Mobility and transverse electric field effects in channel conduction of wrap-around-gate nanowire MOSFETs


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Published in IEE Proceedings – Circuits, Devices and Systems, Vol: 151, Issue: 5, pp. 422-430, 15 Oct 04

14. ABSTRACT
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15. SUBJECT TERMS
Transverse electric field effects; Channel conduction; Conduction process; Doping profiles; gate length; gate oxide thickness; Interferometric lithography; Nanowire device

16. SECURITY CLASSIFICATION OF:
a. REPORT Unclassified
b. ABSTRACT Unclassified
c. THIS PAGE Unclassified

17. LIMITATION OF ABSTRACT
Unlimited

18. NUMBER OF PAGES
10

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1 Introduction

Scaling of semiconductor devices to the nanoscale regime can lead to device and performance parameter improvements including reduction in operating voltage, increased speed and greater packaging densities. As silicon is the material of choice for a large percentage of semiconductor devices, the fabrication, analysis and testing of scaled down versions of existing Si devices has been an active research subject [1, 2]. The scaling of device parameters of many structures is under consideration and theories for improved effective channel length for a fully depleted, surrounding-gate MOSFET and double-gate SOI MOSFET have been proposed [3, 4]. Dimension reduction for current technologies, however, has its limits set by optical lithography, and scaling of MOSFETs has complexities of short-channel-effects (SCEs). Scaling of double gate and silicon-on-insulator (SOI) Delta MOSFETs to the nanoscale regime shows promise but further scaling has been limited due to fabrication difficulties [5].

For MOS transistors, scaling studies have mainly focused on decreasing channel length to submicron dimensions while the width has remained several microns in size due to the necessity of maintaining the current driving capability (width-to-length ratio) of the transistor. True nanoscaling requires the reduction of the overall size of the transistor and not just the gate length. Such studies have recently attracted considerable research interest since the electrical, optical and thermodynamic properties of nanostructures can be significantly different from those of bulk material of the same composition [6]. MOSFETs with a nanowire channel wrap-around-gate (WAG) structure have been shown to have significantly improved carrier transport properties over conventional devices because of reduced scattering and better gate control. Additional study is necessary in order to fully determine the physical processes impacting the transport mechanisms [7].

In this paper we demonstrate that the current density is enhanced in nanowire channel WAG MOSFETs as a result of higher carrier mobilities. We discuss the physical processes contributing to the increased mobility, specifically quasi-1D transport at the channel centre of such devices. Equations for the mobility model and a physical interpretation are provided. For this study, we fabricated ~50 nm diameter nanowire, wrap-around-gate MOSFETs with single and multiple parallel channels and compared their characteristics with ~2 μm wide, 200 nm thick slab, top-only-gate MOSFETs that were identical in all aspects except for dimensionality of the channel region. In order to focus on the effects of scaling the channel width region, the nanowire channel length and the slab gate length were both made intentionally long (~2 μm) for this study so that short channel effects would be minimised. Simulations of carrier mobility for both nanowire WAG and slab gate devices are presented. The device conduction processes are explained in
terms of changes in the channel mobility, the influence of transverse and parallel components of the channel electric field, and the impurity distribution within the channel as a result of the fabrication process.

2 Nanowire fabrication

Interferometric lithography (IL) is a well-developed technique for inexpensive, large-area nanopatterning and was used in the nanowire fabrication process [8]. In its simplest version, IL is interference between two coherent waves resulting in a 1D periodic pattern with a pitch of \( \frac{\lambda}{2 \sin \theta} \) where \( \lambda \) is the optical wavelength and \( 2\theta \) is the included angle between the interfering beams. A typical IL configuration consists of a collimated laser beam incident on a Fresnel mirror (FM) mounted on a rotation stage for period variation [9]. There is no depth dependence to an IL exposure pattern, for which the depth-of-field is limited only by the laser coherence length and beam overlaps. The 1D nanoscale patterns were first formed in photoresist followed by pattern transfer on to the underlying substrate using reactive-ion-etching (RIE) in a parallel plate reactor using CHF\(_3\)/O\(_2\) plasma chemistry [10]. Figure 1 shows cross-sectional views of these structures after thermal oxidation. These nanowires form the channel region of a wrapped-around-gate nanochannel MOSFET as described in Section 3.

