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Stievenard

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Evidence of electron-phonon interaction on transport in *n*- and *p*-type silicon nanowires

F. Vaurette,^{a)} R. Leturcq, J. P. Nys, D. Deresmes, B. Grandidier, and D. Stiévenard^{b)}

Département ISEN, Institut d'Electronique, de Microélectronique et de Nanotechnologie, IEMN, (CNRS, UMR 8520), 41 bd Vauban, 59046 Lille Cedex, France

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The authors studied the transport in *n*- and *p*-type silicon nanowires. When the temperature decreases from 325 to 75 K, they observed a variation of the nanowire resistance, consistent with a transport governed by electron-phonon scattering. The lateral size of the nanowire down to 25 nm is not found to cause further surface scattering, due to the presence of interface states which create a depleted region in the nanowires. Such depleted region allows thus to keep a carrier mobility in the nanowires similar to the bulk one. © 2008 American Institute of Physics.

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For more than 40 years, there has been a continuous scaling of the device dimensions to obtain higher integration and better performances. The scaling of the complementary metal oxide semiconductor technology, according to the International Technology Roadmap of Semiconductors, leads to quasi-one-dimensional nanowire (NW) devices. Moreover, due to the compatibility with the established silicon-based technology processes and the better performances of silicon-on-insulator (SOI) based devices, SOI NWs get an increasing importance as building blocks of nanodevices. So, the knowledge of their transport properties compared to the bulk ones is of prime importance in order to simulate and modelize the electrical performances of future devices.

Electron mobility in silicon NWs has been theoretically investigated¹⁻³ and the phonon scattering has been identified as a key parameter. Despite the importance of the temperature behavior of silicon NWs, there are very few experimental⁴⁻⁸ and theoretical results⁹ dealing with it. In addition to phonon scattering, as the surface over volume ratio increases when the cross section of the NW decreases, transport should also become limited by scattering effects due to surface roughness or electron coupling to localized surface phonon modes.

We present transport studies in *n*- and *p*-type silicon NWs, for temperature ranging from 4 to 325 K. We show that the increase in the NW resistance, when the temperature increases, is mainly due electron-phonon interactions. However, due to the presence of a depleted layer associated with surface states, the carriers do not interact with the surface of the NWs and therefore, we observed that the resistivity does not depend on the width of the NWs. Only bulk phonons have to be considered.

Silicon NWs were fabricated using e-beam lithography and reactive-ion etching (RIE) on SOI substrates. The thickness of the silicon layer was carefully measured using the ellipsometry technique and, as during the technological process of fabrication, two HF treatments were used, one for initial cleaning of the surface and the second for removing the hydrogen silsesquioxane (HSQ) resist, we subtract

1.5 nm (Ref. 10) on the initial measured value h_0 (typically, h_0 is on the order of 20 nm).

The top silicon layers were intentionally doped with a few $9 \times 10^{19} \text{ cm}^{-3}$ arsenic and $5 \times 10^{19} \text{ cm}^{-3}$ boron atoms, respectively. The thickness of silicon dioxide is 145 nm, with a silicon substrate thickness of 700 μm . Combining HSQ resist as mask with RIE with a $\text{SF}_6/\text{N}_2/\text{O}_2$ plasma, we obtain NW widths W from typically 100 down to 25 nm, with a constant length L of 1400 nm. The structures are connected with evaporated metallic contacts. For *n*-type layers, the Ohmic contact is made of 50 nm of titanium covered by 100 nm of gold. For *p*-type layers, the Ohmic contact is made of 12 nm of titanium, 200 nm of aluminum, 40 nm of nickel, and a final layer of 100 nm of gold.

The widths of the NWs were determined by scanning electron microscopy and by atomic force microscopy (AFM). A typical layout is given in Fig. 1(a), and a typical tapping-mode AFM image of a NW is given in Fig. 1(b). In these structures, there are metallic (Ohmic) contacts on both

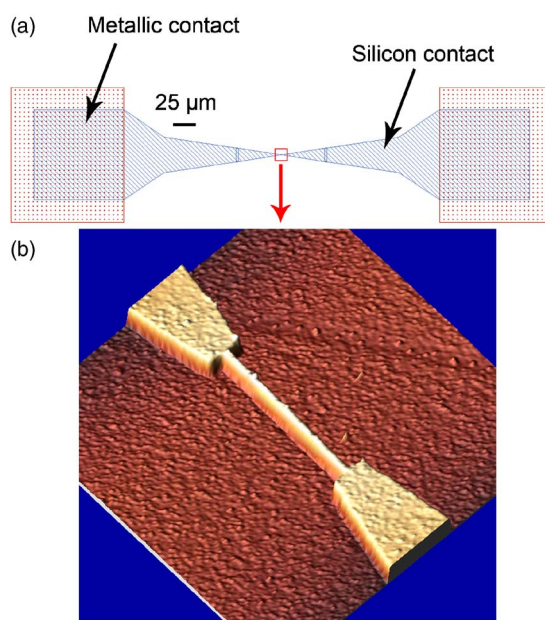


FIG. 1. (Color online) (a) Typical layout for the NWs with their contacts. (b) three-dimensional tapping-mode AFM image of a NW with a length of 1400 nm and a width of 35 nm. Z scale ranges from 0 to 25 nm.

