



Unusual impact of electron-phonon scattering in Si nanowire field-effect-transistors: A possible route for energy harvesting

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ABSTRACT

In the current work, the impact of electron-phonon scattering phenomena on the transport behaviour of silicon nanowire field-effect-transistors with sub-mean free path channel length has been investigated by developing a theoretical model that incorporates the responses of carrier effective mass mismatch between the channel and source/drain. For this purpose, a set of relevant quantum field equations has been solved by non-equilibrium Green's function formalism. The obtained device current for a particular set of biases is found to decrease due to phonon scattering below a certain doping level of source/drain, above which it is observed to enhance anomalously. Analyses of the quantified scattering lifetime and power dissipation at various confinement modes of the device indicates that such unusual enhancement of current is originated from the power served by phonons instead of associated decay processes. The power generation has been observed to improve by using high-k materials as gate insulator. Such results may contribute significantly to the future nano-electronic applications for energy harvesting.

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1. Introduction

Aiming at high performance electronic devices in terms of speed, power and packing density, the continual miniaturization of nanowire field-effect-transistors (NWFETs) has led the technological node to enter ballistic regime, where physical dimension of the device is scaled beyond its carrier mean free path (MFP) [1]. Incidentally, silicon (Si) based NWFETs have attracted a great deal of attention since 97% of the electronic devices in this era is dominated by Si. Fabrication of such nanowire devices have been subject to investigation by taking up two reverse approaches known as 'top-down' and 'bottom-up' [2–11]. The impact of morphology and dimensional extents of Si nanowires on their physical and electrical properties have been studied in detail [12–14]. Ballisticity of Si NWFET has already been claimed to realize experimentally as a function of physical gate length of the device [1,15]. However, electron-phonon (e-ph) scattering phenomena are not negligible even in the sub-MFP NWFETs, and can contribute significantly to the electrical characteristics of the devices, thereby posing a greater challenge to achieve ballistic current in practice. Several reports predicting the effect of e-ph interaction in Si NWFETs show that the carrier mobility and consequently, the output current gets reduced considerably in presence of such scattering due to power dissipation at the scattering terminals [16–26]. Therefore, notifying 'no new breakthroughs', the journey in this field these days has been identified by the International Technology Roadmap for Semiconductors (ITRS) as '3D Power Scaling',

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recognizing the trip as a combination of 3-dimensional (3D) architecture and low power device that “will usher the (Third) Era of Scaling” [27].

Nevertheless, the NWFETs, whatever the channel length be, are conventionally considered as 2D-confined device, since the carriers are confined in the transverse dimensions and transported only along the wire direction from one reservoir (source (S)) to another (drain (D)). The discrete energy levels of an isolated nanowire are broadened due to coupling with the reservoirs during transport resulting to such 1D (i.e. 2D-confined) -density of states (DOS) in the nanowire [28]. However, it has been shown that, in the absence of phonon scattering, the difference of carrier effective mass in the intrinsic channel and the heavily doped reservoirs leads to level sharpening thereby tending to 3D quasi-confinement in the nanowire due to weak coupling [29]. On the other hand, without considering the effective mass mismatch between nanowire and reservoirs, theoretical models incorporating electron-phonon scattering predicts a net current depreciation due to scattering induced level broadening and local self-heating of the nanostructure lattice [30–32]. Thus it motivates further investigation of the transport behaviour and consequent device characteristics of sub-MFP NWFETs taking into consideration both, the effective mass mismatch and phonon scattering, so as to find the perturbing impact of phononic vibrations on the 3D quasi-confined nanowire active device coupled with the thermodynamic reservoirs. It should also be noted that the high- k materials are being preferably used as gate dielectrics for improved short channel effects, without affecting the gate control, in nanoscale FETs [33] and therefore the effect of using such gate materials need to be specially addressed.

The current work deals with the development of a theoretical model to predict the mutually counter-affecting influences of carrier effective mass mismatch and phonon scattering on the performance of sub-MFP Si NWFETs. To study the effects of confinement-induced discontinuities in the energy space within the nanowire, its coupling with the reservoirs in presence of phononic vibrations, and to incorporate a particulate view to such many-particle system where electron-electron interaction is also very strong, a set of relevant quantum field equations has been set up. Such coupled equations consisting of the second quantization field operators for electrons and phonons are solved by non-equilibrium Green's function (NEGF) formalism by achieving self-consistency with Poisson's equation. A comparative representation of the electrical characteristics of such devices in presence of e-ph scattering and in an ideal ballistic condition (i.e. without considering phonon scattering) is illustrated. The result has been analyzed in detail by quantifying the e-ph scattering lifetime and the corresponding power dissipation at various confinement modes and S/D doping levels. A comparative study of the impact of using several high- k gate dielectrics on the generation of scattering power has also been performed.

2. Theoretical model

The basic equations describing the system are given by Ref. [30],

$$i\hbar \frac{d}{dt} c_i = H_{iso} c_i + \sum_{j,\alpha} \left(\tau_{ir}^{\alpha} c_j b_{\alpha} + \tau_{ir}^{\alpha*} c_j b_{\alpha}^{\dagger} \right) + \sum_r \zeta_{ir} C_r \quad (1.a)$$

$$i\hbar \frac{d}{dt} C_r = H_R C_r + \sum_i \zeta_{ri}^* c_i \quad (1.b)$$

$$i\hbar \frac{d}{dt} b_{\alpha} = \hbar \omega_{\alpha} b_{\alpha} + \sum_{ij} \left(\tau_{ij}^{\alpha*} c_i c_j^{\dagger} + \tau_{ji}^{\alpha} c_j c_i^{\dagger} \right) \quad (1.c)$$

where, c_i and C_r are the electron annihilation operator at i -th and r -th mode in the nanowire and the reservoirs, respectively; and b_{α} is the annihilation operator for phonon at α -mode with angular frequency of ω_{α} . Correspondingly, the b 's and c 's obey Bose-Einstein (BE) commutation and Fermi-Dirac (FD) anti-commutation relations. H_{iso} stands for the Hamiltonian of isolated nanowire, and that of the reservoirs are H_R where all the dissipative processes are assumed to maintain the electrons in local equilibrium. The electron-phonon interaction potential is represented by τ , which depends on the corresponding deformation potential [34–36], and ζ indicates the coupling of nanowire with the reservoirs. Solving the equations (Eq. (1a)–(c)) for c_i using Green's function (G) to calculate the correlation function for filled states, $n_{ij}(t, t') = \langle c_j^{\dagger}(t') c_i(t) \rangle$, which by Fourier transform into energy domain gives rise to the matrix,

$$[n(E)] = [G(E)] \left(\left[\Sigma_R^{in}(E) \right] + \left[\Sigma_{Sc}^{in}(E) \right] \right) \left[G^+(E) \right] \quad (2)$$

where, the carrier inflow matrices from reservoirs and the scattering terminals are obtained to be, respectively,

$$\left[\Sigma_R^{in}(E) \right] = [\zeta] \left[n_R(E) \right] \left[\zeta^+ \right] \quad (3.a)$$

$$\left[\Sigma_{Sc}^{in}(E) \right] = \sum_{\alpha} (N_{\omega_{\alpha}} + 1) [\tau^{\alpha}] [n(E + \hbar \omega_{\alpha})] \left[\tau^{\alpha+} \right] + N_{\omega_{\alpha}} \left[\tau^{\alpha+} \right] [n(E - \hbar \omega_{\alpha})] \left[\tau^{\alpha} \right] \quad (3.b)$$

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