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Analysis of charge sensitivity and low frequency noise limitation in silicon nanowire sensors

Jae Woo Lee,[1,2,a] Doyoung Jang,[1,2] Gyu Tae Kim,[2] Mireille Mouis,[1] and Gérard Ghibaudo[1]
[1]*Institut de Microélectronique, Electromagnétisme et Photonique, INPG/MINATEC, 3 parvis Louis Néel, BP 257, 38016 Grenoble Cedex 1, France*
[2]*School of Electrical Engineering, Korea University, Seoul 136-701, Republic of Korea*

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This paper discusses the limit of the sensitivity that can be given to the design of nanowire sensors when the low frequency (LF) noise, due to trapping-detrapping at the nanowire surface, is taken into account. The sensitivity is calculated as the relative conductance variation per unit of external charge density. The LF noise is shown to limit the minimum detectable charge density. Our modeling approach shows how the performance can be optimized by tuning the channel length and the width, and the doping concentration. The implications of these developments are outlined as useful features for the design and the optimization of silicon nanowire sensors. © *2010 American Institute of Physics*. [doi:10.1063/1.3294961]

Currently, nanomaterials are attracting more interest for their practical applications based on the advantages of their small dimension. Among them, silicon nanowires have the advantage, that Si is a well understood material based on its longstanding use in semiconductor technology. Silicon nanowires can be fabricated either by the bottom-up[1,2] or top-down approaches.[3–5] In recent years, many research papers about silicon nanowire-based chemical or biosensors have been published.[6–9] For instance, among many other examples, Lieber's group reported on functionalized nanowires that could detect cancer biomarkers.[10] Electrically addressable integrated nanowire sensor chips have been developed and showing a great possibility for the mass production. Device modeling, prior to the fabrication, can save time and experimental trial-and-errors by providing a starting design that can be better optimized in terms of sensing performance. The modeling and the simulation of nanowire sensors have been the subject of many recent publications, with detailed account of the role of electrostatic mechanisms on the sensitivity.[11–14] However, to the best of our knowledge, noise issues have not been discussed, while the low frequency noise associated to trapping-detrapping of carriers [i.e., generation-recombination, (GR)] in the nanowire can put a severe limit to the sensitivity, due to the signal to noise ratio (SNR) degradation it induces.

It is the aim of this paper to discuss the trade-off between the sensitivity and the SNR in nanowire sensors. This imposes to use the same modeling framework for both issues. This framework was chosen simple enough to allow a fast evaluation of the design trends but complete enough to include the main effects.

The sensitivity of the nanowire was first calculated as a function of the geometrical design of the nanowire (dimensions and doping level) and was compared to a simple analytical model. Compared to most previous approaches, the thickness of the passivation oxide layer and the field effect mobility degradation were taken into account. For the sake of analytical calculation, the external charge attached around the silicon nanowire was assumed homogeneous. The conductance variation and the charge sensitivity of the silicon nanowire sensor were obtained by solving Poisson equation across a two-dimensional section of the nanowire and coupling it to the drift-diffusion equation. This was done numerically using FLEXPDE 5. FLEXPDE 5 is the software solving partial differential equations with a finite element method. An external homogeneous charge density N_{ext} (cm^{-2}), surrounding the passivation layer of silicon dioxide was used for simplification. The conductance of the nanowire was calculated for the various geometries of silicon nanowire (length L and radius r_{si}) with nominal values of doping concentration ($N_d=10^{18}\ cm^{-3}$) and the thickness of the silicon oxide layer ($t_{ox}=2$ nm) at room temperature (T=300 K). The results for the n-type silicon nanowires can be applied to the p-type in the same way with the proper choice of carrier mobility with a reversed sign. All the simulations were assumed at room temperature (300 K). In the simulation, the carrier mobility has been considered either as constant throughout the nanowire section (solid lines) or degraded by the radial electric field E_r induced by the external charge (doted lines). We used the standard equation of the mobility degradation $\mu=\mu_0/(1+E_r/E_c)$, where μ_0 is the low field mobility and E_c a critical field ($\approx 10^5$ V/cm for silicon devices).[15] Figure 1(a) shows the normalized conductance change ($\Delta G/G_0$), as a function of the adsorbed charge density N_{ext} (cm^{-2}) at the surface of nanowires depending on the radius of nanowires. As expected, the conductance change increases with a positive N_{ext} values as n-type silicon nanowire due to a stronger accumulation of majority carrier in the n-type silicon nanowires. On the contrary, for negative N_{ext} values, the conductance change is negligible owing to the formation of the inversion regime where the hole charge dominates. It is important to note that we define the sensitivity of the nanowire sensor as the ratio between the conductance change $\Delta G/G_0$ (the output) and the external density of

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[a] Electronic mail: orion627@hanmail.net.

