Carrier injection at silicide/silicon interfaces in nanowire based-nanocontacts

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ABSTRACT

In this article, we investigate the silicide/Si nanowire (Si NW) interface properties based on a detailed characterization of PtSi/NW nanocontacts. For that purpose, we fabricate two-terminal structures implemented on vertical Si NWs arrays defined by a top-down approach with an ultra-high density. Each termination of Si NWs is silicided and contacted to an external metal line. The temperature dependence and the non-linearity of current–voltage (I–V) characteristics are identified as a clear signature indicating that contacts dominate the overall resistance of the Si NW arrays. It is demonstrated that this trend remains valid in the limit of extremely small NW radii and that trap-induced surface depletion also reduces the contact injection cross-section. In this context, the electrostatic landscape at the vicinity of the silicide-to-semiconductor contact interface is dominated by the field effect imposed by peripheral surface states and not by the Schottky barrier height.

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1. Introduction

Electrical studies of Si NWs have been addressed by many groups through the characterization of individual NWs [1–3]. However, the electrical characterization of single NW leads to large fluctuations inherent not only to the statistical distribution of dopants but also due to process variability in such isolated nano-objects [4]. Considering for instance a doping concentration of 1017 cm−3, dopants are theoretically separated by 32 nm in 20 nm diameter NWs. To overcome fluctuations associated to an individual nano-object, the characterization of a large assembly of NWs in parallel is a solution to obtain a better statistical analysis [5]. In previous works [6,7], we demonstrated the formation of highly dense vertical Si NW arrays by a top-down approach, with 100% reproducibility, and a perfect control of the diameter and the position. Although vertical integration is a particularly attractive approach owing to its three dimensional (3D) nature, contacting vertical NW arrays remains a challenging task, especially when dense and large vertical NW arrays are considered. To solve this problem, local probing with Pt/Ir tips has for instance been used to connect the top of single NW [8,9] under the control of a high-resolution scanning electron microscope (SEM). However, this technique is difficult to implement and is not compatible with multiple NWs in parallel. Therefore, a new method to integrate two terminal contacts on a large array of vertical NWs is required to characterize them. For a proper electrical analysis, it is of the utmost importance to consider that both the NW semiconductor body and the contact interface can significantly influence transport properties. This point is of even more critical importance in the case of confined systems, especially when surface effects dominate over volume properties. In that context, the scope of this article is to get an improved understanding of the surface/volume effects in NWs based on a statistically-sound approach. For that sake, arrays of vertical NWs with a reduced length (200 nm) and a high doping level (8 × 1018 cm−3) have been considered to minimize the Si body resistance and to make it lower than the contact resistance. Under these conditions, the peripheral depletion region created by interface charges at the outer surface of NWs is expected to reduce not only the conductive cross-sectional area in the semiconductor but also that at the contact-to-semiconductor. In small diameter NWs, we thus demonstrate that the electrostatic landscape at the vicinity of the contact to semiconductor interface does not dominate over the field effect imposed by peripheral surface states.

Vertical Si NWs were fabricated from a p-type (100) Si wafer, with an 8 × 1018 cm−3 boron concentration. Electron beam lithography (Vistec EBPG 5000+ system) was used to expose circular patterns in a negative-tone resist, namely hydrogen silsesquioxane (HSQ). After exposure, HSQ was developed by immersion in 25% tetramethylammonium hydroxide (TMAH) for 1 min. HSQ patterns were subsequently transferred to the silicon substrate by reactive ion etching (RIE) (Oxford Plasma100) in a Cl2 plasma based chemistry and under optimized process parameters, i.e. chamber pressure 2 mTorr and source power 95 W, to promote the etching anisotropy [6]. After stripping of the remaining resist in a HF solution, a 15 nm platinum layer was anisotropically deposited by electron beam evaporation in order to cover the top and the bottom of the NWs. Silicidation was activated with an annealing step under forming gas atmosphere...
(N₂:H₂ 95:5%) at 350 °C for 3 min. The sample positioning perpendicularly to the evaporation source is important to prevent metallic deposition on the sidewall of the NWs. In addition, a wet etching step in diluted aqua regia for 3 min was performed to remove any metallic contaminant on the sidewall. Aqua regia also slightly oxidizes the outer surface of NWs contributing to trap eventual atomic residues in the grown oxide. No attempt has been made to remove this oxide as it is believed to reduce the concentration of surface traps. As in the grown oxide, the oxide layer was etched back down to the Si NW top terminations separated by a series resistance of the NWs. In particular to the evaporation source is important to prevent metallic deposition on the sidewall of the NWs. In addition, a wet etching step in 5% diluted aqua regia for 3 min was performed to remove any metallic contaminant on the sidewall of the NWs. Inset: SEM image of a 30 nm thick PtSi contact on top of a Si NW. (b) SEM image (40° titled view) of Al extrinsic measurement pads. Inset: Image zoom on NWs arrays.

