Influence of Dopant Concentration on the Electrical Transport at Low Temperature in Silicon Nanowires

I. Ionica, L. Montès, J. Zimmermann
Institut de Microélectronique, Electromagnétisme et Photonique (IMEP), UMR CNRS-INPG-UJF 5130
Grenoble, France
irina.ionica@grenoble.cnrs.fr

I. Ionica, L. Saminadayar, V. Bouchiat
Centre de Recherche sur les Très Basses Températures (CRTBT), UPR CNRS 5001
Grenoble, France

***Abstract*—We demonstrate the correlation between the the doping atoms concentration and the Coulomb blockade phenomenon in silicon nanowires. At room and intermediate temperatures nanowires show a field effect, while at low temperature current oscillations due to Coulomb blockade dominate transport close to the conduction threshold. Detailed experimental results on samples with two different doping levels allowed Coulomb blockade to be related to the presence of the dopants. In the limit of a few dopants per cross section, as for low doping level ($2.5x10^{17}cm^{-3}$), the electrical behavior of the nanowire is similar to that of a one dimensional array of dots. In nanowires with a high doping level ($10^{19}cm^{-3}$), transport can be modeled on the basis of a two dimensional arrays of dots.**

Keywords-nanowires, Coulomb blockade, doping level, tunnel junction arrays.

I. INTRODUCTION

The study of electrical properties of the silicon nanostructures is of increasing interest. Firstly, scaling microelectronic devices has reached limits where the electrical properties are influenced by small dimensions due to phenomena like tunneling effect or by the dopant fluctuations along the conduction channel. Silicon nanostructures are also interesting for the fabrication of single electron devices. Coulomb blockade is associated with the presence of isolated islands capacitively coupled to source and drain electrodes and to a gate. In silicon nanostructures, Coulomb blockade was explained by geometrically defined dots [1], [2] or by the granularity of the material (e.g. polycrystalline silicon [3]). Single electron charging effects were also observed in monocrystalline silicon nanowires and in this case were explained by dopant fluctuations and by surface roughness [4]. Here we focus on the influence of the doping level on Coulomb blockade in low roughness silicon nanostructures. The presence of random dopant distribution inside the devices is known to induce fluctuations in the functioning parameters. An important step forward to a ordered distribution of dopant atoms in the devices was recently done by Shinada et al [5], but until these kind of techniques are widely used, the dopant fluctuations will affect the electrical behavior especially for small dimension devices, having a size of the same order of magnitude as the average distance between doping atoms.

In this paper, we study the electrical behavior of doped silicon nanowires fabricated by AFM lithography. The fabrication technique and its advantages are briefly presented. The electrical behavior at room and intermediate temperature is then investigated. The low temperature measurements on nanowires of two different doping levels are detailed in the last part of this paper. We analyze our experimental data in the framework of the Middleton model [6]. The electrical transport is then understood by using a model of one or two dimensional array of dots.

II. FABRICATION TECHNIQUE AND ELECTRICAL BEHAVIOR

The devices presented in this paper were fabricated by a non-conventional top-down method: Atomic Force Microscope (AFM) lithography on UNIBOND® Silicon-on-Insulator (SOI) substrates. An oxide mask is directly drawn by local oxidation on the top silicon layer of the SOI under low-energy electrons emitted by the AFM tip in the near-field [7]. The resolution of this technique is not limited by diffusion phenomena or proximity effects that affect other lithography methods. A wet etching step is then used to reveal the silicon nanostructures. Silicon nanowires have been fabricated on a highly doped n-type (As) ultra-thin (15nm) SOI between pre-processed contact pads (Fig. 1a). Two doping levels were used: $2.5x10^{17}cm^{-3}$ and $10^{19}cm^{-3}$. The fabrication technique is detailed elsewhere [8]. We just want to underline here that the AFM lithography technique together with the wet etching allow fabrication of silicon nanowires with very low roughness.

