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Understanding the effect of inelastic electron-phonon scattering and channel inhomogeneities on a nanowire FET

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ABSTRACT

Using self-consistent Non-Equilibrium Green's Function formalism, the effect of the inelastic scattering due to electron-phonon interaction on the transfer and output characteristics of a coaxially gated generic nanowire field effect transistor has been studied in detail. The scattering strength D_o is varied from 0.003 eV^2 to 0.3 eV^2. There is change in the threshold voltage and suppression of channel current with increasing scattering strength. We also studied the effect of channel inhomogeneities on electron energy. The channel inhomogeneities are invoked by introducing potential step inside the channel. We study the energy relaxation due to inelastic scattering and channel inhomogeneities by comparing the normalized terminal current per energy for the source and drain terminals.

1. Introduction

Development of growth techniques in the field of quantum wires has led to the advent of nanowire field effect transistors [1–5]. Several groups have synthesized nanowires of different semiconductor materials having various dimensions and orientations [6–8]. It is now possible to produce high yield of nanowires with desirable electronic properties. Apart from obtaining structures of high crystalline quality, axial and radial nanowire hetrostructures are also been fabricated [9–12]. Now it is possible to sustain a controlled dimensional growth of nanowires which is extremely important to realize the critical device channel lengths and cross-sections. These high quality device channels show less scattering and high carrier mobility which is ideal for low power and high speed devices. Therefore a wrap round gate over a nanowire structure is an ideal candidate for nano-scale FET.

In spite of having such desirable properties for the futuristic device, there always exist an omnipresent inelastic scattering in the device channel due to electron-phonon scattering and channel inhomogeneities. This electron-phonon coupling play a very important role on the transfer and output device characteristics. Due to the continuous down-scaling of MOSFETs, it become extremely important to study these devices using more accurate simulation methods which incorporate quantum confinement, channel inhomogeneities and the effect of electron-phonon coupling on the overall device performance. Hence, it is extremely important to study the interesting physics of these low dimensional FETs using self-consistent quantum transport(SCQT) simulations to model these quantum effects. The electron-phonon interaction can be treated in a self-consistent first Born approximation by considering only one-phonon scattering. On the other hand, the phonons can be modeled as a bath of independent oscillators which interact with the electrons locally under a simple model of deformation potential where the potential felt by the electrons is proportional to the ionic displacement. To study this a rigorous

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application of Non-Equilibrium Green's Function(NEGF) Method which is formulated from the works of Schwinger, Keldysh, Kadanoff and Baym is used which take into account the effect of the electron-phonon interaction in the device channel [13–18]. Several groups have reported the study of transport properties of Si-nanowire and GNR transistors focusing on the effect of the elastic and inelastic electron-phonon interactions in the device channel [19–21]. It is extremely important to identify the phonon modes which contribute mostly to the inelastic scattering in the device channel. Also the effect of channel inhomogeneity and local imperfections in combination with electron-phonon interaction on the channel current is important for understanding the dissipation and relaxation mechanisms of the charge carriers in these nanoscale FETs.

In this work, we study the effect on the transfer and output characteristics of a generic Nanowire FET under the influence of phonon scattering and channel inhomogeneities. We study the device characteristics under different phonon scattering strengths. We introduce a potential step inside the channel of the device and analyze the energy resolved current spectrum and study the energy relaxation inside the nanowire channel under various conditions. This work is divided into four sections. In Section 2 we describe briefly the important theoretical aspects and the NEGF procedure for such nano-scale devices and the physics of the device operation under electron-phonon scattering. The device under operation is discretized in the computational domain using finite difference method and it is treated as an open quantum system and NEGF method incorporate the influence of the drain terminal, source terminal and the electron-phonon interaction on the channel. In Section 3 we explain the SCQT results. Finally, we summarize our work in Section 4.

2. Theoretical background and the SCQT methodology

2.1. Device modeling through Green's function formalism and the physics of electron-phonon interaction

The most important aspect of the nano-scale device modeling is based on the NEGF formulation which involve solving the Green's function for the device channel recursively using a self-consistent method. Fig. 1 show the generic FET structure under study. The device consist of an oxide layer of dielectric constant ε_r between the nanowire channel and the coaxial metal gate.

The positive gate voltage V_G is responsible for the enhancement of the channel conductivity in the device. The source and the drain electrodes act as the reservoirs of electrons and their contacts with the channel are manifested as self energies Σ_S and Σ_D. Apart from the source and drain electrodes, there is an S-contact which is manifested as a scattering terminal that take into account all the inelastic scattering processes in the device channel.

The Schrodinger equation for the channel which is an open-quantum system is given as:

$$[EI - H_0 - U(\vec{r}) - \Sigma_S - \Sigma_D - \Sigma_{SC}]\{\psi\} = \{S\} \tag{1}$$

Now, the solution of the above equation can be further written as

$$\{\psi\} = G^R\{S\} \tag{2}$$

Here, G^R is the Retarded Green's function for the device channel and it is given as,

$$G^R = [EI - H_0 - U - \Sigma_S - \Sigma_D - \Sigma_{sc}]^{-1} \tag{3}$$

which is the impulse response of the channel which satisfy the following differential equation in the position representation:

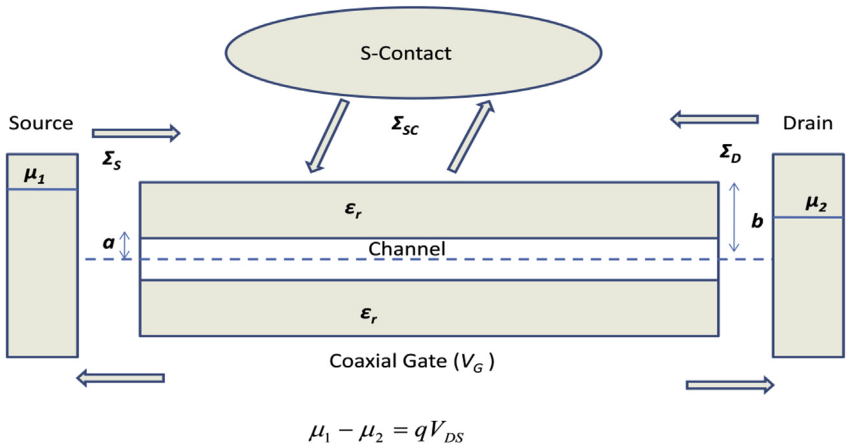

Fig. 1. A Nano-Scale Coaxially Gated MOSFET with a dielectric between the nanowire channel and the coaxial metal gate. The source and the drain contacts are manifested in the self-energies Σ_S and Σ_D respectively. S-contact is the scattering terminal for the device. The arrows( ) indicate the inflow and outflow of the electrons.

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