Peltier cooling in carbon nanotube circuits

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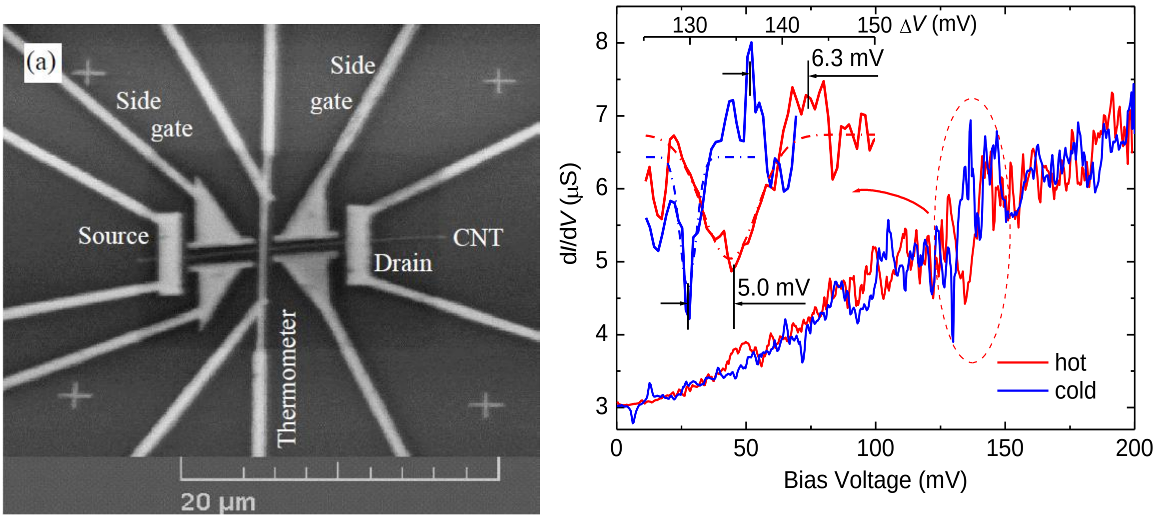
Abstract

Conversion of the heat energy directly into electricity and vice versa attracts a significant attention nowadays [1,2]. Systematic study of thermoelectric phenomena allows for better understanding of the intrinsic mechanisms of the energy transformation and dissipation on the nanoscale. A bias electric voltage ΔV, applied to a conducting sample, pulls the charge carriers, thereby inducing a finite electric current $I_e = G_e \Delta V$, where G_e is the electric conductance. Since the bias voltage ΔV also induces an inhomogeneity of charge carrier density along the sample, it leads to a finite temperature difference hot cold $\Delta T = T_{hot} - T_{cold}$, where $T_{hot(cold)}$ is the temperature of the hot (cold) part of the sample. The thermoelectric effect is described as $\Delta V = S\Delta T$ where S is a linear-response, two-terminal property known as Seebeck coefficient. Thermoelectric effect is measured using two sequentially-connected carbon nanotube (CNT) field-effect transistors (FETs), each with charge carriers of opposite sign, either electrons or holes, whose concentration is controlled by the side gate electrodes. A change ΔT of the intrinsic temperature is determined from the change of the position and width of spectral singularities manifested in the experimental curves of the source-drain electric conductance. We deduce an impressive Peltier effect $\pm\Delta T$ = 57 K inside the CNT associated with cooling and heating, depending on the direction of the electric current. The effect can be utilized for building thermoelectric devices having a figure of merit up to cold $ZT = 7.5 >> 1$ and the cooling power density $P_{cooling}$~80 kW/cm^2.

References

[1] S. Mayle, T. Gupta, S. Davis, V. Chandrasekhar, and S. Shafraniuk, J. of Appl. Phys. 117 (2015) 194305.
[2] S. Shafraniuk, Graphene: Fundamentals, Dev. and Appl., Pan Standford Publishing, (2015) 634 pp.

Figures



Left: SEM images of typical CNT nano-circuits used in the experiments. Side gates are employed to apply an electric field to the CNT. Right: Measured differential conductance $G_e\ \Delta V$ of the CNT thermoelectric circuit with Ti electrodes at the bath temperature of 77 K. Blue curve is for the cooling process sketched in Fig. 2b, whereas the red curve is for the heating process shown in Fig. 2c. Localized energy levels are identified as sharp features in the conductivity in the energy interval from 125 to 150 meV (marked by dashed line). A blowup of this region is shown in the inset. From the plot we find that $\Gamma_{cool} = 1.75 \pm 0.5$ meV and $\Gamma_{hot} = 5.6 \pm 0.7$ meV giving an estimate of T_{hot}-T_{cold}~114 $\pm$ 7 K.