3 Nanowire WAG channel and top-only-gate slab MOSFET fabrication

Nanowires were fabricated using the processes described in Section 2 in localised channel/gate areas of the MOSFET devices using IL, along with conventional I-line contact mask printing [11] for defining the device source and drain regions. For comparison, we also fabricated MOSFET devices with slab top-only-gate regions.

Figure 2 shows a process flow sequence. A 10–22 Ω-per-square bare silicon on insulator (SOI) wafer with a 200 nm thick active Si layer on top of a 400 nm thick buried oxide (BOX) isolation layer was spin coated with photoresist (PR) and exposed to an interference pattern as described above. A 30 nm thick blanket layer of Cr was then deposited by e-beam evaporation and a lift-off step was used to create an array of Cr lines that are an effective RIE etch mask. In order to localise the Cr lines to the regions where the wires would be produced, the wafer was again spin coated with a PR layer and a mask was then used to selectively pattern the PR to protect portions of the Cr lines from a chemical

![Fig. 1 SEM micrographs showing results of thermal oxidation](image1)

- a SOI slab gate region
- b single nanowire surrounded by thermally grown SiO\(_2\)
- c multiple parallel nanowires surrounded by thermally grown SiO\(_2\)

![Fig. 2 Process flow sequence for fabrication of nanowire wrap-around-gate MOSFET (left) and slab-top-only-gate MOSFET device (right)](image2)
Cr etch solution. Once the Cr was etched from the unwanted regions, the PR was removed. Once again a layer of PR was applied on to the sample to define the source and drain regions. The source and drain definition mask was aligned to the Cr lines (gate pattern). After the exposure and develop processes, the remaining structure had source and drain mesas masked by PR and Cr lines masking the gate region between the source and drain regions. The samples were then etched to the BOX layer by RIE, thus defining the channel and source/drain regions. Figure 3 shows SEM micrographs of a slab gate and nanowire gate structures before thermal oxidation. Basically at this point we have two mesa structures (source and drain regions) connected by a wide slab or by wires, respectively. After the RIE step the PR and the Cr etch mask lines were removed. There is considerable damage left by the RIE step. In order to remove some of this damage, two rapid thermal anneal (RTA) steps were performed. The first RTA was performed at 900°C for 5 min in a nitrogen environment to anneal the damaged surface [12] followed by a second RTA step for 3 min at 450°C in a hydrogen environment to passivate the Si surfaces. Next a thick ~0.5 μm thick silicon nitride layer was deposited on to the samples to be used as a diffusion mask. A layer of PR was spin coated on to the wafer and windows were opened in the nitride layer above the source and drain regions using buffered oxide etch (BOE) solution. PR was removed and a layer of phosphorous spin on glass (PSG) was coated on to the sample for the pre-deposition step that was performed at ~900°C for 5 min. Next the PSG and nitride layers were removed using BOE. The gate oxidation and dopant drive-in were performed in a single thermal step using an oxidation furnace at 1000°C. As a thermal oxide was grown around the wire structures it consumed the Si, thus decreasing the width of the wire. Careful characterisations were performed in order to optimise the thermal process in order to result in a Si nanowire region diameter of ~50 nm. This process grew a gate oxide that was ~60 nm thick around the nanowires. Similarly a ~60 nm gate oxide was grown on the slab gate devices in order to minimise any oxide capacitance \( C_{ox} \) effects in our final analysis. The time for the oxidation to yield ~50 nm diameter Si wires drove some of the dopant into the channel region. Figure 4a shows a process simulation of the predicted phosphorous impurity content in the wires. The resultant doping profile resulted in an \( n^+ \) structure as shown in the process simulation (Fig. 4b–4c), which shows the modelled impurity profiles before and after the oxidation/diffusion process. Next a layer of PR was deposited and patterned for metallisation. A 300 nm thick Al layer was e-beam deposited using multiple shadow evaporations and liftoff in order to achieve conformal gate coverage. The samples were cleaned and annealed at ~430°C in a rapid thermal anneal (RTA) to create ohmic contacts at the source and drain region. Completely fabricated single and multiple nanowire channel WAG MOSFETs and top-only-gate slab MOSFET are shown in Fig. 5.

