Quantum simulation of self-heating effects in rough Si nanowire FETs

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INTRODUCTION

Nanoscale electron devices as FDSOI, FinFETs and Si nanowire (NW) FETs have been identified as promising candidates to fulfill the ITRS requirements for the next technological nodes. However, their performance could be degraded by self-heating phenomena arising from the difficult evacuation of the heat generated by the electron-phonon scattering in structures surrounded by oxides and high-k dielectrics. Moreover, despite the relatively large thermal conductivity k_{th} of bulk silicon, spatial confinement [1] and surface roughness (SR) [2] can induce a significant reduction of k_{th}, thus further enhancing self-heating phenomena. In this paper, we present a self-consistent quantum simulation of self-heating effects in SiNW FETs with rough surfaces.

MODELS AND RESULTS

The spatial-dependent lattice temperature along the axis of the NW (x) was computed by solving the 1D non-linear heat equation

$$-\frac{\partial}{\partial x}\left[k_{th}(x)\frac{\partial}{\partial x}T(x)\right]A + g\left[T(x)-T_0\right] = Q(x). \quad (1)$$

Here, A is the NW section area, g is the heat transfer rate through the oxide and Q is the heat power density exchanged between electrons and phonon bath, which was supposed to be locally at equilibrium with the temperature $T(x)$, and T_0 =300 K is the temperature of the oxide. Thermal conductivities for Si NWs with SR were computed according to an atomistic valence force model [3]. SR was geometrically generated basing on an exponential autocorrelation function [4] characterized by the root mean square Δ_m and the correlation length L_m. Fig. 1 represents a rough SiNW and the corresponding k_{th} for Δ_m =0.1, 0.2 and 0.4 nm and L_m =1 nm. The heat power Q in Eq. (1) allows us to self-consistently couple the heat equation with the Poisson and the quantum transport equations. Dynamics and statistics of electrons were computed within the Keldysh-Green's function formalism and the scattering with acoustic and optical phonons was accounted for *via* the self-consistent Born approximation. The heat power was evaluated at each transverse section i of the device as the sum of the incoming and the outgoing energy current densities, as

$$Q(x_i) = \int \frac{dE}{q} E\left[J_{i,i+1}(E) + J_{i,i-1}(E)\right] / \Delta x \ , (2)$$

where $J_{i,i+1}$ is the energy spectrum of the current flowing between the sections i and $i+1$.

We considered tri-gate rectangular Si NW FETs with cross section of 5x5nm^2 and gate length L_G=14 nm. Fig. 2 shows an example of energy spectrum of the heat source along the transport direction. It is interesting to compare this result obtained from Eq. (2) with the one shown in Figure 3 for the classical expression of the steady-state power density $J(E)dF/dx$, where F is the quasi-Fermi level. The quantum formula gives a result much less localized both in energy and space. Fig. 4 shows the temperature distribution along the NW length for devices with different Δ_m. The maximal temperature always occurs in the region close to the channel-drain junction. Fig. 5 compares the output characteristics obtained with and without considering self-heating effects. The difference between the two simulations increases with V_D in the linear regime and then stabilizes in the saturation regime. Finally, Fig. 6 summarizes the correction to the current due to self-heating for the devices considered in this work.

CONCLUSION

By exploiting self-consistent quantum simulations we have shown that self-heating effects can induce an on-current reduction of at least 10% in SiNW transistors.

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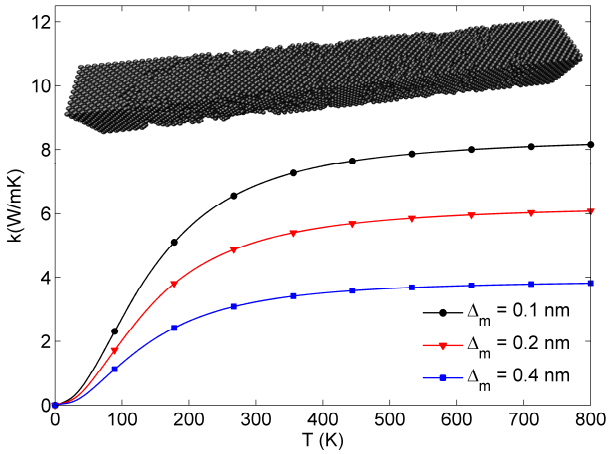

Fig. 1. Sketch of a Si NW with surface roughness and thermal conductivity for different values of Δ_m. The correlation length is L_m=1nm throughout the paper.

