The Effect of Optical Phonon Scattering on the On-Current and Gate Delay Time of CNT-FETs

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Abstract

The performance of carbon nanotube field-effect transistors is analyzed, using the non-equilibrium Green's function formalism. The role of the inelastic electron-phonon interaction on the both on-current and gate delay time of these devices is studied. For the calculation of the gate delay time the quasi-static approximation is assumed. The results confirm experimental data of carbon nanotube transistors, where the on-current can be close to the ballistic limit, but the gate delay time can be far below that limit.

1 Introduction

Carbon nanotube field-effect transistors (CNT-FETs) have been studied in recent years as potential alternatives to CMOS devices. A CNT can be viewed as a rolled-up sheet of graphene with a diameter of a few nano-meters. Depending on the chiral angle the CNT can be either metallic or semiconducting. Semiconducting CNTs can be used as channels for transistors.
The non-equilibrium Green's function (NEGF) method has been successfully utilized to investigate the characteristics of nano-scale silicon transistors [1], CNT-FETs [2], and molecular devices [3]. To extend our previous works [4, 5], the NEGF formalism is employed to study the effect of inelastic electron-phonon interaction on the on-current and gate delay time of CNT-FETs in more detail.

2 Approach

Using the NEGF formalism quantum phenomena like tunneling and scattering processes can be rigorously modeled [6]. Based on the NEGF formalism we investigated the effect of the electron-phonon interaction on the performance of CNT-FETs. Details of our approach are presented in [6]. The interaction of electrons with optical phonons is inelastic. The lesser self-energy can be written as

$$\Sigma^{<}_{\mathrm{inel}}(E) = \sum_{\nu} D_{\nu} \left(n_{\mathrm{B},\nu} + \frac{1}{2} \pm \frac{1}{2} \right) G^{<}(E \pm \hbar\omega_{\nu}) \tag{1}$$

where $\hbar\omega_{\nu}$ denotes the phonon energy of branch ν, $n_{\mathrm{B},\nu}$ the average phonon occupation number, and D_{ν} are the matrix elements of the interaction Hamiltonian. These parameters depend on the diameter and the chirality of the CNT and can be calculated as presented in [7, 8].

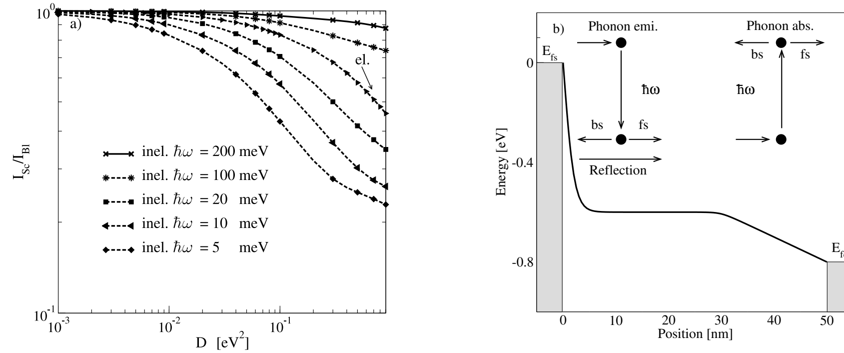

Figure 1: a) Ballisticity versus electron-phonon coupling strength for a CNT-FET of 50 nm channel length. $V_G = V_D = 1$ V. b) Sketch of phonon emission and absorption processes in the channel.

3 Simulation Results

Fig. 1-a shows the ballisticity as a function of the electron-phonon coupling strength. The ballisticity is defined as I_{Sc}/I_{Bl}, the ratio of the on-current in the presence of electron-phonon interaction to the current in the ballistic case [9]. The left part of Fig. 1-b illustrates an electron losing kinetic energy by emitting a phonon. The electron will be scattered either forward or backward. In the case of backward scattering the electron faces a thick barrier near the source contact and will be reflected with high probability, such that its momentum will again be directed towards the drain contact.
Fig. 2-a shows the dependence of the ballisticity with respect to the phonon energy. With increasing phonon energy the effect of phonon scattering on the current is reduced, because in this case electrons lose more kinetic energy and the probability for traveling back to the source contact decreases. The considerable decrease of ballisticity for low energy phonons is due to the phonon absorption process. As the phonon energy is reduced, the phonon occupation number increases exponentially, and the self-energy contributions of these two components increase. However, due to the higher probability for back-scattering of electrons in the case of phonon absorption, this component reduces the total current more effectively than the phonon emission process does.
To illustrate the effect of electron-phonon interaction on the dynamic response of the device, the gate delay time defined as $\tau = (Q_{on} - Q_{off})/I_{on}$ [10] is considered on the basis of the quasi-static approximation. Fig. 2-b shows the ratio of the gate delay time in the presence of electron-phonon interaction to that in the ballistic case, τ_{Sc}/τ_{Bl}, as a function of the electron-phonon coupling strength. As the phonon energy increases, the gate delay time increases. This behavior can be attributed to the electron group velocity in the channel, which is high for ballistic electrons and low for electrons scattered to lower energy states. Electrons can emit a single phonon or a couple of phonons to reach lower energy states. The probability of n sequential electron-phonon interaction events decrease as n increases. Therefore, as the phonon energy increases, the mean velocity of electrons decreases, and the carrier concentration in the channel increases (Fig. 3). The increased charge in the channel results in an increased gate delay time.