^{a)}Electronic mail: francois.vaurette@isen.iemn.univ-lille1.fr.

^{b)}Electronic mail: didier.stievenard@isen.fr.

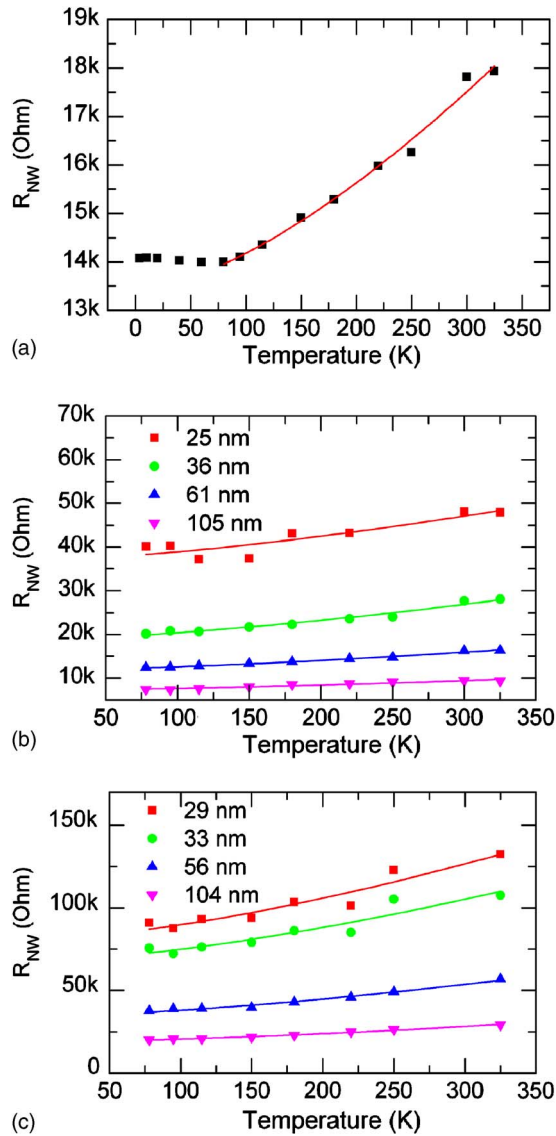


FIG. 2. (Color online) Variation of the resistance of NWs vs the temperature: (a) typical variation for a 50 nm width, *n*-type NW, from 4 to 325 K, (b) *n*-type NWs with widths ranging from 25 to 105 nm, and (c) *p*-type NWs with widths ranging from 29 to 104 nm.

sides of the NW but also silicon structure between the NW and the Ohmic contact. This structure adds a serial resistance R_S in series with the NW that we can easily measure and subtract to get the resistance of the NW.¹¹ As the NWs are covered by a native oxide layer on their surface, there are numerous interface states, which can trap free carriers and create a space charge region (having a width L_d) in the Si NWs, modifying thus their resistance. Thanks to the use of a series of two terminals connected NWs with various lengths and widths, the density of interface states, their charge state, as well as the resistivity of the NWs can be unambiguously determined, as described in Ref. 11. As a result, a value L_d of 1.2 and 4 nm is found in *n*- and *p*-type NWs, respectively, with associated concentrations of interface states of $1.05 \pm 0.01 \times 10^{13}$ and $1.81 \pm 0.06 \times 10^{13} \text{ cm}^{-2}$. As the NWs are highly doped, we can assume that this depletion width does not vary with the temperature.

We studied the variation of the resistance with the temperature from 4 to 325 K, for *n*- and *p*-doped NWs. This is illustrated in Fig. 2. A typical variation is given in Fig. 2(a),

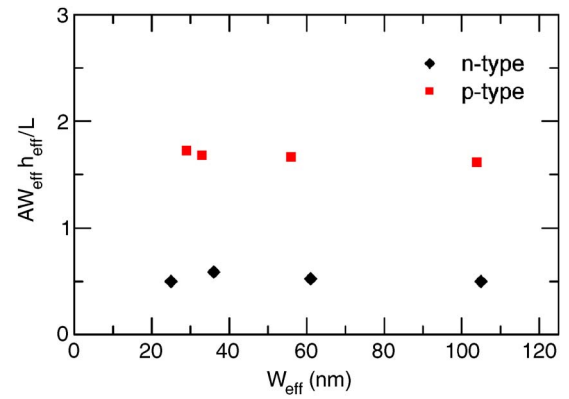


FIG. 3. (Color online) Variation of the coefficient $A \cdot W_{eff}^* h_{eff} / L$ vs W_{eff} for *n*- and *p*-type NWs.

which represents the variation for a *n*-type NW, with a 50 nm width. Two regimes are observed: a plateau, from 4 to 75 K, with in fact a weak increase in the lowest temperatures, followed by a continuous increase from 75 to 325 K. Figures 2(b) and 2(c) show a similar behavior for all the NWs, from 75 to 325 K: increase in resistance with the temperature. While weak localization effects can be at the origin the resistance behavior below 75 K, as observed in metallic NWs (Ref. 12), the increase in the resistance observed when the temperature rises is best fitted by a law given by

$$R = \frac{A}{T^{-3/2}} + B, \quad (1)$$

where A and B are constants.