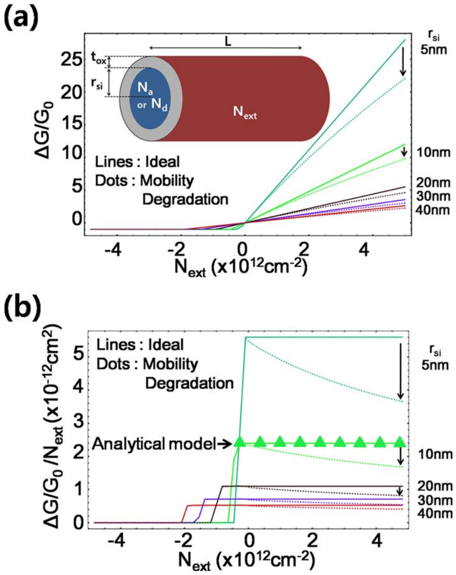

FIG. 1. (Color online) (a) Normalized conductance variation ($\Delta G/G_0$) for the constant mobility or the mobility degradation. The inset shows the schematic geometry of the silicon nanowire sensor. The external charge added by target molecules is represented by a uniform charge areal density N_{ext} (cm^{-2}). (b) Sensitivity of the silicon nanowire sensor. Solid lines and dotted lines show the numerical simulation results. Triangles are obtained from the analytic model of Eq. (4) when $r_{si}=10$ nm and $t_{ox}=2$ nm.

charge N_{ext} (the input). Figure 1(b) clearly indicates that the sensitivity can be enhanced in the close-to-neutrality and the accumulation regions of the operation with a smaller cross-section nanowire. This means that both p-type and n-type silicon nanowires are required for probing the positive and the negative external charges with a high sensitivity. It should be noted that the mobility degradation at high field, i.e., large external charge densities will reduce the nanowire sensitivity of nanowire sensors and, in turn, alter the linear response of the charge sensor, which can explain the nonlinear sensitivity reported in the previous literatures.[8,10,16]

Figure 2 plots the conductance G•L and the normalized conductance $\Delta G/G_0$ as a function of the cross-section area A. $\Delta G/G_0$ varies almost following $1/A^{0.5}$ except for the small areas below 10^{-15} cm^2 as in Fig. 2(b). In order to interpret these simulation results, we have derived an analytical model of the conductance of silicon nanowires as follows. The nominal conductance of the silicon nanowire will be given under the charge neutrality condition

$$G_0=\frac{q\mu}{L^2}\pi r_{si}^2 N_d L=\frac{q\mu N}{L^2}, \tag{1}$$

where q is the electric unit charge (1.6×10^{-19} C), N_d the doping concentration of the silicon nanowire (cm^{-3}), and N the total number of carriers in the nanowire. By considering the global charge neutrality in the structure, the absolute change of charge induced by the total external charge on the carrier number in the nanowire is given by

