The Effect of Inelastic Phonon Scattering on Carbon Nanotube-Based Transistor Performance

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Carbon nanotube (CNT) based transistors have been studied in recent years as potential alternatives to CMOS devices because of their capability of near ballistic transport. In this work the non-equilibrium Green's function (NEGF) formalism is used to perform a comprehensive study of CNT based transistors. Extending our previous work [1] the effect of inelastic phonon scattering on the gate-delay time of CNT based transistors is studied in detail for a wide range of phonon energies. The results indicate that depending on the phonon energy, inelastic scattering affects the steady-state on-current and switching response of CNT based transistors quite differently. The results confirm experimental data of CNT based transistors, indicating that the on-current can be close to the ballistic limit, whereas the gate delay time is far below that limit.

Our approach has been described in [1]. A comprehensive study of the role of electron-phonon interaction on the characteristics of CNT based transistors is presented in [2]. To get a deeper insight into device operation we investigated the effect of electron-phonon interaction on the device characteristics for different phonon energies.

Fig. 1-a shows the ballisticity a function of the electron-phonon coupling strength. The ballisticity is defined as $I_{\mathrm{Sc}}/I_{\mathrm{Bl}}$, the ratio of the on-current in the presence of electron-phonon interaction to the current in the ballistic case [3]. With increasing phonon energy the effect of phonon scattering on the current is reduced, because scattered 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 [2].

The ratio of the gate-delay times in the presence of electron-phonon interaction to that in the ballistic case, $\tau_{\mathrm{Sc}}/\tau_{\mathrm{Bl}}$, as a function of the electron-phonon coupling strength is also shown in Fig. 1-a. The gate-delay time increases with increasing phonon energy. This behavior can be attributed to the average electron velocity in the channel, which is high for ballistic electrons and low for electrons scattered to lower energy states. Fig. 1-b shows the spectra of the source and drain currents for different inelastic phonon energies. Electrons can emit a single phonon or a couple of phonons to reach lower energy states. The probability of a sequence of phonon emissions is reduced as the number of interactions increases. Therefore, as the phonon energy increases, the occupation of electrons at lower energy states increases too. As shown in Fig. 1-b, the electron population close to the conduction band-edge considerably increases as the phonon energy increases. Therefore, as the phonon energy increases the mean velocity of electrons is reduced and the carrier concentration in the channel increases (Fig. 2). The increased charge in the channel results in an enlarged gate-delay time.

Inelastic scattering is induced by OP, RBM, and K-point phonons. Considering the CNTs relevant to electronic applications with diameters in the range $d_{\mathrm{CNT}} = 1-2$ nm, the phonon energies of the these structures are $\hbar\omega_{\mathrm{OP}} \approx 200$ meV, $\hbar\omega_{\mathrm{RBM}} \approx 20-30$ meV, and $\hbar\omega_{\mathrm{K}_1} \approx 160$ and $\hbar\omega_{\mathrm{K}_2} \approx 180$ meV [4]. The corresponding coupling coefficients are $D_{\mathrm{OP}} \approx 40\times10^{-3}\ \mathrm{eV}^2$, $D_{\mathrm{RBM}} \approx 10^{-3}\ \mathrm{eV}^2$, and $D_{\mathrm{K}_1} \approx 10^{-4}$ and $D_{\mathrm{K}_2} \approx 50\times10^{-3}\ \mathrm{eV}^2$ [3].

As discussed, high energy phonons such as OP and K-point phonons reduce the on-current only weakly, but enlarge the gate delay time considerably due to a charge pileup in the channel. Low energy phonons such as the RBM phonon reduces the on-current more effectively, but have a weaker effect on the gate delay time. In a CNT at room temperature scattering processes are mostly due to electron-phonon interaction with high energy phonons. Therefore, the on-current of CNT-FETs can be close to the ballistic limit [5], whereas the switching time is found to be significantly below that limit [6, 7].

The intrinsic gate delay time for the ballistic case can be approximated as $\tau \approx 1.7\ \mathrm{ps}/\mu\mathrm{m}$, or equivalently $f_T \approx 100\ \mathrm{GHz}/\mu\mathrm{m}$ [8]. The highest reported intrinsic cutoff frequency for a device with a length of 300 nm is $f_T \approx 30$ GHz [9], which is far below the ballistic limit. Inelastic electron-phonon interaction with high energy phonon has to be considered to explain the results.

