Self-Heating Effects in Nanowire Transistors

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ABSTRACT

We investigate the role of self-heating effects on the electrical characteristics of a silicon nanowire transistor using a 3-D Monte Carlo device simulator that includes self-consistent solution of the energy balance equations for both acoustic and optical phonons. We find that self-heating effects in the nanowire transistor lead to more than 10.35 % degradation in the ON-current for $V_G=V_D=1$ V.

Keywords: Acoustic and optical phonons, Boltzmann transport equation, phonon energy balance equations.

1 INTRODUCTION

As the conventional silicon metal-oxide-semiconductor field-effect transistor (MOSFET) approaches its scaling limits, many novel device structures are being extensively explored. Among them, the silicon nanowire transistor (SNWT) has attracted broad attention from both the semiconductor industry and academia. To understand device physics in depth and to assess the performance limits of SNWTs, simulation is becoming increasingly important. Because the active channel region in SNWT structures is surrounded with gate oxide or some form of high-k dielectric, self-heating becomes more of an issue than in planar device structures such as the basic fully-depleted device structure. In particular, understanding the influence of self-heating effect on the ON-state operation of a SNWT is becoming critical. For this purpose, we investigate for the first time self-heating effects in the SNWT proposed and fabricated by Majima *et al*. [1] and schematically shown in Fig. 1. In this device structure, the threshold voltage not only depends on the SOI thickness but also on the channel width, because horizontal carrier confinement also takes place in the narrow channel. It is referred to this channel width dependency of the threshold voltage by quantum confinement as the quantum mechanical narrow channel effect and this is extensively studied in Ref. [2]. Here we examine the amount of self-heating and how it influences the magnitude of the ON-current.

2 SIMULATION MODEL

We need to solve the coupled Boltzmann transport equations for the electron and phonon systems together to properly treat heating in nanometer devices. But, it is very difficult to directly solve phonon Boltzmann equation since mathematically expressing the anharmonic phonon decay process is difficult. In addition to this it is required to solve separate phonon Boltzmann equation for each mode of the acoustic and optical branches. So, to simplify the global picture some approximations need to be made. In this work, we use the opctical phonon and the acoustic phonon energy balance equations dervied from the phonon Boltzmann equations by Majumder et al. [3,4].

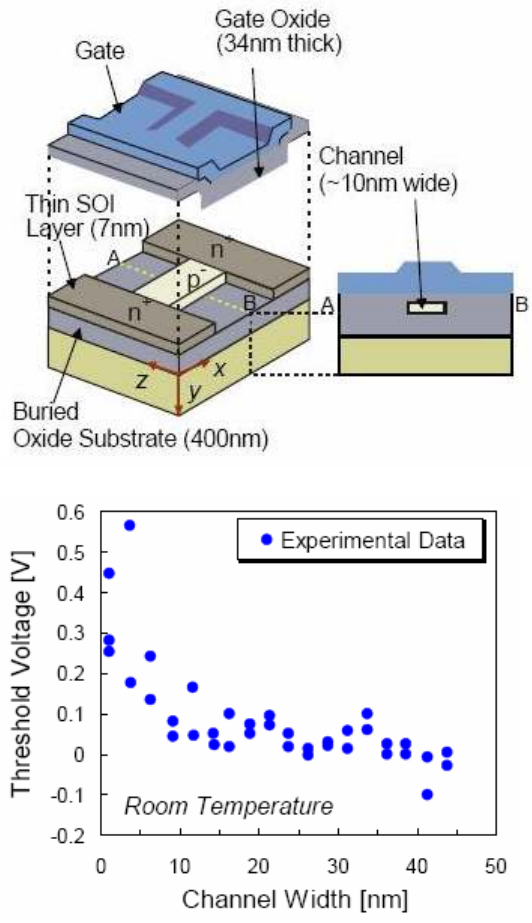

Fig.1. Top panel - Device structure of ultra-narrow channel FD-SOI device. Bottom panel - Threshold voltage fluctuations as a function of channel width and device variations for the same channel width due to unintentional dopants.