At room temperature, these nanostructures act as field effect transistors due to the backgate bias voltage V_{BG} applied on the substrate (Fig. 1b). In order to study the effect of the dopant fluctuations inside a nanowire we need to investigate its electrical behavior at low temperatures. The curves $I_D - V_{BG}$ in Fig. 1c show the evolution of the electrical transport with the temperature. For temperatures down to 100K, the field effect follows the behavior predicted by the MOS transistors theory. Below 100K, the exponential increase of the current due to field effect is in competition with current oscillations that become dominant as temperature decreases. These current peaks do not change their position in the backgate voltage scale as temperature decreases. These peaks feature single electron charging. We associate the Coulomb blockade in these nanowires to the presence of the doping atoms.

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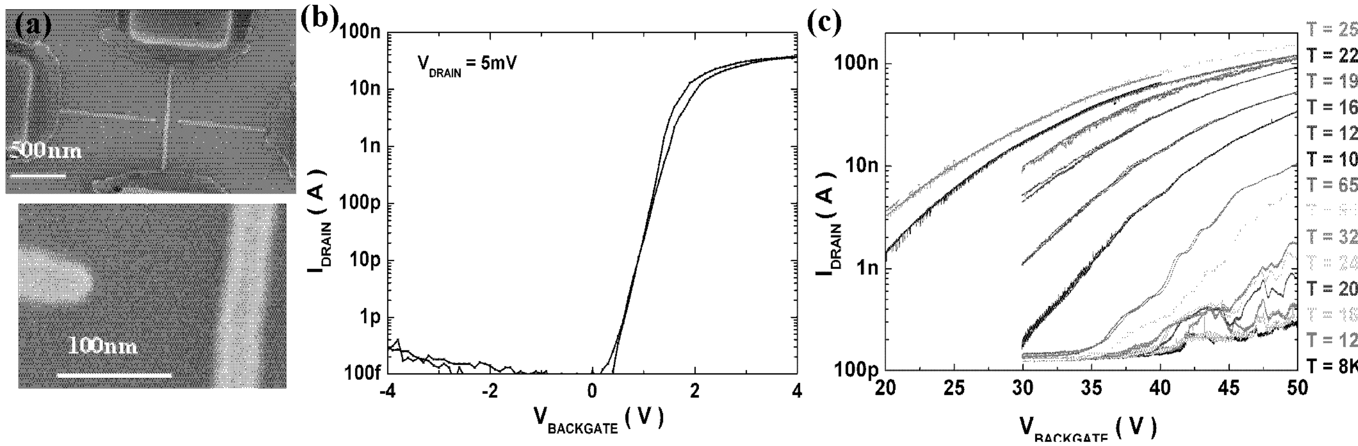

Figure 1. (a) Scanning electron micrograph of a silicon nanowire with lateral "finger" gates after full process. The AFM lithography allows obtaining 30nm resolution without proximity effects. (b) Influence of the backgate voltage on the current through a wire 800nm long, 70nm wide and 15nm thick. The doping level for this nanowire is $10^{19}cm^{-3}$. Transport is dominated by field effect due to backgating. (c) $I_D - V_{BG}$ evolution with the temperature for 50mV drain voltage. For temperatures lower than 100K, current oscillations are superimposed to the field effect behavior. As the temperature is decreasing, the oscillations dominate over the conductance by field effect. The nanowire under test is 1.2µm long, 150nm wide and has a doping level of $10^{19}cm^{-3}$.

III. Coulomb Blockade and Doping Level

For single island systems, the Coulomb blockade gives rise to periodic current oscillations versus gate voltage. The periodicity is related to the dimension of the dot. For more complex cases such as the multi-dot systems, oscillations of different periods are superimposed and the result is a current oscillation with no obvious periodicity. So, we underline that the absence of a clear periodicity does not mean that there is no Coulomb blockade but rather that the system is more complex than a simple dot. Analysis of current versus gate voltage gives information about the dimension of the electrically active dot. We then look for a relation of this dimension with the average distance between the dopant atoms.