4 Current–voltage measurements, modelling, and analysis

Experimental \( I–V \) plots for both the nanowire and slab devices are shown in Fig. 6. The drain current \( I_d \) as a function of drain-to-source voltage \( V_{ds} \) for various gate biases was measured using a digital curve tracer. As seen from the plots, for similar doping profiles, gate length and gate oxide thicknesses the current–voltage characteristics of the nanowire and slab MOSFET are considerably different. The drain current in the nanowire is rather flat in the saturation region \( (V_{ds} > 1 V) \) compared to the significant slope in the slab device. This is due to the geometry of the slab MOSFET, in which the fringing fields at the edges of the slab significantly impact the drain current. As the channel approaches pinch-off, the carrier charge drops at the drain end and the lateral fringing field increases at the edges of the slab. Further increasing \( V_{ds} \) causes the high-field region at the drain end to widen the channel enough to accommodate the additional potential drop, thus resulting in a further increase in the drain current. In contrast, when...
the nanowire device is biased in the saturation region, the effective channel length of the nanowire device is essentially unaffected since the depletion region at the drain terminal is physically restricted to \( B \leq 50 \text{ nm} \). This effect, known as channel length modulation, is a well-known phenomenon in conventional transistor designs [13]. This phenomenon is more dominant in conventional short channel devices.

Suppressing such effects in the \( B \leq 1 \text{ V}_{ds} \) nanowire device (as is the case here) is of significant benefit, specifically in the development of low voltage circuit applications.

Figure 6 shows that in the nanowire MOSFET the current is an order of magnitude less than for the slab device. Scaling to the cross-sectional area shows that the nanowire device current density is three times higher than that of the planar slab device. From the experimental data the resultant conductivities for the slab and nanowire devices are \( \sigma_{\text{slab}} \approx 9 \times 10^3 \text{ A/V cm}^2 \) and \( \sigma_{\text{wire}} \approx 3 \times 10^4 \text{ A/V cm}^2 \). This means that we can obtain the same amount of total current driving capability in nanowire channel devices that have much smaller cross-sections by configuring several nanowires in parallel. In order to understand and improve the current characteristics of the nanodevice, we also modelled the current–voltage characteristics of the transistors. We are not aware of any reported standard nanowire channel wrap-around-gate MOSFET drain current–voltage (\( I_d–V_{ds} \)) relations and in order simulate the results we developed a very simple model based on the 2-D sketch of Fig. 7a.

Poisson’s equation in cylindrical coordinates can be written as

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \psi}{\partial r} \right) = -\frac{\rho}{\varepsilon_0} \quad (1)
\]
the charge density per unit volume, and source and cylindrical nanowire oxide capacitance.

\[ Q_{\text{average}} \approx (Q_s + Q_D)/2 \]  

(2)

where \( Q_s \) is the charge per unit area in the channel near the source and \( Q_D \) near the drain regions. The current density in the channel can be then approximated by

\[ J_d \approx -Q_{\text{average}} V_{\text{drift}} \]  

(3)

where \( V_{\text{drift}} \) is the channel region carrier drift velocity. The cylindrical nanowire oxide capacitance \( C_{\text{ox}} \) near the source and drain regions can be written as a function of the regional charge and applied source, drain and gate potentials as follows:

\[ C_{\text{ox}} = -(Q_s/V_s - V) \]

\[ = -(Q_D/V_D - V), \text{ where } V_{\text{Drift}} = V_s - V_d \]  

(4)

where \( V_s \) is the gate-to-source potential, \( V_d \) is the drain-to-gate potential, and \( V \) is the threshold voltage.