Using the Matthiessen's rule, the mobility is proportional to a factor varying as $T^{3/2}$, associated with a Coulomb interaction between the carriers and the ionized doping atoms and a second factor, varying as $T^{-3/2}$, bound to electron-phonon interaction.¹³ The variations observed in Fig. 2 allow to rule out Coulomb interaction and to show that electron-phonon scattering is the dominant interaction in these NWs. Phonon scattering variation depends on two opposite factors with decreasing wire widths: the reduction in the final density of states for the electrons to scatter and an increase in the electron-phonon wave function overlap. The first one results in an enhanced mobility while the second one results in mobility degradation. In narrow NWs, the increase in the electron-phonon wave function overlap is expected to dominate over the density of states reduction, resulting in a net decrease in the electron mobility. Figure 3 gives the variation of the coefficients A times $W_{eff} h_{eff} / L$, i.e., the resistivity of the NWs versus W_{eff} (W_{eff} is obtained by subtracting twice L_d to the geometric value of the width). Even for NWs with width down to 25 nm, where scattering associated with the edges of the NWs is expected to increase, (as already observed in metallic NWs (Ref. 11) for size on the order of 25 nm), no variation is observed. In fact, we believe that the electrons do not interact with the surface due to the presence of a depleted layer induced by the charges located on the surface of the NWs.¹⁰ If there is a variation of the mobility with the size, following the Ohmic law given in

$$R = \left[\frac{1}{n(T)\mu(T)e} \right] \frac{L}{Wh_0} \quad (2)$$

at a given temperature, one expects that the resistance of a NW, for given length and height, varies as the inverse of the

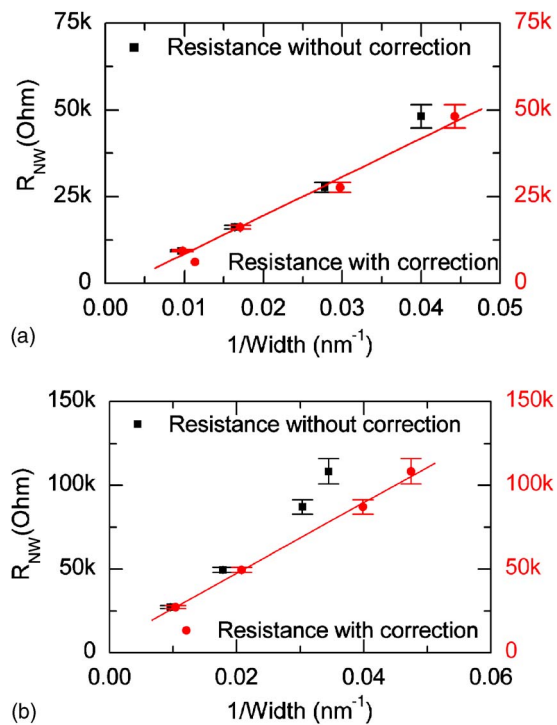


FIG. 4. (Color online) Variation of the NW resistances vs the inverse of the width for (a) *n*-type and (b) *p*-type NWs. For the correction, we take into account the depletion width (L_d) to get the effective width (W_{eff}).

square of the width (n is the concentration of carriers and μ is their mobility). We have plotted in Fig. 4 the resistance at 300 K of the NWs [*n*-type, Fig. 4(a) and *p*-type Fig. 4(b)] versus the inverse of the width, corrected or not by the presence of a depleted layer.¹⁰ The filled squares correspond to the geometric value of the width whereas the filled circles correspond to the effective value of the width. As L_d is larger for the *p*-type NWs than for the *n*-type ones, the corrections are more important. In each case, we observe a linear dependence of the resistance versus the inverse of the width, down to 25 nm (for *n*-type and *p*-type NWs). According to the relation (2), we find that the mobility is independent of the

size (as the temperature is constant, we admit that the number n of carriers is constant), in agreement with the previous observations of the coefficients A and B times $W_{\text{eff}}h_{\text{eff}}/L$.

In conclusion, we studied the transport in *n*- and *p*-type silicon NWs, with height equal to 17 nm and widths ranging from 100 to 25 nm. The main physical conclusions are (i) the mobility is constant and independent of the size of the NWs and (ii) the main interaction which affects this mobility is an electron-phonon interaction, and not an electrostatic interaction between the electrons and the ionized doping atoms, in large concentration. Finally, the phonon modes cannot be localized surface ones because, due to the presence of a depleted layer associated with surface states, the carriers do not interact with the edges of the NWs.

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