Looking at arrays of dots, coupled with a gate capacitance, Middleton et al [6] have calculated the current through the array I_D versus the bias voltage applied to the array V_D. The disorder effects are introduced by way of offset charges. The model used is based on the propagation of an interface and lead to a current expression given by (1):

$$I_D \propto \left(\frac{V_D}{V_T} - 1 \right)^{\zeta} \qquad (1)$$

The threshold voltage V_T is the minimum value to be applied to the array in order to remove the Coulomb blockade in all the dots along the array. The value of the scaling factor ζ depends on the dimensionality of the array: ζ is equal to 1 for one-dimensional arrays and ζ is equal to 5/3 (1.67) for the two-dimensional arrays of dots. The Middleton model has been successfully applied to cobalt superlattices [9] Applying this model to our case of study, we can estimate whether or not the dimension of the electrically active array corresponds to that of the array of dopants in the nanowire.

In order to confirm our hypothesis of a link between Coulomb blockade and the presence of the dopants, electrical tests were performed on nanowires with two doping levels.

A. Lower doping level: $2.5x10^{17}cm^{-3}$

At $2.5x10^{17}cm^{-3}$, the average distance between dopants is about 16nm. All our structures are 15nm thick, corresponding to an average of one dopant per height. The typical width of the nanowires under test is about 50nm, which means that there are three dopant atoms per cross section at the maximum.

Fig. 2a shows periodic oscillations of the $I_D - V_{BG}$ curves for two different drain voltages for a low doped nanowire. The periodicity of the current oscillations is about 0.25V, corresponding to a total gate capacitance of 0.64aF. The dimension of the dot is given by the ratio of the total gate capacitance over the capacitance per length unit. The capacitance per length unit for a nanowire of diameter a and a gate oxide thickness h is given by (2):

$$C_{G\_length} = \frac{4 \cdot \pi \cdot \varepsilon}{2 \cdot ln\left(\frac{h + \sqrt{h^2 - a^2}}{a} \right)} \qquad (2)$$

The nanowire tested is 40nm wide and considering that a is half the sum of thickness and width, C_{G_length} is 66aF/µm. The size of the dot is given by the ratio of the total capacitance by the capacitance per length unit. The dot size then is 10nm. The average distance between the dopant atoms for this sample is of about 16nm. The dot size then is consistent with the average distance between the dopant atoms.

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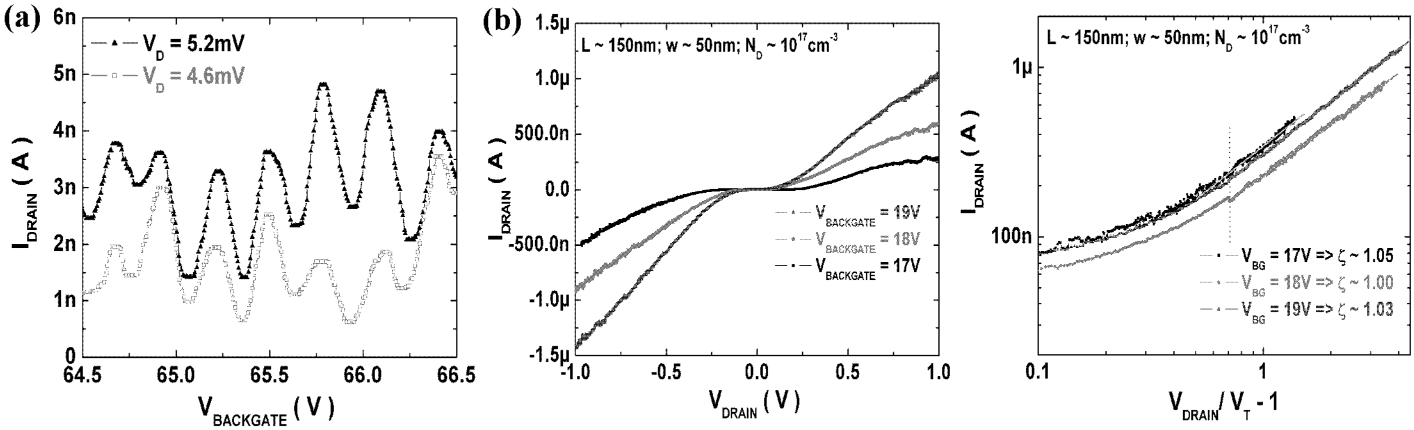