Fig. 1. (a) SEM image of vertical NWs arrays (18 × 18 = 324 in parallel) with Φ = 32 nm ± 3 nm, L = 200 nm, 100% reproducibility and hetero structure PtSi/Si after 350 °C annealing. Inset: SEM image of a 30 nm thick PtSi contact on top of a Si NW. (b) SEM image (40° titled view) of Al extrinsic measurement pads. Inset: Image zoom on NWs arrays.

Fig. 2. I–V characteristics at 20 °C of 2 contacts’ device with a varying number of NWs associated in parallel from 1 to 1296 with Φ = 52 nm ± 3 nm. (a) Total current (linear scale) with, in inset, the schematic cross section view of the measurement set-up that can be schematized by two back to back metal–semiconductor junctions separated by a series resistance. (b) Average current per NW (log scale) with, in inset, current evolution with the temperature.
severe effects in ultra small devices like deeply scaled MOSFETs with nanometer-sized channel body and source/drain extension [12]. For an average doping level of $8 \times 10^{18}$ cm$^{-3}$, a 200 nm long NW with a 52 nm diameter is however expected to host approximately 3400 doping atoms and should not be critically prone to RDF. The situation is markedly different at the close proximity of the silicided contacts for two main reasons. First, it is well established that the Schottky barrier height at a metal or silicide/silicon junction depends critically on the morphology of the interface. Although the mechanism of silicidation generally produces a sharp interface, it is not reproducible at the atomic level and hence gives rise to inhomogeneities of the Schottky barrier height, even for epitaxially-controlled silicides [13]. Secondly, the specific contact resistance partially depends on the Schottky barrier height but is also significantly reduced by the introduction of doping at the vicinity of silicon/silicide interface. Doping induces a sharp bending of the silicon energy bands leading to a dramatic increase of carrier injection by tunneling. As tunnel takes place through a few nanometers from the interface. In the specific case of NWs, granularity associated to the presence and placement of doping atoms becomes critical and is invoked as a source of significant variability. As shown in Fig. 2(b), the interest of addressing a large assembly of nanostructures in parallel is to mitigate the effect of RDF on the silicide/silicon contact resistance as carrier injection is averaged over a much larger total surface.