$$\Delta N=2\pi(r_{si}+t_{ox})N_{ext}L. \tag{2}$$

Assuming a constant mobility in the first order, the conductance change reads

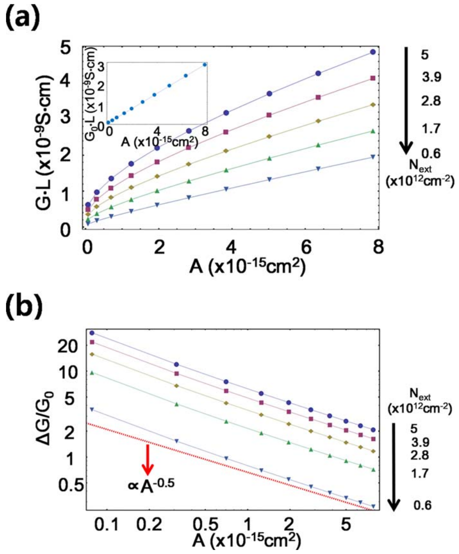

FIG. 2. (Color online) (a) Conductance nonlinearly depending on the cross-section area (a) of the silicon nanowire. On the other hand, the initial conductance G_0 is proportional to A. (Inset) (b) $\Delta G/G_0$ variation as a function of nanowire area A. Deviation from the general $A^{-0.5}$ trend is noticeable, attributed to the influence of t_{ox}.

$$\Delta G=\frac{q\mu}{L^2}\Delta N, \tag{3}$$

yielding

$$\left.\frac{\Delta G}{G_0}\right|_{ext}=\frac{2(r_{si}+t_{ox})N_{ext}}{r_{si}^2 N_d}. \tag{4}$$

Equation (4) explains the sensitivity plot depending on the square root of the cross-section area of the nanowire for $r_{si} \gg t_{ox}$ [Figs. 1(b) and 2(b)], whereas it should increase as 1/A for very small cross section. Equation (4) also indicates that the reduction in the doping concentration can increase the nanowire sensitivity, enabling the optimized design of the nanowire sensor.

However, the nanowire sensitivity can be limited by the low frequency noise arising from the random trapping-detrapping (GR) of carriers into traps, of areal density N_{it} (cm^{-2}), located at the Si/SiO_2 interface.[17,18] The random fluctuations of the number of the total interface charges, N_{trap}, give rise to random fluctuations in carrier number, resulting in the conductance fluctuation of nanowires. This might limit the sensitivity of the detection. The power spectral density (PSD) associated with charge traps at the interface can be written as[19,20]

$$S_{Ntrap}(f)=\frac{4\langle \Delta N_{trap}^2\rangle\tau}{1+(2\pi\tau f)^2}, \tag{5}$$

where $\langle \Delta N_{trap}^2\rangle$ is the variance of the total number of the interface trap charges and τ the trapping time constant. For the interface traps obeying the distribution of Poisson's law,[19,20] the variance is simply equal to the mean value of the total number of the interface trap charge,

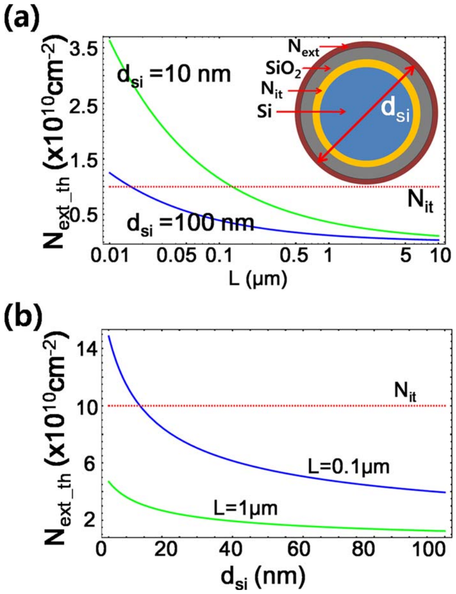

FIG. 3. (Color online) Sensing threshold density as a function of (a) the length L and (b) the diameter d_{si} of the silicon nanowire; the other parameter being set to be constant value. In order to be detectable, the external charge density must be higher than the sensing threshold density.

$$\langle\Delta N_{trap}^2\rangle = \int_0^\infty df S_{Ntrap}(f) = \langle N_{trap}\rangle = 2\pi r_{si} N_{it} L. \tag{6}$$

The condition of global charge neutrality, i.e., $\Delta N=\Delta N_{trap}$, enables the PSD and the total variance of the conductance to be derived from Eqs. (3)–(6) as

$$S_G(f) = \frac{q^2\mu^2}{L^4} S_{Ntrap}(f) \tag{7}$$

and

$$\left.\frac{\langle\Delta G^2\rangle}{G_0^2}\right|_{noise} = \frac{2N_{it}}{\pi r_{si}^3 N_d^2 L}. \tag{8}$$