Figure 2. Low temperature measurements for nanostructures with a doping level of $2.5 \times 10^{17} cm^{-3}$. (a) $I_D - V_{BG}$ curves at 4.2K, for different drain voltages. The nanowire under test is 40nm wide, 1.2µm long and 15nm thick. The curves show periodic conductance fluctuations, which are the specific feature of Coulomb blockade. (b) $I_D - V_D$ curves at 4.2K, for different backgate voltages. The nanowire under test is 150nm long, 50nm wide and 15nm thick. The Coulomb blockade induces the appearance of a zero conductance region around 0V on the drain, called Coulomb gap. (c) Drain current versus the normalized drain voltage for the curves presented in (b). For normalized voltages higher than 1, a linear dependance is observed. The slope gives the scaling factor which is equal to 1, corresponding to an electrical behavior of an one-dimensional array of dots.

The Middleton model was applied on the $I_D - V_D$ curves for three different backgate voltages (Fig. 2b). Fig. 2c shows the drain current versus the normalized drain voltage $(V_{DRAIN}/V_T)-1$. For normalized voltages higher than 1, the curves can be fitted by lines and their slopes give the scaling factor. The scaling factor is about 1 for this nanowire. As a matter of fact, the scaling factor obtained for the nanowires with the same low doping level, varies between 0.85 and 1.2. So, generally the low doped nanowires act as one-dimensional arrays of electrically active dots. This is consistent with the fact that these wires have a maximum of 3 dopant atoms per cross section and, so, the array of dopants inside the nanowire is one dimensional.

B. *Higher doping level: $10^{19} cm^{-3}$*

For this doping level, the average distance between the doping atoms is about 5nm. The number of doping atoms per cross section is about 30, but the number of atoms per height is three at the maximum. This means that the matrix of doping atoms inside these nanowires can be approximated to an two-dimensional array.

Firstly we want to compare the dimension of the electrically active dot to the average distance between the dopant atoms. Fig. 3a shows experimental curves I_D - V_{BG} obtained at 4.2K for different drain voltages. The periodicity is not obvious in this case. A fast Fourier transform (FFT) analysis allows discovering a hidden periodicity of these oscillations (inset of Fig. 3a). A peak at $2V^{-1}$ was found for all the drain voltages tested. This peak in the spectrum rather shows the pseudo periodicity of the current oscillations.

The periodicity obtained in the spectrum is about 0.5V, which corresponds to a calculated total gate capacitance of 0.29aF. The nanowire under test is 15nm thick and 70nm wide. Considering that a is half of the sum of thickness and width, C_{G_length} is about 75.4aF/µm. In this case, the dot is about 4nm long. We notice that the size of the electrically active dot corresponds to the average distance between the doping atoms (5nm for this doping level).

An example of the Middleton model applied to the high doping level nanowires is shown in the Fig. 3b. The drain current versus normalized drain voltage curves are fitted with lines (Fig. 3c). The scaling factor increases at the increasing backgate voltages, from 1.75 to 2.01.

The scaling factor generally obtained for these nanowires lies between 1.5 and 2.5, corresponding to two- (or maybe three-) dimensional arrays of electrically active dots. This electrical behavior is consistent with the fact that the doping atoms inside these nanowires are similar to two-dimensional arrays.

C. *Discussion*

The dopants inside the nanowires form an array of randomly distributed atoms. We saw that the electrical behavior of the nanowires is explained by the transport through an array of electrically active dots. For both doping levels we noticed a very good agreement between the parameters concerning the dopant array (average distance between dopants, number of dopants per cross section) and the electrical parameters of the array of dots (dot dimension, dimensionality of the array). There exists a strong connection between the presence of the doping atoms and the electrical properties. Actually, the doping atoms create potential fluctuations inside the nanowire [10]. The potential wells formed act as dots for the Coulomb blockade. The backgate voltage affects the filling of these wells by electrons and their dimensions as well.

The transport through the nanowires is the result of all the percolation paths present in the system of dots created within the width and the length of the nanostructure. Depending on the number of dopants in a nanowire, the array can be one-dimensional or two-dimensional.