In the present case, the total resistance ($R_{\text{total}}$) of a test structure can be divided into three components: the contact resistance ($R_{\text{contact}}$) that characterize charge transport at the silicide/Si interface, the intrinsic resistance ($R_{\text{nw}}$) associated to the Si NW body and the pads' resistance ($R_{\text{pad}}$). In the preceding discussion, the temperature dependence and the non-linearity of $I$–$V$ characteristics have been involved as a clear signature indicating that PtSi/Si junction contacts dominate the overall conductivity of the NW arrays. This remark holds for NWs with a relatively large diameter, i.e. 52 nm in the case under study. In the opposite limit of small NW radii, the question naturally arises to know whether trap induced surface depletion also reduces the contact injection cross-section or, if not the case, whether it can transform $R_{\text{nw}}$ into the dominant contribution. The last section of this letter is therefore an attempt to elucidate this question. For that sake, Fig. 3(a) presents the current per NW scaled by the physical section ($r_{\text{phys}}^2$) of the nanostructure. It can be observed that this current density is not constant but decreases when the physical diameter is reduced from 93 nm to 32 nm. This effect is ascribed to the presence of a peripheral depletion layer that reduces the cross-section of the conductive path. Depletion is known to result from charged interface traps at the NW surface [14–17]. As schematized in the inset of Fig. 3, a large surface-to-volume ratio inherent to the rod-like geometry tends to exacerbate this effect. It is well established that traps at the bare surface of Si and at the Si/SiO2 interface are due to a large extent, to unpaired electrons in dangling bonds [18,19]. A dominant trap is the so-called $P_b$ center that features two peaked distributions, the first at $E_F + 0.25$–0.35 eV corresponding to donor states ($0/+$) and the second at $E_F + 0.7$–0.85 eV associated to acceptor states ($−/0$). In the case of p-type doping, the Fermi level remains well below energy levels associated to acceptor states. They therefore remain empty of electrons resulting in a neutral charge state. Only empty donor states at the valence band edge and with energies above the Fermi level contribute to build-up a positive surface charge. Accounting for a donor density $N_d$ charge balance in the nanostructure can be simply described by Eq. (1), where $N_d$ is the dopant concentration, $r_{\text{phys}}^s$ is the physical radius of Si NWs, $r_{\text{phys}}$ is the effective electrical radius of the non-depleted cylindrical region of NWs and $L$ is its length determined by the distance between the two PtSi contacts. The expression of electrical surface ($S_{\text{elec}}$), given in Eq. (2) for a conductive region is extracted from Eq. (1).

\[
N_d 2\pi r_{\text{phys}}^s N_d = N_d \pi (r_{\text{phys}}^2 - r_{\text{elec}}^2)
\]

\[
S_{\text{elec}} = r_{\text{elec}}^2 = \pi r_{\text{phys}}^2 \left(1 - \frac{2N_d}{r_{\text{phys}} N_d}\right)
\]

For the smallest diameters, the entire NW volume can be fully depleted upon the influence of surface states, thus impeding charge transport. In the present case, the current collapses for a NW diameter less than 30 nm regardless of the applied voltage, indicating that $S_{\text{elec}}$ tends to zero. Inserting this critical diameter into Eq. (2), a surface charge density of $6 \times 10^{12}$ cm$^{-2}$, representative of a Si/native oxide interface [20], can be extracted. Based on this analysis, the effective current density scaled by the electrical surface ($S_{\text{elec}}$), can be evaluated as shown in Fig. 3(b). Compared to Fig. 3(a), two major observations can be made: i) first, the conservative nature of current density is now properly recovered using a scaling by $S_{\text{elec}}$ ii) $I$–$V$ characteristics are nonlinear regardless of the NW diameter indicating that the resistance of the silicide/Si junction contacts remains dominant over the Si body counterpart. It naturally comes out that the injection cross-section at the silicide/Si interface is also governed by the radial depletion generated by surface traps.

Although this result could appear a priori intuitive or evident, it is far from being the case because electrostatics at the close vicinity of metal-semiconductor contacts is in general tightly controlled by

![Fig. 3. (a) Current density based on physical surface measured on p-type NWs with physical diameter from 32 nm to 93 nm (± 3 nm) at 20 ºC. Inset: schematic view of the nanostructure showing the depletion layer. (b) Current density based on electrical surface extracted from previous measurements (NWs with physical diameter from 32 nm to 93 nm).](image-url)
the Schottky barrier height [21]. It can be further added that many contributions [15–17,20] have outlined the critical role of the trap-related peripheral depletion layer without clearly discussing the respective contribution of the contacts and of the semiconductor body. In this work, the use of short and highly doped NWs has allowed to clarify this point. Furthermore, measurements performed on large (up to 5100 NWs in parallel) and dense (3 × 10^9 NWs cm\(^{-2}\)) arrays of NWs proved to be efficient to considerably attenuate variability associated to the stochastic nature fabrication process steps at nanoscale.

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References