Substituting \( Q_s \) and \( Q_D \) into the equation for \( J_d \) results in

\[ J_d \approx C_{\text{ox}}[(2V_s - Vt - V_d)/2]V_{\text{Drift}} \]  

(5)

Thus the current density \( J_d \) depends on the drift velocity, the drain and gate biases and the channel capacitance. Any variation in these parameters will be reflected in the current density value. Since the channel capacitance per unit area (F/cm²) is fixed for a given oxide thickness and because the oxide thickness is about the same (~60 nm) for both the nanowire and the bulk devices, the capacitance per unit area effect may not contribute significantly to the current density. Neglecting contributions from the terminal bias effects, the major contribution comes from the drift velocity component. The drift velocity is a function of carrier mobility while the mobility itself depends on the electric field in the channel. The electric field at any channel region is the vector sum of the parallel \( (E_p) \) and transverse \( (E_\perp) \) component, where \( E_p \) is in the direction of the current flow. It may be noted that even without significant change in 'actual' mobility, changes in parallel and transverse electric field component can alter the mobility (carrier velocity) components (and hence the drain current) significantly. For example, the magnitude of the \( E \)-field at any point can be written as \( |\vec{E}| = \sqrt{E_p^2 + E_\perp^2} \) which can be satisfied by various values for \( E_\perp \) and \( E_p \). (e.g. \( |E| = \sqrt{50} \text{ kV/m} \) is satisfied for \( E_\perp = 5 \text{ kV/m} \) and \( E_p = 5 \text{ kV/m}, \) or \( E_\perp = 1 \text{ kV/m} \) and \( E_p = 7 \text{ kV/m} \)). The increase in \( E_\perp \) (second case), results in an increase in the parallel drift velocity, thus increasing current flow. The hypothesis stated above was tested through incorporating mathematical models for mobility and electric fields in the channel regions of the devices. Most mobility models incorporate saturation at high parallel field of the form as suggested by Thornber [14],

\[ v_{\text{Drift}}(E_p, E_\perp, N_1, T) = \mu(E_\perp, N_1, T) \{1 + [\mu(E_\perp, N_1, T)E_p//v_t(T)]^\beta \} E_p \]  

(6)
where \( n \) is the local impurity concentration, and \( T \) is the absolute temperature. The carrier saturation velocity, \( v_s \), in the channel region is assumed independent of normal electric field, impurity concentration, and direction of current flow with respect to the crystal orientation. The fitting parameter \( \beta \) has been well characterised with a value of 2 for both electrons and holes [15]. Besides the electric field dependence, other mechanisms such as acoustic phonon scattering, impurity scattering and surface scattering also contribute to the mobility. Thus the mobility can be approximated by the sum of the following terms, [16, 17]:

\[
1/\mu = 1/\mu_{ac} + 1/\mu_b + 1/\mu_{sr} + 1/\mu_{Coulomb}
\]

where \( \mu_{ac} \) is the mobility limited by scattering acoustic phonons and is given by [17]

\[
\mu_{ac} = q\hbar \mu_b m^* / (m^* m_d Z_A^2 k_B T)
\]

where \( q \) is the elementary charge, \( h \) is Dirac constant, \( \mu_b \) is the sound velocity, \( m^* \) and \( m_d \) is the effective mass and mobility mass, respectively, \( Z_A \) is the deformation potential, \( k_B \) is the Boltzmann constant, and \( T \) is the absolute temperature and \( \rho \) is the areal mass density of silicon.

The bulk mobility of silicon \( \mu_b \) is given by [18]

\[
\mu_b(N_l, T) = \mu_0 + (\mu_{\text{max}}(T) - \mu_0)/[1 + (N_l/C_T)^2]
\]

\[ - \mu_1/[1 + (C_s/N_l)^2] \]

where \( N_l \) is the local impurity concentration, \( \mu_{\text{max}} \) is the ohmic (pure-lattice) electron mobility, \( C_T \) and \( C_s \) are fitting parameters and \( \alpha \), \( \beta \), \( \mu_1 \) are model parameters for electrons or holes where the values can be found in Masetti et al. [16].

