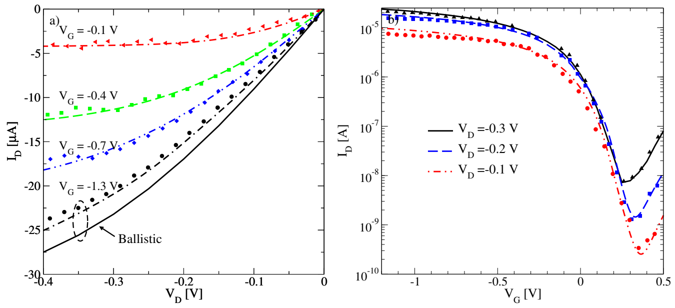

Fig. 10. Comparison of the simulation results and experimental data for the a) output and b) transfer characteristics. Lines show the simulation results and symbols show experimental data. The result for $V_{\mathrm{G}} = -1.3$ V is compared with the ballistic limit. Experimental data have been adopted from [37].

VI. Discussion

In general the electron-phonon interaction parameters depend on the diameter and the chirality of the CNT [29]. CNTs with a diameter $d_{\mathrm{CNT}} > 2$ nm have a band gap $E_{\mathrm{G}} < 0.4$ eV, which render them unsuitable as channel for transistors. Since the fabrication of devices with a diameter $d_{\mathrm{CNT}} < 1$ nm is very difficult, we concentrate our study on zigzag CNTs with diameters in the range of $d_{\mathrm{CNT}} = 1-2$ nm.

Scattering with acoustic phonons is treated as an elastic process. The electron-phonon coupling is also weak for acoustic phonons ($D_{\mathrm{AP}} < 10^{-3}\ \mathrm{eV}^2$), which implies that elastic back-scattering of carriers is weak. Inelastic scattering is induced by optical (OP), radial breathing mode (RBM), and K-point phonons [9, 38]. Considering the class of CNTs discussed, energies of these phonons are $\hbar\omega_{\mathrm{OP}} \approx 200$ meV, $\hbar\omega_{\mathrm{RBM}} \approx 25$ meV, $\hbar\omega_{\mathrm{K_1}} \approx 160$ meV, and $\hbar\omega_{\mathrm{K_2}} \approx 180$ meV [34, 38]. The corresponding coupling coefficients are $D_{\mathrm{OP}} \approx 40 \times 10^{-3}\ \mathrm{eV}^2$, $D_{\mathrm{RBM}} \approx 10^{-3}\ \mathrm{eV}^2$, $D_{\mathrm{K_1}} \approx 10^{-4}\ \mathrm{eV}^2$, and $D_{\mathrm{K_2}} \approx 10^{-3}\ \mathrm{eV}^2$ [34].

As discussed in Section V-B, 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, at room temperature the on-current of short CNT-FETs can be close to the ballistic limit [37] (see Fig. 10), whereas the gate-delay time can be significantly below that limit [39, 40].

The intrinsic (without parasitic capacitances) gate-delay time for the ballistic case can be approximated as $\tau \approx 1.7\ \mathrm{ps}/\mu\mathrm{m}$, or equivalently $f_T \approx 100\ \mathrm{GHz}/\mu\mathrm{m}$ [35]. The highest reported intrinsic cutoff frequency for a device with a length of 300 nm is $f_T \approx 30$ GHz [41], which is far below the ballistic limit. Inelastic electron-phonon interaction with high energy phonons has to be considered to explain the results.

VII. Conclusion

For rigorously modeling current transport in CNT-FETs the coupled system of transport equations and the Poisson equation must be solved self-consistently. A tight-binding Hamiltonian is used to describe the transport phenomena in CNT-FETs. Employing the described model, both the electron-photon and electron-phonon interactions in CNT-FETs can be investigated. The results show that the local scattering approximation, which is widely used in quantum transport simulations, fails to predict the behavior of devices where electron-photon interaction is present. For accurate simulations a non-local self-energy must be taken into consideration. The effect of electron-phonon interaction on the device characteristics is discussed in detail. In agreement with experimental data, the results indicate that at room temperature electron phonon interaction affects the steady-state current of CNT-FETs only weakly, whereas the switching response of such devices can be significantly affected.

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