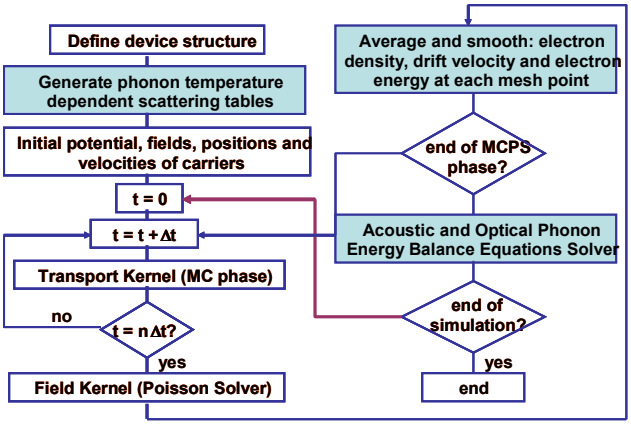

Fig 2. Coupling of the Monte Carlo solver for the electrons and the energy balance solvers for the acoustic and optical phonons.

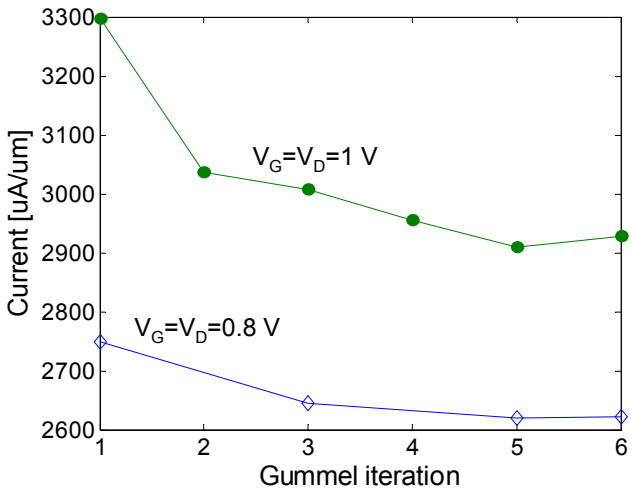

Fig 3. Convergence of the solver when the device is in the ON-state. Note that Gummel iteration=1 corresponds to the isothermal results.

The energy balance eqution for the acoustic and optical phonons are

$$C_{LO}\frac{\partial T_{LO}}{\partial t}=\frac{3}{2}nk_B\left(\frac{T_e-T_{LO}}{\tau_{e-LO}}\right)+\frac{nm^*v_d^{\,2}}{2\tau_{e-LO}}-C_{LO}\left(\frac{T_{LO}-T_A}{\tau_{LO-A}}\right) \quad (1)$$

$$C_A\frac{\partial T_A}{\partial t}=\nabla(\kappa_A\nabla T_A)+C_{LO}\left(\frac{T_{LO}-T_A}{\tau_{LO-A}}\right) \quad (2)$$

where C_A and C_{LO} are the specific heat capacity of acoustic and optical phonons respectively, κ_A is the thermal conductivity, T_A is the acoustic bath temperature, T_{LO} is the optical phonon temperature, Te is the electron temperature, v_d is the electron drift velocity, n is the electron density and $\tau_{LO\text{-}A}$ is the momentum relaxation time that describes the average time for decay of longitudinal optical (LO) modes into acoustic (A) modes.