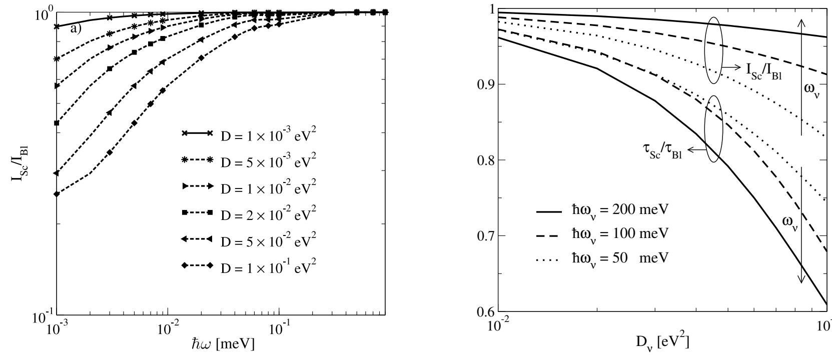

Figure 2: a) Ballisticity versus phonon energy for a CNT of 50 nm length for different electron-phonon coupling strengths. $V_{\mathrm{G}} = V_{\mathrm{D}} = 1$ V. b) The ratio of the gate delay time in the presence of electron-phonon interaction to the gate delay time in the ballistic case, $\tau_{\mathrm{Sc}}/\tau_{\mathrm{Bl}}$, as a function of the electron-phonon coupling strength. For comparison, the ballisticity $I_{\mathrm{Sc}}/I_{\mathrm{Bl}}$ is also shown. As the phonon energy increases, the device delay time increases. This behavior is due to the reduction of the average electron velocity in the channel and the resulting charge pile up.

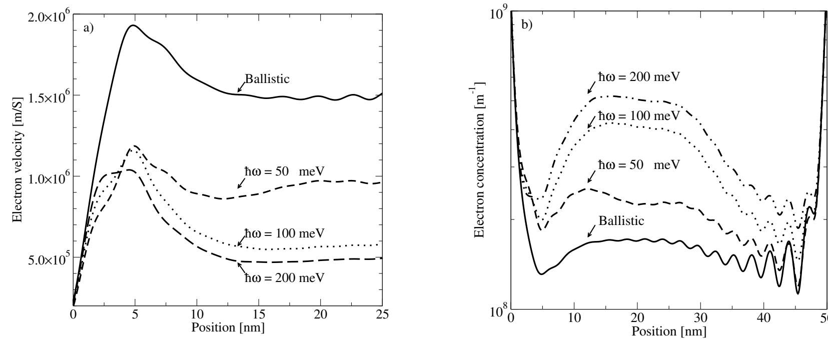

Figure 3: a) The profile of the electron velocity near the source contact. b) The profile of the electron concentration along the channel. The results for the ballistic case and for electron-phonon interaction are shown. As the phonon energy increases, the electrons scatter to lower energy states. Therefore, the electron velocity decreases and the carrier concentration increases. The electron-phonon coupling strength is $D = 10^{-1}$ eV^2 and the bias point is $V_{\mathrm{G}} = V_{\mathrm{D}} = 1$ V.

4 Discussion

Considering CNTs with diameters in the range of $1-2$ nm, the energies of the dominant inelastic phonons are $\hbar\omega_{\mathrm{OP}} \approx 200$ meV, $\hbar\omega_{\mathrm{RBM}} \approx 30$ meV, $\hbar\omega_{\mathrm{K}_1} \approx 160$ meV, and $\hbar\omega_{\mathrm{K}_2} \approx 180$ meV [9, 11]. The corresponding coupling coefficients are $D_{\mathrm{OP}} \approx 40 \times 10^{-3}$ eV^2, $D_{\mathrm{RBM}} \approx 10^{-3}$ eV^2, $D_{\mathrm{K}_1} \approx 10^{-4}$, and $D_{\mathrm{K}_2} \approx 50 \times 10^{-3}$ eV^2 [7, 9].

As discussed, high energy phonons such as OP and K-point phonons reduce the on-current only weakly, but can increase the gate delay time considerably due to charge pileup in the channel. Low energy phonons such as the RBM phonon can reduce the on-current more effectively, but have a weaker effect on the gate delay time. However, due to strong coupling, scattering processes are mostly due to electron-phonon interaction with high energy phonons. Therefore, the on-current of short CNT-FETs can be close to the ballistic limit [12], whereas the gate-delay time can be significantly below that limit.

The gate delay time for the ballistic case can be approximated as $\tau \approx 1.7$ ps$/\mu$m, or equivalently $f_T \approx 100$ GHz$/\mu$m [10]. The highest reported cut-off frequency for a device with a length below 1μm is $f_T \approx 10$ GHz [13], which is far below the ballistic limit. Apart from parasitic capacitances, inelastic electron-phonon interaction with high energy phonon has to be considered to explain the results.

5 Conclusion

The effect of the electron-phonon interaction parameters on the performance of CNT-FETs is studied, using the NEGF formalism. Inelastic scattering with high energy phonons reduces the on-current only weakly, whereas it can increase the gate delay time considerably. The results explain the reason why the measured on-currents of short CNT-FETs can be close to the ballistic limit, whereas the highest achieved cutoff frequency is significantly below that limit.

Acknowledgements

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