Influence of anharmonic phonon decay on self-heating in Si nanowire transistors

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Introduction: The recent replacement of planar metal-oxide-semiconductor field-effect-transistors (MOSFETs) by 3-D FinFETs (22 nm technology node) [1] will momentarily stabilize the increase of heat dissipation and power consumption in integrated circuits (ICs). However, in the future, FinFETs might need to evolve towards gate-all-around nanowire field-effect transistors (GAA NWFETs) when their gate length will shrink below 10 nm [2]. A NW diameter smaller than 5 nm might also be necessary at this scale, which would significantly decrease the thermal conductivity of these devices and question their heat dissipation capabilities [3].

Ultra-scaled GAA NWFETs might eventually enter mass production in 10 years from now, but it is important to start evaluate their thermal properties early enough to identify potential deficiencies. Numerical device simulations could be really useful for that purpose, provided that the considered approach captures the quantum mechanical (QM) effects that dominate the behavior of nanostructures. There have been some recent attempts to combine electron and phonon transport at a QM level [4], [5], [6], but none of them took anharmonic phonon-phonon scattering (anharmonic phonon decay) into account. Here, we propose to fill this gap and to demonstrate how the decay of optical phonons into pairs of acoustic ones affects self-heating in Si GAA NWFETs.

Method: The Non-equilibrium Green's Function (NEGF) formalism is utilized to treat electron and phonon transport in Si nanowire transistors as shown in Fig. 1. The electron equations are formulated in a nearest-neighbor $sp^3d^5s^*$ tight-binding basis [7], those of phonons in a valence-force-field (VFF) basis [8]. The coupling between electrons and phonons as well as the anharmonic phonon-phonon interactions are computed through scattering self-energies [6], [9]. Three different cases are investigated labeled (i) *standard scattering* (electrons are coupled to equilibrium phonons, no spatial temperature variation as reported in Fig. 2(a)), (ii) *self-heating* (fully coupled non-equilibrium electron-phonon system with energy exchange and local temperature increases as in Fig. 2(b)), and (iii) *self-heating+anharmonic* (same as the previous case, but with the inclusion of anharmonic phonon decay). The resulting currents are referred as $I_{d,scatt}$, $I_{d,self}$, and $I_{d,self+anh}$, respectively.

Results: The simulated Si GAA NWFETs have a diameter d=3 nm and gate length L_g=5 nm. The source and drain extensions measure 15 nm each and are heavily doped (N_D=10^{20} cm^{-3}). The transfer characteristics I_d-V_{gs} at V_{ds}=0.6 V corresponding to the three cases mentioned above are shown in Fig. 3. As first reported in [6], self-heating induces a 30 % current decrease at large V_{gs}, but is negligible for V_{gs}<0.4 V. The inclusion of anharmonic phonon decay partly compensates the current reduction caused by self-heating ($\approx$ 10 % current increase when comparing $I_{d,self+anh}$ with $I_{d,self}$). Figures 4 and 5(a)-5(b) explain this behavior through the phonon spectral energy current and population distribution of a typical Si GAA NWFET.

Without anharmonic phonon decay, an artificial accumulation of optical phonons can be observed. Since electrons interact more strongly with optical phonons in Si nanowires [10], a decrease of their population leads to a current increase. At the same time, the presence of more acoustic phonons, which are characterized by a higher group velocity, allows for the effective lattice temperature T_{eff} to more rapidly decrease close to the source and drain contacts, as illustrated in Fig. 5(c). Note that the maximum of T_{eff} remains the same, with and without anharmonic phonon decay. Finally, in Fig. 6, the maximum and minimum effective lattice temperature along the nanowire x-axis are given as a function of the dissipated power. The rearrangement of the phonon population due to anharmonic phonon-phonon scattering leads to a decrease of T_{eff} at a fixed power dissipation.

