect alignment between the energy levels of the two dots at the same time. Actually in this case it is the small dot which modulates the blocked regions. In the parallel case the total current is the sum of the current through each dot. The blocked regions are smaller and the Coulomb gap is canceled at peculiar backgate voltages, as it is enough to have one conductive dot in order to have a total current different from zero. The stability diagram consists of a series of large and narrow diamonds. The Coulomb diamonds evaluated by the serial dots model have the same shape as those obtained experimentally for the long single channel nanowire, while the parallel dots model predicts well the shape of the experimental Coulomb diamonds of the double channel nanostructure.

4. Conclusion

In this paper we have studied the impact of the geometry on the Coulomb blockade in highly doped silicon nanostructures fabricated by AFM lithography. We have proved that for a double-channel silicon nanostructure, the peak structure in the drain current versus backgate voltage curves at low temperature is modulated by the backgate voltage. Single periodical peaks are evidenced in low backgate voltages while peaks with double periodicity appear for higher backgate voltages. A change in the conduction regime is possible by changing the backgate voltage. The geometry has its own signature in the Coulomb blockade phenomenon. This way, for the long nanowire, the Coulomb blockade appears in an array with a high number of dots, but the stability diagram is quite simple because the total conduction through the nanowire is mainly driven by the smallest dot in the array. For the double-channel nanostructure the total conduction is a superposition of the electrical paths through both channels. The stability diagrams for the double-channel and for the single channel nanostructures have completely different particularities corresponding to a model of serial dots – for the single channel nanowire – and to a model of parallel dots – for the double-channel nanostructure.

5. Acknowledgements

The authors thank D. Fraboulet, D. Mariolle and J. Gautier from LETI/CEA Grenoble for providing the ultra-thin SOI substrates.

References:

[1] H. Jin, Z. A. K. Durrani, and H. Ahmed, "Two-way switch for binary decision diagram logic using silicon single-electron transistors", Microelectronic Engineering., vol. 74, pp. 712-18, 2004.

[2] Y. Ono, A. Fujiwara, K. Nishiguchi, H. Inokawa, and Y. Takahashi, "Manipulation and detection of single electrons for future information processing", Journal of Applied Physics, vol. 97, pp. 31101-1, 2005.

[3] X. T. Zhou, J. Q. Hu, C. P. Li, D. D. D. Ma, C. S. Lee, and S. T. Lee, "Silicon nanowires as chemical sensors", Chemical Physics Letters, vol. 369, pp. 220-4, 2003.

[4] I. Ionica, L. Montès, S. Ferraton, J. Zimmermann, V. Bouchiat, and L. Saminadayar, "Silicon Nanostructures Patterned on SOI by AFM Lithography", Nanotech Conference Proceedings, vol. 3, pp. 165-8, Boston, USA, 2004.

[5] I. Ionica, L. Montès, S. Ferraton, J. Zimmermann, V. Bouchiat, and L. Saminadayar, "Field Effect and Coulomb Blockade in Gated Silicon on Insulator Nanowires", EUROSOI Conference, Granada, Spain, 2005.

[6] A. Tilke, R. H. Blick, H. Lorenz, and J. P. Kotthaus, "Single-electron tunneling in highly doped silicon nanowires in a dual-gate configuration", Journal of Applied Physics, vol. 89, pp. 8159-62, 2001.

[7] "Single Charge Tunneling", edited by H. Grabert and M.H. Devoret, vol. 294. New York and London: Plenum Publishing Corporation, 1991.

[8] W. G. van-der-Wiel, S. De-Franceschi, J. M. Elzerman, T. Fujisawa, S. Tarucha, and L. P. Kouwenhoven, "Electron transport through double quantum dots", Reviews of Modern Physics., vol. 75, pp. 1-22, 2003.