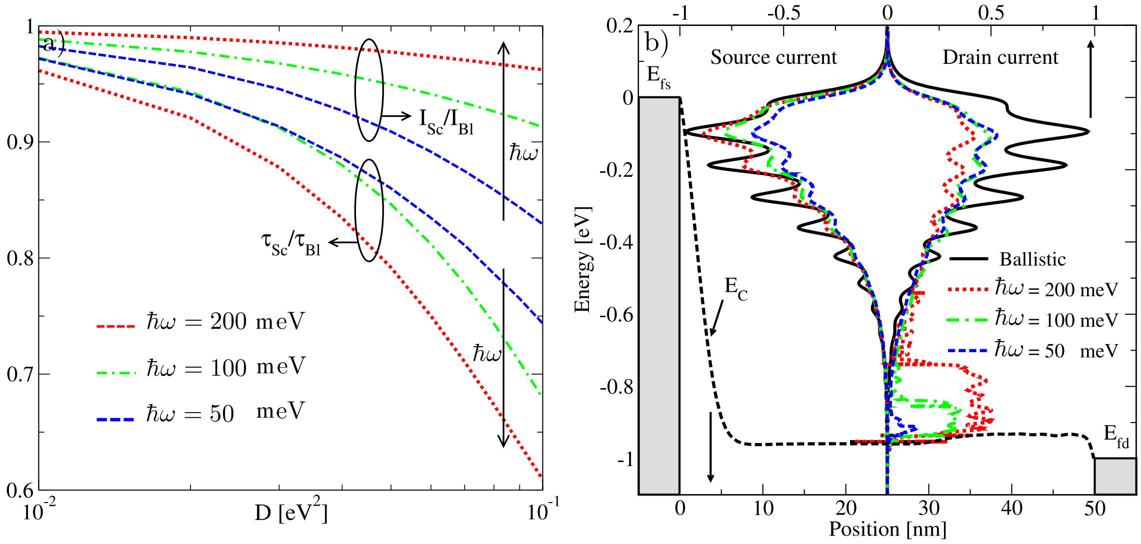

Figure 1: a) The ratio of the gate-delay time in the presence of electron-phonon interaction to the gate-delay time in the ballistic case, $\tau_{\mathrm{Sc}}/\tau_{\mathrm{Bl}}$, as a function of the electron-phonon coupling strength. For comparison, the ratio $I_{\mathrm{Sc}}/I_{\mathrm{Bl}}$ is also shown. As the phonon energy increases the gate-delay time increases. This behavior is due to the reduction of the electron velocity in the channel and the resulting charge pile up. b) The spectra of the source and drain currents. The effect of inelastic scattering with different phonon energies is shown. The electron-phonon coupling strength is $D = 2 \times 10^{-1}\ \mathrm{eV}^2$. The figure shows a considerable increase of the electron population close to the conduction band-edge as the phonon energy increases.

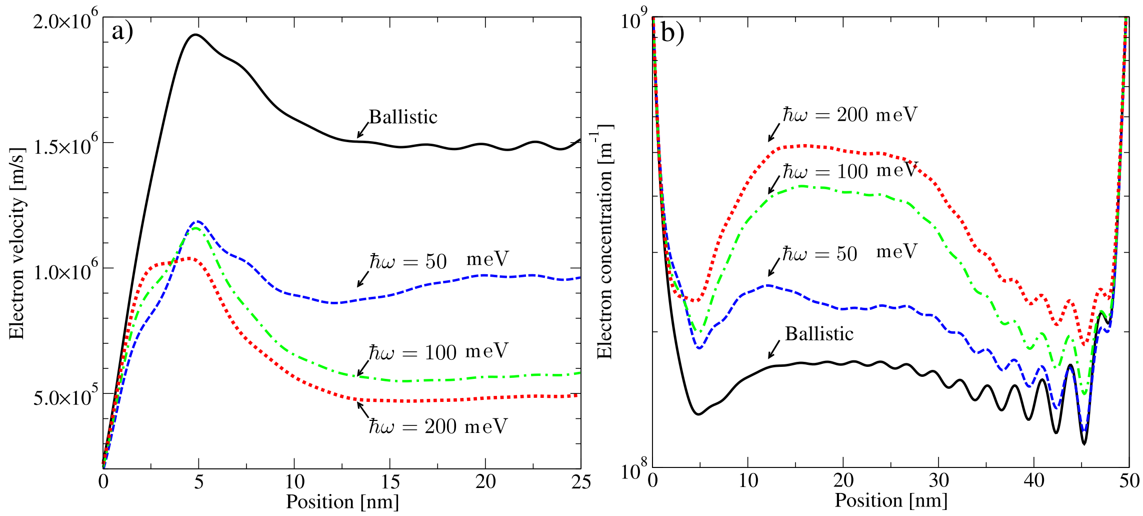

Figure 2: a) The profile of the electron velocity near the source contact. b) The profile of the electron concentration along the device. The results for the ballistic case and for electron-phonon interaction are shown. As the phonon energy increases the electrons scatter to lower energy states. Therefore,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

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