Full quantum investigation of low field mobility in short-channel Silicon nanowire FETs

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Abstract— **A computational study on short-channel Silicon-nanowire-FETs is proposed by means of a 3-D full-quantum treatment within the coupled mode space non-equilibrium Green's function formalism. Electron-phonon interaction and surface roughness are considered as limiting scattering mechanisms. The dependence of the effective mobility on the channel length is addressed showing the importance of quantum-phase-coherence in ultra-scaled devices and analyzing the impact of the different scattering mechanisms. The scaling trends for the back-scattering coefficient is also investigated.**

I. INTRODUCTION

Recently, both experimental and theoretical studies have been devoted to investigate the mobility reduction in short-channel devices, showing that it is probably due to the effect of ballistic electrons and the increasing importance of many other sources of scattering like thickness fluctuations, surface roughness (SR) at the Si–SiO$_2$ interface, doping pockets and random impurities [1]–[11].

As device dimensions are further scaled and a quasi-ballistic regime is achieved, a full-quantum transport simulation is envisaged to correctly describe the ballistic component of the current and the elastic scattering mechanisms which are ruled by quantum-phase-coherence. In this work we present a computational study on short-channel Silicon-nanowire (SiNW) FETs based on a self-consistent 3-D full-quantum treatment via the coupled mode-space (CMS) non equilibrium Green's function (NEGF) method [8], [9] and the Keldysh formalism in the parabolic effective-mass approximation. We address elastic scattering due to surface roughness via a microscopic description of potential fluctuations at the Si/SiO$_2$ interface [10] and inelastic electron-phonon (PH) scattering via the self-consistent Born approximation. The dependence of the effective mobility on the channel length is investigated showing the importance of quantum-phase-coherence in ultra-scaled devices and analyzing the impact of the different scattering mechanisms. Finally, we discuss the scaling trend for the back-scattering coefficient.

II. METHODS

We focus on gate-all-around (GAA) rectangular SiNWs with ideal ohmic contacts, doped source/drain regions and undoped channel. The numerical analysis is carried out through the self-consistent solution of the Schrödinger and Poisson equations in the dissipative transport regime and in the presence of rough Si/SiO$_2$ interfaces. The solution of the Schrödinger equation is performed within the parabolic effective-mass approximation. Focusing on the linear regime analysis of transport (low V_{DS} biases) the parabolic effective-mass approximation is still expected to give realistic simulation results, although quantitative variations on the effective mobility values have been reported using a non-parabolic model [12]. Electron effective mass variation in the oxide is also considered. The CMS approach is used within the NEGF formalism. This is found to be a good approximation of the real-space solution when a large number of transverse modes is considered.

The electron-phonon interaction is described within the self-consistent Born approximation in the Keldysh formalism through the lesser(greater)-than self-energies [13], considering the phonon system as an unperturbed bath. Bulk acoustic phonon scattering in the elastic approximation and bulk dispersionless optical phonon scattering are assumed neglecting the effect of confinement on phonon band structure [14]. Two optical inter-valley f-type processes and a intra-valley g-process are accounted for with the same parameters as defined in [15].

Surface roughness is included only in the channel region and is described in the continuous-space domain via spatial displacements obeying the exponential autocovariance function

$$C(r) = \Delta_{\mathrm{m}}^2 e^{-\sqrt{2}r/L_{\mathrm{m}}} \ , \tag{1}$$

where Δ_{m} is the root-mean-square (RMS) of the fluctuations and L_{m} the correlation length [16]. The rough Si/SiO$_2$ interfaces are then mapped into the 3-D discrete domain using a discretization step of 0.2 nm. Such spatial fluctuations give rise to strong intravalley coupling between propagating modes which is taken into account via the CMS approach.

The extraction of the effective-mobility is performed in the linear transport regime ($V_{\mathrm{DS}} = 5$ mV) following the method presented in [10], [11] as $\mu_{\mathrm{eff}} = GL_{\mathrm{ch}}/qN_{\mathrm{Inv}}$ where G is the channel conductance, N_{Inv} is the channel electron density, L_{ch} is channel length, and q is the electron charge. The evaluation of the effective mobility for such short channel devices accounts for the non-local effect of the apparent or ballistic mobility component linearly depending on the channel length. In order to isolate a purely scattering-limited mobility, μ_{sc}, we adopt the Shur's model [17]

$$\mu_{\mathrm{sc}} = (\mu_{\mathrm{eff}}^{-1} - \mu_{\mathrm{bal}}^{-1})^{-1}, \tag{2}$$

where μ_{bal} is the ballistic component as evaluated on an ideal device, and μ_{sc} is used in the presence of either PH scattering