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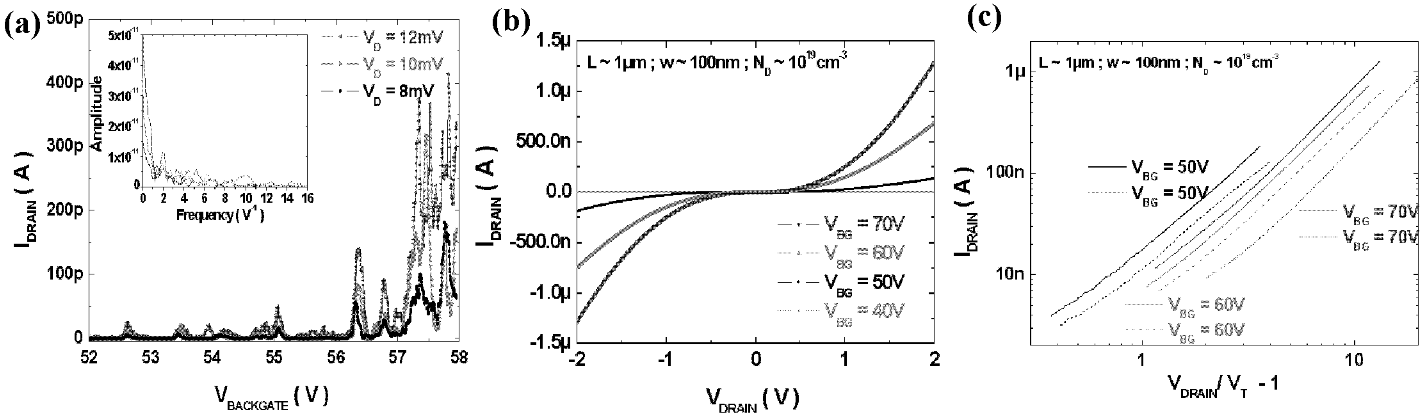

Figure 3. Low temperature measurements of nanowires with a doping level of 10^{19}cm^{-3}. (a) $I_D - V_{BG}$ curves at 4.2K, for different drain voltages. The nanowire under test is 70nm wide, 1.2μm long and 15nm thick. The curves are showing pseudo periodical peaks. In the inset, the fast Fourier transforms of these curves are showing a peak at 2V^{-1}, confirming a periodicity in the current oscillations. (b) $I_D - V_D$ curves for a nanowire being 1μm long, 100nm in wide. (c) Drain current versus normalized drain voltage for the curves shown in (b) (in dotted lines, the curves obtained from the negative drain voltages and in solid lines, the curves obtained for the positive drain voltages). Scaling factors are 1.75, 1.97 and 2 (at increasing backgate voltages).

With low doped wires, the number of dots per cross section is of the order of unity and the structures have the same electrical behavior as an one-dimensional (1D) array of dots. For small ranges of backgate voltage, the smallest dot in the array can block the transport by Coulomb blockade, and the current oscillations can be periodic.

With the high doping levels, the number of dopants per cross section is larger and can reach up to 50. The nanowire can be described as a two-dimensional (2D) array of dots. For small values of the drain voltage, it is possible to reach the limit of a conduction through a few number of dots only. The current oscillations are then the result of the superposition of current oscillations provoked by each dot and the periodicity can be lost.

IV. CONCLUSION

We have studied the electrical behavior of highly doped silicon nanostructures fabricated by AFM lithography. The transport through the nanowires is dominated by the field effect for temperatures between 100 and 300K. Below 100K, Coulomb blockade oscillations are superimposed to the field effect and eventually completely dominate the transport at 4.2K. Our hypothesis that the origin of the Coulomb blockade in this system is linked to the presence of the doping atoms was tested on structures of two different doping levels. A strong connection between the periodicity of the current peaks and the average distance between doping atoms proves that Coulomb blockade depends on the presence of the doping atoms in these nanostructures. We could associate a physical characteristic, the matrix of the dopant atoms inside the nanowire, to an electrical behavior, the transport through an array of dots. Even though we only had two different dopings for our experiments, each shows one of two options of conduction: one-dimensional at low dopings, two-dimensional at high dopings. One can expect a smooth transition from one to the other to exist in the intermediate range near 10^{18}cm^{-3}.

ACKNOWLEDGEMENTS

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

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