Supplementary Materials: An essential mechanism of heat dissipation in carbon nanotube electronics

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SELF-CONSISTENT CURRENT-VOLTAGE CURVES FOR SPP THERMAL CONDUCTANCE MECHANISM

As shown in Fig. 3a, our modeling predicts the self-consistent temperature of the NT FET channel taking into account the SPP thermal conductance mechanisms. Supplementary Figure 1 presents the current-voltage curves for the same device as in Fig. 3a. One can see that the doping level has a major influence on the drain current (cf. red and purple curves). We also plot here the current-voltage curve for $\rho = 0.4\ e/nm$ with the current divided by 4 (thin purple curve), which is comparable then with the other current-voltage curves with the lower $\rho = 0.1\ e/nm$. The drift velocity drops at the higher doping level, which leads to some additional current suppression.

There is a little influence of the bare thermal coupling g_0 on the current-voltage curves (cf. red and blue curves), which confirms that the SPP thermal coupling dominates over the bare (starting) phonon coupling in the self-consistent model.

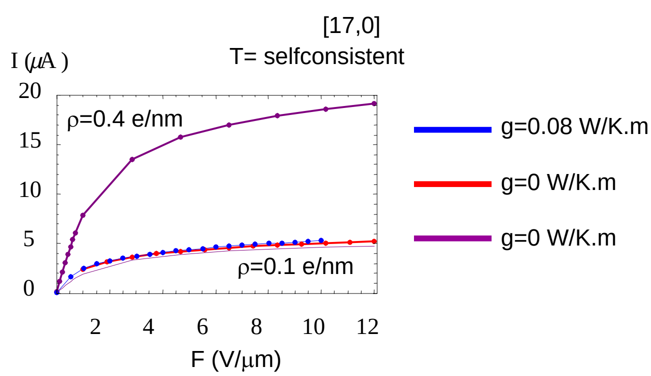

FIG. 1: Self-consistent current-voltage curve for [17,0] NT (the drain current vs. the applied electric field). Bare thermal coupling values and doping levels are shown in the legend. The temperature distribution for the same device is given in Fig. 3b. Thin purple line is derived by decreasing the current for $\rho = 0.4\ e/nm$ 4 times to scale it down and compare with lower $\rho = 0.1\ e/nm$ current-voltage curves.

DOPING LEVEL DEPENDENCE OF THE SPP AND NT SCATTERING CHANNELS

We found that the losses due to the SPP mechanism have almost linear dependence on the doping level (gate bias). Supplementary Figure 2 presents the losses to both SPP and NT channel, compared to the total losses which shows a clear linear slope.

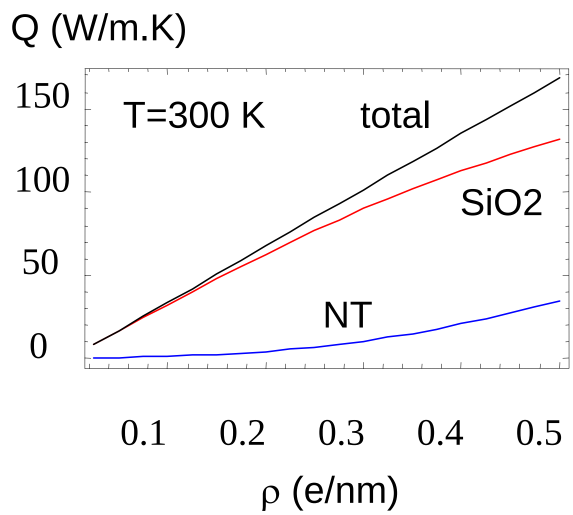

FIG. 2: Hot electron energy losses for [17,0] NT vs. the doping level ρ. Red, blue and black curves correspond to the SPP, NT and total losses.

SCATTERING RATES AND LOSS RATIO DUE TO THE SPP AND NT PHONONS FOR DIFFERENT SUBBANDS

In Supplementary Fig. 3 we show scattering rate of electrons due to the SPP and NT phonons in different subbands. In the first two lowest energy subbands the SPP scattering dominates over the NT scattering, while at higher energy subbands the NT scattering becomes comparable to that of the SPP scattering. This is because in the SPP scattering the angular momentum is essentially conserved $\Delta m = 0$ [27], such that only intra-subband scattering takes place, while NT optical phonons can have both intra and inter-subband scattering and the phase space for scattering grows with the subband index.

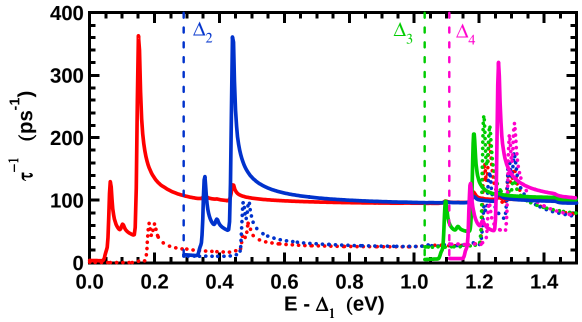

FIG. 3: Scattering rate as a function of energy in the first four bands shown by red, blue, green, and magenta colors correspondingly. Solid curves show scattering rates due the SPP phonons and dotted curves due to NT phonons. Vertical lines show bottom of the second, third and fourth bands.

Therefore, as the tail of electronic distribution extends to higher energies at high fields and phonon temperatures, the role of SPP scattering in the heat sink becomes less significant. To quantify the effect of electronic distribution and phonon scattering on the heat loss ratio due to the NT and SPP phonons we show in Supplementary Fig. 4 loss ratio calculated at two different temperatures and the hypothetical losses calculated with the electronic distribution using high phonon temperature and scattering rates using low phonon temperatures. As it can be seen from Fig. 4, the electronic distribution function primarily responsible for the loss ratio at high bias regime.

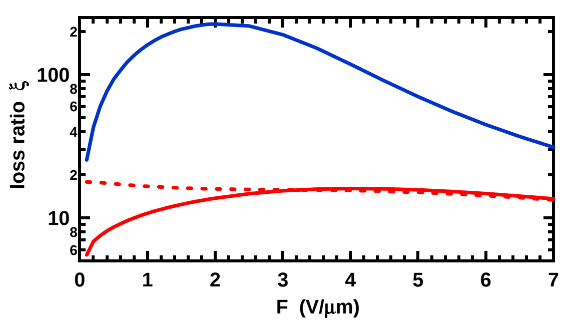

FIG. 4: The ratio of the SPP partial losses to the NT partial losses at T=150 K (blue solid curve) and T=450 K (red solid curve). The red dashed curve shows hypothetical loss ratio calculated with the distribution function from the Boltzmann equation solution for scattering calculated with phonon temperatures of T=450 K and losses calculated using scattering rate for T=150 K.