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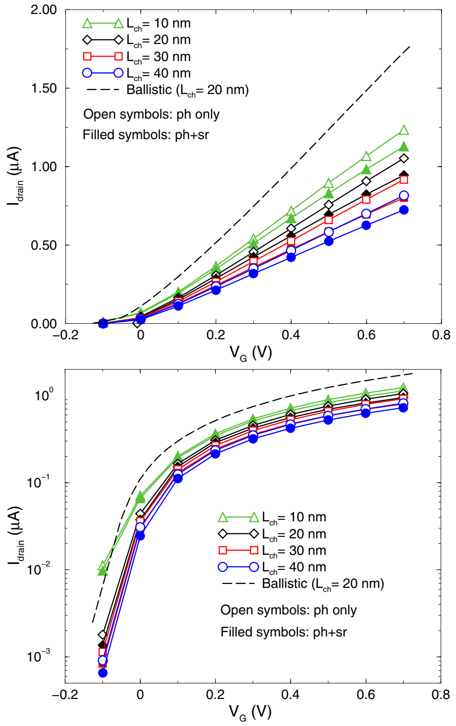

Fig. 1. (Top) Turn-on characteristics as a function of $V_{\rm GS}$ in linear and (bottom) logarithmic scale for different channel lengths in the presence of (opens symbols) only PH and (filled symbols) both PH and SR scattering. (Black dashed line) Ballistic reference for a device with $L_{\rm ch} = 20$ nm. $V_{\rm DS} = 5$ meV.

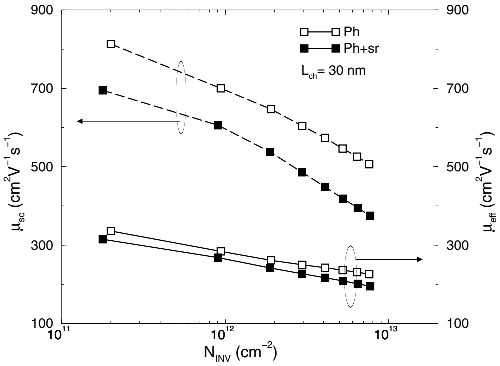

Fig. 2. (Solid lines) Effective and (dashed lines) scattering-limited mobility in the presence of (open symbols) only PH and (filled symbols) both PH and SR scattering as a function of the channel carrier density. A normalization of $N_{\rm Inv}$ with respect to the wire perimeter is supposed. The channel length is fixed at $L_{\rm ch} = 30$ nm.

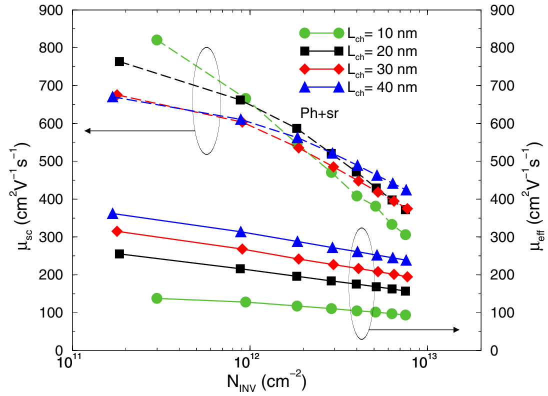

Fig. 3. (Solid lines) Effective and (dashed lines) scattering-limited mobility in the presence of both PH and SR scattering as a function of the channel carrier density and different channel lengths. A normalization of $N_{\rm Inv}$ with respect to the wire perimeter is supposed.

or both PH and SR scattering.

III. Results

We consider GAA SiNW-FETs with a cross section of 5×5 nm^2, a high-κ gate stack of 2 nm with a SiO$_2$ interfacial layer of 1 nm. The source and drain contacts are supposed with a donor doping of 2×10^{20} cm^{-3} and the channel is left intrinsic. The channel length is varied from 10 to 40 nm, while the source and drain extensions are kept fixed to 10 nm. The RMS and correlation length of the surface roughness power density spectrum are set to 0.2 nm and 1.0 nm, respectively. Since a small dependence on the specific SR realization of electrical performance of SiNWs was found in [10] for the considered SR parameters and wire section, we adopt a single SR realization for each device length.

In Fig. 1 we show the output characteristics at a low drain bias in the presence of only PH scattering and of both PH and SR scattering for the different channel lengths in both (top) linear and (bottom) logarithmic scale. A ballistic reference curve is added for a device with $L_{\rm ch} = 20$ nm. SR is responsible for a threshold voltage shift (few mV depending on the channel length), but leaves the sub-threshold slope unchanged, accordingly to [18]. Moreover, besides the performance deterioration due to short-channel effects, we notice the presence of direct tunneling for the shortest device with $L_{\rm ch}$= 10 nm.