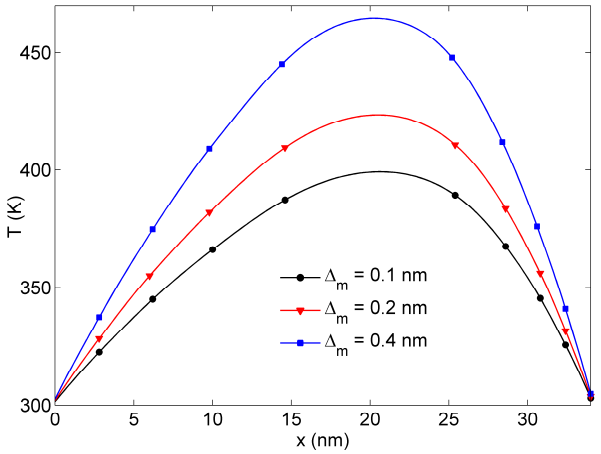

Fig. 4. Lattice temperature along the Si NW resulting from the self-consistent coupling Eq. (1) with the Poisson and the Keldysh-Green's function equations at V_{GS}=V_{DS}=V_{DD}=0.75V

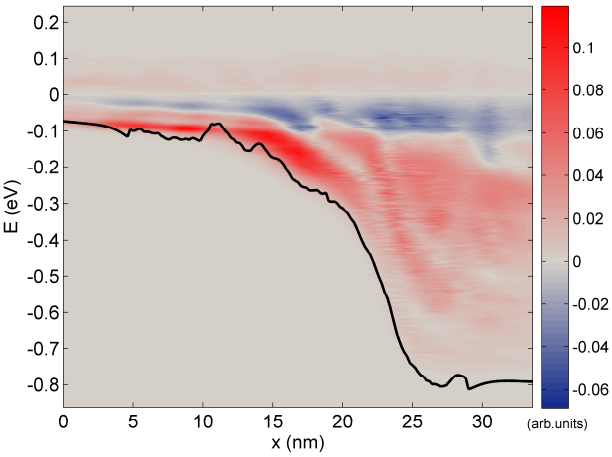

Fig. 2. Energy spectrum of the heat power density computed according to the quantum formula (2) at V_{GS}=V_{DS}=V_{DD}=0.75V and Δ_m=0.4nm.

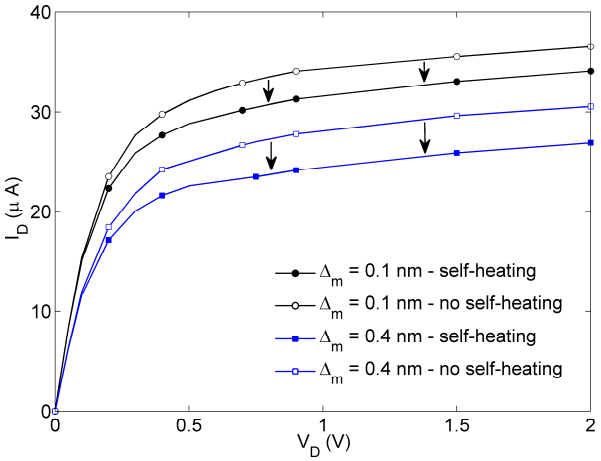

Fig. 5. Output characteristics computed with and without self-heating effects at V_{GS}=V_{DD}=0.75V.

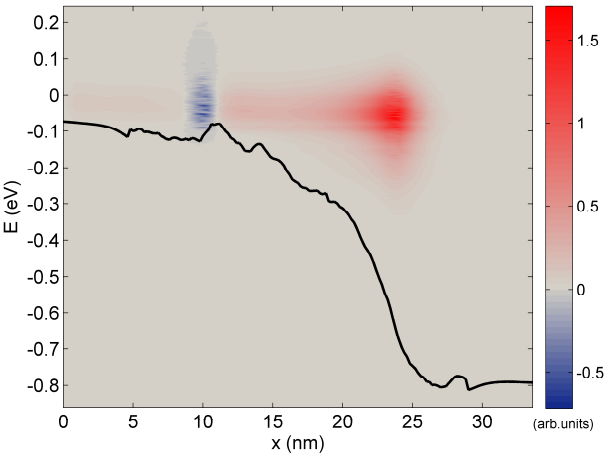

Fig. 3. Energy spectrum of the heat power density computed according to the classical formula *J(E)dF/dx* at V_{GS}=V_{DS}=V_{DD}=0.75V and Δ_m=0.4nm.

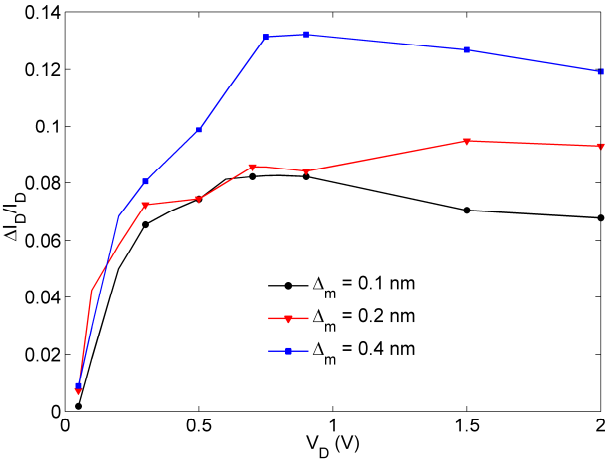

Fig. 6. Relative correction of the drain current induced by the self-heating as a function of V_{DS} at V_{GS}=V_{DD}=0.75V.