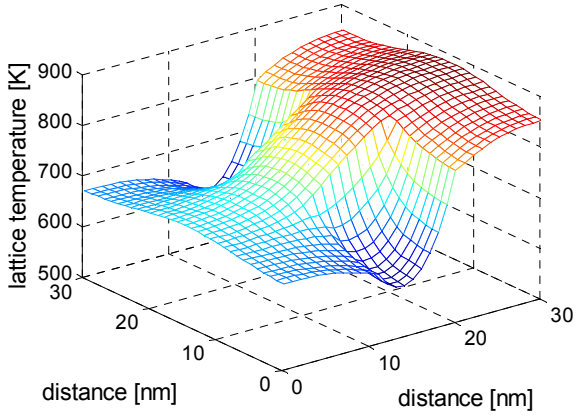

Fig 4. Lattice Temperature profile for V_G= V_D=0.8 V

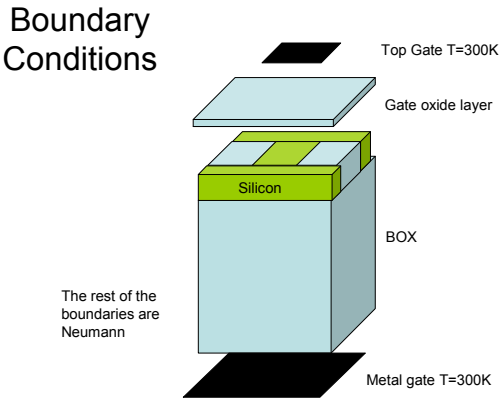

Fig 5. The boundary conditions used in these simulations.

Equations (1) and (2) are self-consistently solved with the Boltzmann Transport equation for the electrons which is solved using the Ensemble Monte Carlo method. The coupling between the Boltzmann solver and the energy balance solvers for the acoustic and optical bath is schematically illustrated in Figure 2.

The convergence of the solver in the ON-state (the outer Gummel cycle) is depicted in Figure 3. We see that it takes 4-5 thermal cycles to achieve convergence in the current with accuracy to the third digit.

3 SIMULATION RESULTS

In this section we present the results of the electro-thermal simulations. In Figure 3 we showed the convergence plot in the ON current for V_G=0.8V and V_D=0.8V. From this plot we also see that the maximum

current degradation when the SNWT is in the ON-state is 4.5 %. For V_G=V_D=1V, the maximum current degradation is 10.35%.

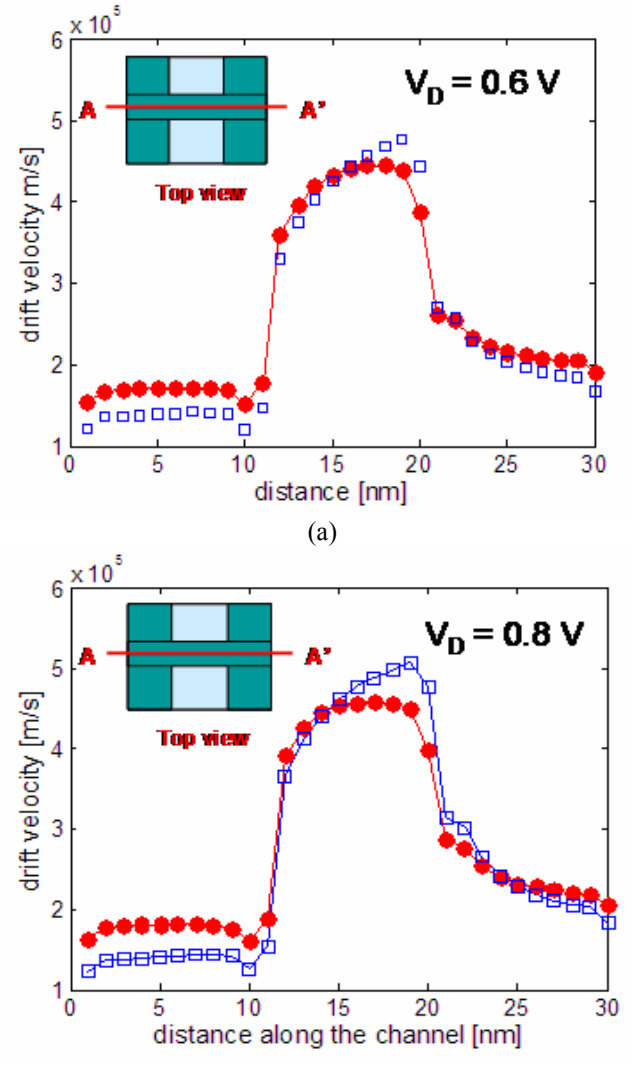

Fig 6. Average drift velocity along the channel for V_D=0.6v (top panel) and for V_D=0.8v (bottom panel). Open squares are isothermal results and filled circles are thermal results that incorporate self-heating effects.