Conclusion: Anharmonic phonon scattering has been included in a fully coupled electro-thermal quantum transport approach. An increase of the current and a modification of the lattice temperature distribution have been observed in Si GAA NWFETs. With or without phonon-phonon scattering, it clearly appears that thermal management will be an issue in those devices.

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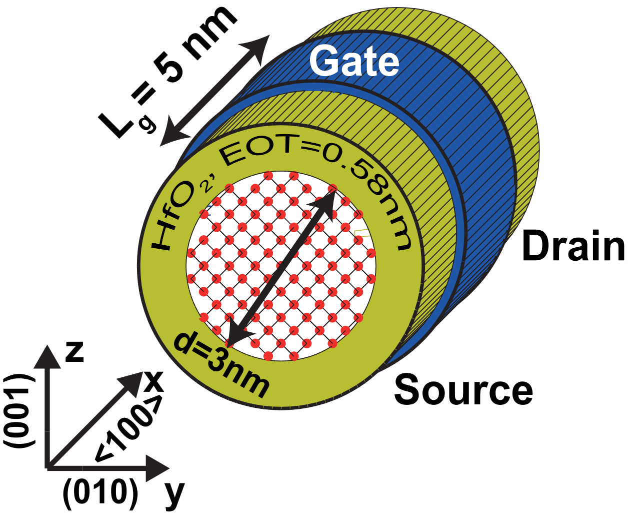

Fig. 1. Schematic view of the n-type Si gate-all-around nanowire transistor (GAA NWFET) simulated in this work. All simulations are performed at a supply voltage V_{DD}=0.6 V and an external temperature T=300 K.

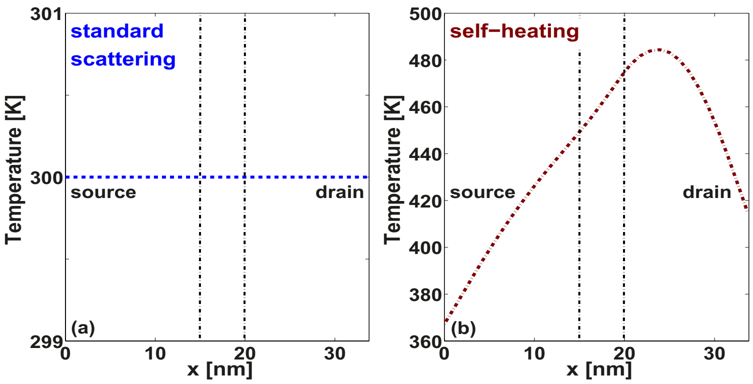

Fig. 2. (a) Temperature distribution in the nanowire structure described in Fig. 1 when equilibrium phonons are considered. (b) Same as (a), but with non-equilibrium phonons. The source and drain regions are indicated in these plots.

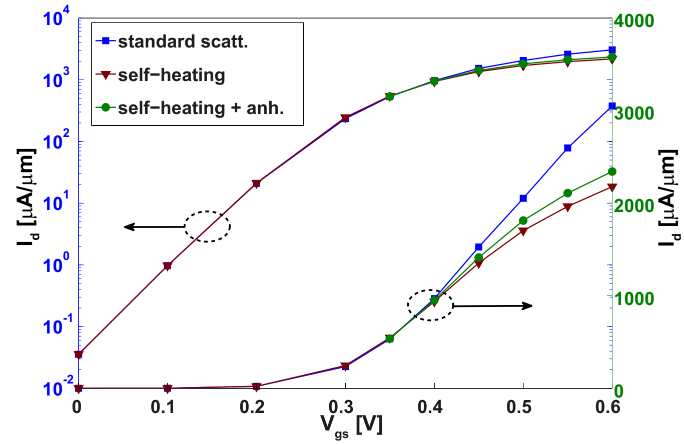

Fig. 3. Transfer characteristics I_d-V_{gs} at V_{ds}=0.6 V of the Si GAA NWFET shown in Fig. 1. The currents $I_{d,scatt}$ (blue lines with squares), $I_{d,self}$ (red lines with triangles), and $I_{d,self+anh}$ (green lines with circles) are represented.