For example, \( \mu_{\text{max}} = 1.417 \text{ cm}^2/\text{Vs} \), \( \mu_0 = 52.2 \) and 44.9 cm²/Vs for electrons and holes respectively. \( \mu_{ac} \) is the mobility limited by surface roughness scattering and is given by [19]

\[
\mu_{sr}(E_\perp) = \delta / E_\perp^2
\]

where \( E_\perp \) is the transverse electric field and \( \delta \) is a model parameter and is \( 5.82 \times 10^{12} \text{V/s} \) and \( 2.0546 \times 10^{14} \text{V/s} \) for electrons and holes respectively [20].

\( \mu_{Coulomb} \) is due to the effect of Coulomb scattering, which is mainly due to oxide fixed charge and surface states charge and can be found from [20]

\[
\mu_{Coulomb} \propto T/Q_f
\]

where \( Q_f \) is the fixed oxide charge and \( T \) is the absolute temperature.

Details of mobility models and parameters for non-planar structures can be found in Lombardi et al. [21] and will not be discussed here. However, it is important to note that \( \mu_{ac} \) is the main reason for the higher mobility in the nanowire devices, and that the values of \( \mu_{ac} \), \( \mu_b \), \( \mu_{Coulomb} \) are comparable for both devices. The carrier transport is based on changes in the mobility components due to transverse and parallel electric fields, and is also due to the physics described in (8)–(11), which is reflected in the final mobility value and hence the drift velocity component. Any reduction in the transverse field (expected to be minimum near the centre of the nanowires) increases the \( \mu_{ac} \) component (10) and the overall mobility value in the Mathiesen’s summation (7). In the slab device, the transverse field is directed from the top towards the substrate, while in the wrap around gate structure, the transverse field is directed from all around and is minimum at the centre. Thus, due to the electric field configuration affecting the surface interactions the mobility is expected to increase at the centre of the nanowires. Figure 7b–7c shows an expected schematic model of the carrier transport mechanism for both nanochannel and slab devices. For reasons discussed above, the nanowire is expected to show “enhanced forward” motion compared to the conventional MOSFET surface scattering model for the slab geometry.

Figures 8 and 9 show a 2D simulation plot of carrier parallel (\( \mu_// \)) and perpendicular (\( \mu_\perp \)) mobilities for both slab and nanochannel devices. In the slab device (Fig. 8a) the mobility is lower at the Si-SiO₂ interface due to surface interactions and the large transverse electric field. Further away from the interface in the perpendicular direction these effects decrease and the mobility increases and levels out to the bulk mobility value. The dip in \( \mu_\perp \) is due to the location of the edge of the depletion region where the field-
dependent component drops rapidly. The nanowire device (Fig. 9a) shows similar trends but the mobility at the channel centre is about three times larger than the slab devices. The enhanced mobility is due to the fact that the transverse field has an equipotential configuration in the channel instead of from the top only as in the slab case. This results in an improved parallel electric field distribution through the centre of the cross-sectional channel region, where the surface scattering and Coulomb effects are also minimal. Figures 8b–8c and 9b–9c show plots of the effects of applying gate bias (transverse electric field) on carrier mobility for both wire and slab devices. As can be seen from the plots the variations in transverse electric field are more pronounced in the slab gate devices compared to the nanowire channel devices. Figure 10 shows simulated $I-V$ characteristics for the ~50 nm channel device at different gate biases. The results are in agreement with the measured $I-V$ for the fabricated single channel device as shown in Fig. 6. The close match between the simulated and measured $I-V$ plots is an indication of the validity of the model and material parameters chosen for the simulation.