This is rather large degradation compared to what had been obtained for conventional FD SOI devices. The results of the simulation of FD SOI devices can be found in Ref. [5]. There is a very simple explanation to this rather high current degradation: (1) the thermal conductivity of the nanowire is small and (2) heat can not be effectively transmitted outside of the active device region because of the presence of the top, bottom and side oxides. Therefore, the lattice temperature will significantly increase as shown in Figure 4. Note that the lattice temperature in the contacts is smaller if the simulation domain is larger (in particular the source and drain contact areas). The boundary conditions used in these simulations are depicted in Figure 5. We also want to point that the use of different boundary conditions at the contacts (Dirichlet instead of Neumann) can also affect the results as is shown in Ref. [6].

The high lattice temperature profile has direct impact on the velocity of the carriers near the drain end of the channel. This is nicely illustrated in Figure 6 where we plot the isothermal and the thermal average velocity along the channel for V_G=V_D=0.6 V and V_G=V_D=0.8 V. As expected, the self-heating effects have more degrading effect on the velocity characteristics for larger drain bias for which both the optical phonon temperatures and the lattice temperature are higher.

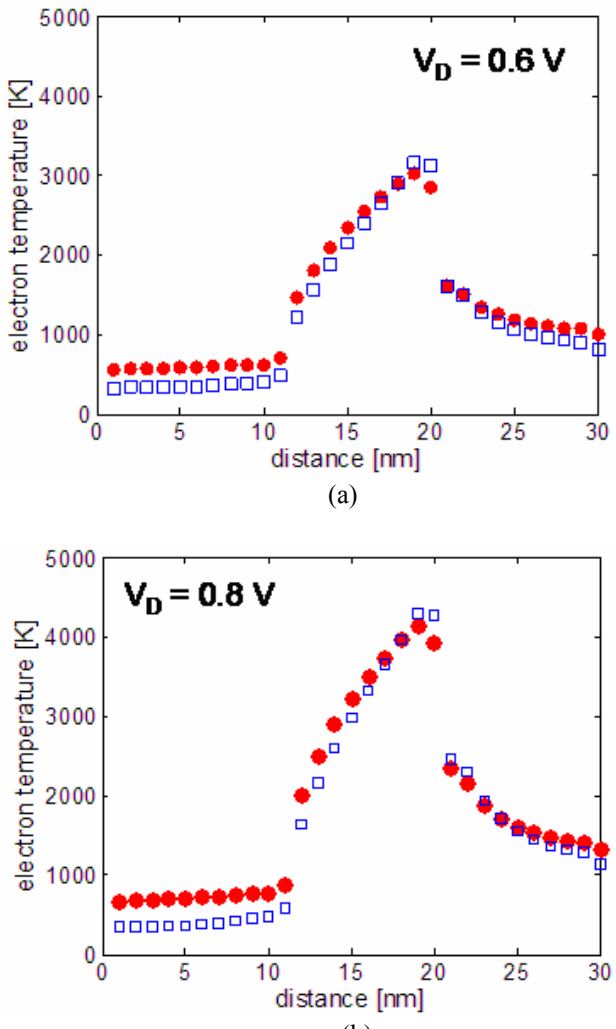

Fig 7. Average electron energy expressed in terms of temperature along the channel for V_D=0.6v (top panel) and for V_D=0.8v (bottom panel). Open squares are isothermal results and filled circles are thermal results that incorporate self-heating effects.

However, even though scattering is increased due to self-heating effects, the average electron energy expressed

in terms of temperature is not degraded that much because even though the momentum is randomized it still contributes equally to the energy profile (see Figure 7).

4 CONCLUSIONS

In this work we investigate the role of self-heating effects on the ON-state operation of SNWTs. We find that self-heating effects are more pronounced in SNWTs with same channel length as the FD SOI devices due to the worse heat transport because of the lateral oxide regions. A maximum of 4.5% current degradation is observed for $V_D=V_G=0.8V$ and this value rises to 10.35% for $V_D=V_G=1V$ (see convergence plot on Figure 3).

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