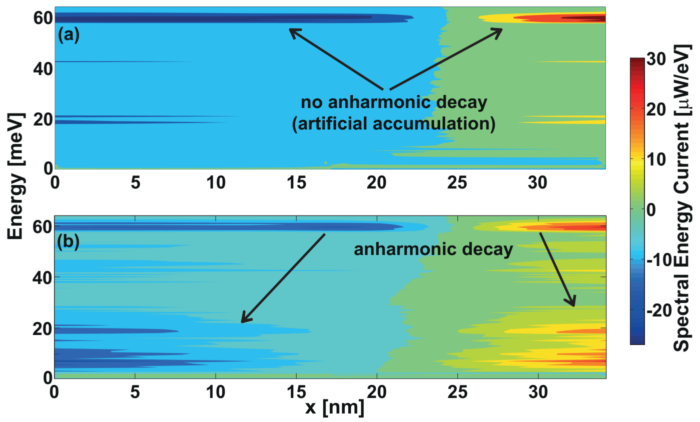

Fig. 4. Energy- and position-resolved phonon energy current in the same NW as in Fig. 1 at V_{gs}=0.6 V (a) without phonon-phonon scattering and (b) with it. Red indicates positive currents, blue negative ones, and green no current.

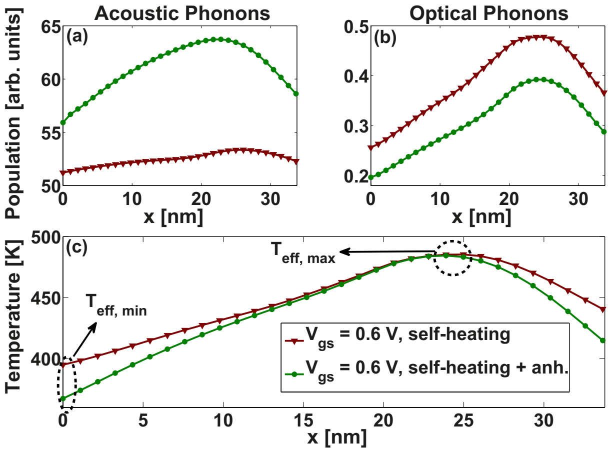

Fig. 5. (a) Acoustic and (b) optical phonon population in a Si NW as in Fig. 1. The red lines with triangles refer to the case without anharmonic phonon scattering, the green line with circles to the case with it. (c) Distribution of the effective lattice temperature T_{eff} [6] along the NW x-axis with and without anharmonic phonon decay.

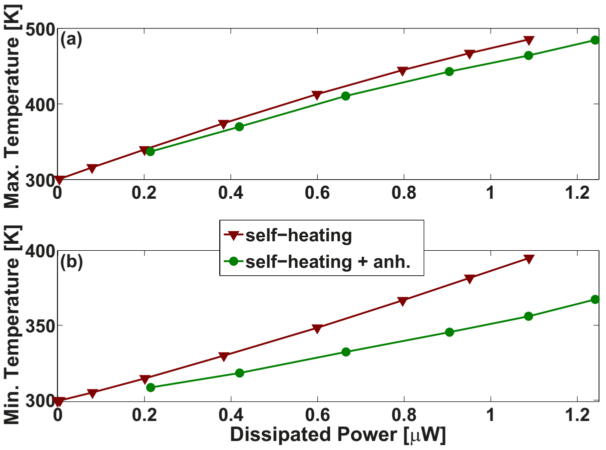

Fig. 6. (a) Maximum ($T_{eff,max}$) and (b) minimum ($T_{eff,min}$) effective lattice temperature extracted as in Fig. 5(c) at different V_{gs}. The cases with (green lines with circles) and without (red lines with triangles) anharmonic phonon-phonon scattering are considered.