The simulation also shows that the nanowire channel device has characteristics that are somewhat similar to a buried channel MOSFET [22]. Our simulations show that the $I-V$ characteristic of the device is very sensitive to the doping profile of the narrow ~50 nm thick channels. The best fit is for the case where an n-type dopant is near the upper surface and decreases monotonically in the $y$-direction (Fig. 4). This profile is expected since during the fabrication process the source and drain were diffused at $1000\,^\circ C$ with an n-type dopant with a peak concentration of $10^{18} \text{cm}^{-3}$. It is very likely that diffusion into the channel region also took place. The net effect is the creation of a device very similar to a normally-on n-buried channel MOSFET. The channel doping profile prior to and following the diffusion process is different as evident from the process simulation in Fig. 4 [23]. As can be anticipated, during device operation the conducting channel is the n-region rather than an inversion layer at the Si–SiO$_2$.
interface as would normally be the case if the p-type channel were the dominant dopant. Buried n-layer MOSFETs have been analysed and the physics of the device $I-V$ characteristics for the linear and saturation regions are different from that for an inversion layer formed at the Si-SiO$_2$ interface [24].

5 Subthreshold currents

The subthreshold region performance is particularly important when evaluating the suitability of MOSFETs for low voltage, low power applications, such as when the MOSFET is used in high bit rate switching applications. The subthreshold currents as a function of gate bias are shown in Fig. 11 for a single WAG nanochannel and slab devices. As can be seen from the figure the current drops about three decades for a small ($\Delta V \sim 0.1$ V) variation in the gate bias. In contrast, the subthreshold current in the slab gate device did not drop one decade for a much larger variation in gate bias. Typical nanochannel devices characterised had $\sim 50$ nm width Si surrounded by $\sim 60$ nm oxide with an Al wrap-around-gate electrode and the slab devices had $\sim 200$ nm thick Si that was $\sim 2\mu$m wide with a $\sim 60$ nm thick oxide with top only Al gate. Both nanochannel and slab channels were $\sim 2\mu$m long. From Fig. 11 we can calculate the gate voltage swing $S$ using the standard definition given by (12), which results in a subthreshold slope of $\sim 100$ mV/decade for the nanowire MOSFET.

$$S = \ln|dV_D/d(\ln I_D)|$$

Since the subthreshold current did not drop even one decade we extrapolated the subthreshold slope to be $\sim 4$ V/decade for the slab gate devices where the current cannot be effectively turned off. This is due to the fact that these devices do not have a typical n-channel MOSFET doping profile but are essentially buried channel devices with an n$n^+$ doping profile in which there are sufficient carriers in the channel for conduction even at 0 V gate bias.

Considering we have a similar doping profile for the nanowire channel device that has a gate oxide thickness of $\sim 60$ nm, the subthreshold performance is truly remarkable. These results also demonstrate that narrow channels provide better control over the channel potential due to the enhanced gate control from all sides in contrast with only the front surface coverage in conventional planar transistors, even for these unconventional device-doping profiles.

6 Analysis and conclusion

Through experiments and simulation, we have explained the carrier transport properties of Si nanowire channel wrap-around-gate MOSFET. Nanowire WAG MOSFET devices were fabricated along with slab top-only-gate MOSFETs for a comparative study. Interferometric lithography was used to define the nanowire in the channel region and conventional lithography was used to define the source and drain regions. Devices characterised had $\sim 50$ nm diameter wire channels and $\sim 200$ nm thick, $\sim 2\mu$m wide slab regions that were both $\sim 2\mu$m in length. In future studies we plan to investigate shorter devices to understand non-equilibrium effects as a function of lateral and transverse dimensions. A semi-empirical carrier mobility model for non-planar silicon structures was used to model the current–voltage characteristics. Simulation results show good agreement with experiment. Analysis showed that the current density is about $\sim 3$ time higher in the nanowire channel WAG devices as then in the slab devices. This is primarily due the average higher carrier mobilities in the nanowire channel devices as well as conformal uniform electric flux densities in the wire devices. Study also shows that MOSFET width scaling is possible while maintaining the current driving capability high by integrating multiple nanowires in parallel. The experimental results showed that the current was a linear function of the number of wires.

7 Acknowledgment

The authors would like to thank Mr Richard Marquardt for assisting in the experimental setup for the subthreshold response, Dr P. Varangis for assisting in the critical fabrication steps of the devices, and Mr George Jzermes for setting up the computer simulations.

8 References