To guarantee the charge detection, the conductance variation due to the external charge must be higher than its random fluctuation due to the trapping-detrapping noise, i.e.,

$$\left.\frac{\Delta G}{G_0}\right|_{ext} > \sqrt{\left.\frac{\langle\Delta G^2\rangle}{G_0^2}\right|_{noise}}. \tag{9}$$

Equations (8) and (9) allow the definition of the sensitivity threshold for detecting the external charges N_{ext_th} as

$$N_{ext\_th} = \frac{1}{r_{si}+t_{ox}}\sqrt{\frac{N_{it} r_{si}}{2\pi L}}. \tag{10}$$

It should be noted that the charge detection threshold N_{ext_th} depends on geometrical parameters and on the interface trap density N_{it}, but is independent of doping concentration. Figure 3 shows the geometric dependence of the sensing threshold N_{ext_th} for a given interface trap density $N_{it}=10^{10}$ cm^{-2}. As can be seen, N_{ext_th} decreases typically as the square root of diameter d_{si} and the length L of the silicon nanowire, indicating that the low frequency noise limitation can be overcome by scaling up the active area of the sensor, $2\pi(r_{si}+t_{ox})L$. This could be achieved by increasing the diameter or the lengh of the nanowire, but at the expense of sensor sensitivity and of nominal nanowire conductance G_0. The only remaining parameter of the nanowire sensor for the optimization is then the doping concentration, which can be chosen for a trade-off between sensitivity and nominal conductance values. In addition, it is worth noting that an external charge density lower than N_{it} can be detected, because the fluctuations of the interface trap scales as the square root of N_{it} in Eq. (10).

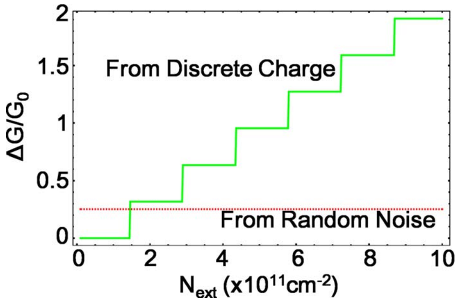

FIG. 4. (Color online) $\Delta G/G_0$ variation from the discrete charge detection and the random noise fluctuation. The charge which makes the variation below 2.5 cannot be sensed.

The detection limit of a single external charge can also be addressed using Eqs. (1) and (3). To this end, one can calculate the conductance change due to one elementary charge variation, i.e., $\Delta N=1$, yielding

$$\left.\frac{\Delta G}{G_0}\right|_{single} = \frac{1}{\pi r_{si}^2 N_d L}. \tag{11}$$

To be detectable over the trapping noise fluctuations, this initial conductance should be larger than the square root of the conductance variance [Eq. (9)], which leads, after simplification, to the condition $N_{it}<1/(2\pi r_{si}L)$. Interestingly, this means that the detection of a single external charge is only possible if the interface trap density N_{it} is sufficiently low, i.e., lower in average than one trap per active surface of the nanowire.

As an illustration of single charge detection, the conductance variation has been evaluated with Eq. (4) for integer values of $\Delta N=2\pi(r_{si}+t_{ox})N_{ext}L$ after setting the nanowire parameters: $L=0.1$ μm, $d_{si}=20$ nm, $t_{ox}=1$ nm, $N_d=10^{17}$ cm^{-3} and $N_{it}=10^{10}$ cm^{-2} [see Fig. 4]. For this geometry, one single charge corresponds to a step in the external charge density $N_{extSingle}=1.32\times10^{10}$ cm^{-2}, and to a conductance change $\Delta G/G_0$ of 0.32. The random noise detection limit for the conductance is given by 0.25, indicating the possibility of the detection of a single charge variation. In other words, the detection is possible because once averaged over the nanowire area, a single charge yields a charge density $N_{extSingle}$ larger than the interface trap density N_{it}.

In summary, by means of simulation and analytical calculation, we have evaluated the charge sensitivity of silicon nanowire sensors as well as their detection limit due to the low frequency trapping noise. The principle and the limitation of single charge detection have also been discussed. The engineering of the sensitive nanowire sensor can be possible by tuning the doping concentration and the diameter of nanowire.

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