In Fig. 2 we report examples of the extracted effective mobility and of the scattering–limited mobility in the presence of only PH scattering and of both PH and SR scattering, where a single device with a channel length of 30 nm is considered. A clear mobility reduction due to SR is reported in the whole range of the channel density $N_{\rm Inv}$ with an increasing impact at large gate overdrives.

The impact of channel length scaling is analyzed in Fig. 3, where the effective and the scattering–limited mobility are reported for devices with $L_{\rm ch}$ varying from 10 to 40 nm as a function of the channel charge density in the presence of both phonon and surface-roughness scattering. A significant dependence on $L_{\rm ch}$ is found for both $\mu_{\rm eff}$ and $\mu_{\rm sc}$. While the dependence of $\mu_{\rm eff}$ can be easily explained as the effect of the variations of the ballistic component directly proportional to the channel length, a non trivial dependence on $L_{\rm ch}$ is found also for $\mu_{\rm sc}$. At low transverse fields the longest devices show a reduced scattering–limited mobility, whereas devices with a shorter channel length show a faster mobility degradation with the increasing channel density, leading a performance

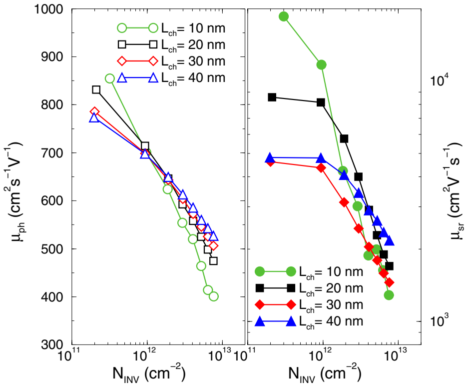

Fig. 4. (Left) PH–limited mobility for different channel lengths as a function of N_{Inv}. (Right) SR–limited mobility for different channel lengths as a function of N_{Inv}.

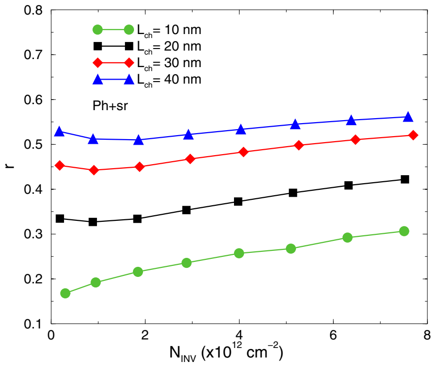

Fig. 5. Back scattering coefficient in linear transport regime as a function of N_{Inv} in the presence of both PH and SR scattering. The channel lengths are $L = 10, 20, 30$ and 40 nm.

reduction at large N_{Inv} as L_{ch} is reduced.

In order to further investigate this result, the scattering–limited mobility behavior for different L_{ch} is analyzed separating the PH–limited (μ_{ph}) and the SR–limited (μ_{sr}) components by means of the Matthiessen-rule. As shown in Fig. 4 (left), a rapid assessment of μ_{ph} is observed as the channel length is increased to more than 20 nm due to the decreasing influence of scattering events occurring in the contact doped regions. On the contrary (right), μ_{sr} presents a larger dependence on L_{ch} in the entire range of inversion charge values. At low N_{Inv} values, the inefficiency of the SR scattering mechanism increases the mobility as L_{ch} is reduced (increased ballisticity). At large N_{Inv} the different degradation of the SR-limited mobility as L_{ch} scales can be considered as an effect of the interplay between the two scattering mechanism limiting the transport in presence of surface-roughness: subband fluctuations and mixing of transverse modes [8], [10]. The former is effective at low densities when electrons are easily backscattered by potential barriers, whereas the latter is more efficient at large overdrives when carriers are pushed towards the rough interfaces. In longer devices electrons have a large probability to be scattered by subband fluctuations with respect to shorter devices, hence presenting a slower mobility degradation as N_{Inv} increases.

Alternatively, in Fig. 5 we analyze the linear back-scattering coefficient r, extracted via the relation $r = 1 - \mu_{\mathrm{eff}}/\mu_{\mathrm{bal}}$ [19]. The trend observed for the mobility is confirmed, showing a faster increase of r for the shorter devices, despite of the higher overall ballisticity.

IV. CONCLUSION

We have presented an analysis of the effective mobility in short-channel SiNW-FETs in the presence of both elastic and inelastic scattering. We have found an intrinsic reduction of low-field mobility for shorter channel lengths due to surface-roughness scattering independently of the role played by the apparent mobility component. This result can contribute to explain the effective mobility reduction observed in ultra-short electron devices.

V. ACKNOWLEDGMENT

Financial support from French ANR (“Quantamonde” project) and EU NANOSIL NoE (contract n. 216171) is gratefully acknowledged

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