Electric Current and Heat Flux in Landauer – Datta – Lundstrom Transport Model for Nano- and Microelectronics

Kruglyak Yu.

Odessa State Environmental University, Odessa, Ukraine

The objectives for this report is to give a condensed summary of Landauer – Datta – Lundstrom (LDL) electron and heat transport model [1] which works at the nano- as well as at macroscale for 1D, 2D, and 3D resistors in ballistic, quasi-ballistic, and diffusive linear response regimes when there are differences in both voltage and temperature across the device.

The generalized LDL transport model for current and heat flux gives:

$$I = \frac{2q}{h}\int T_{el}(E)M_{el}(E)\left(f_1 - f_2\right)dE\,[A],\quad Q = \frac{1}{h}\int (\hbar\omega)T_{ph}(\hbar\omega)M_{ph}(\hbar\omega)\left(n_1 - n_2\right)d(\hbar\omega),\ [W]$$

where M is the number of modes of conductivity at energy E or phonon modes at energy $\hbar\omega$, the transmission $T = \lambda/[\lambda + L]$, where λ is the mean-free-path for backscattering for electrons or phonons and L is the length of the resistor, Fermi function $f(E)$ and Bose function $n(\hbar\omega)$ are indexed with the resistor contact numbers 1 and 2, Fermi energy as well as temperature may be different at both contacts.

Equation for transmission is valid not only in the ballistic and diffusion limits, but in between as well: Diffusive: $L >> \lambda$, $T = \lambda/L << 1$; Quasi-ballistic: $L \approx \lambda$, $T < 1$; Ballistic: $L << \lambda$, $T \rightarrow 1$.

The LDL transport model is developed for linear response regime giving for electric conductance $G = 2q^2h^{-1}\int T_{el}(E)M_{el}(E)W_{el}(E)dE\,[S]$ with the Fermi conductance window $W_{el}(E) = (-)\partial f_0/\partial E$, where the quantum of conductance $G_0 = 2q^2/h$ relates to Klitzing constant and for lattice thermal conductance $K_L = 3\pi^2k^2T\,h^{-1}\int T_{ph}(\hbar\omega)M_{ph}(\hbar\omega)W_{ph}(\hbar\omega)d(\hbar\omega)$ with phonon transport window $W_{ph}(\hbar\omega) = (3/\pi^2)(\hbar\omega/kT)(\partial n_0/\partial(\hbar\omega))$, where the quantum of thermal conductance $g_0 \equiv \pi^2k^2T/3h \approx (9.456\times10^{-13}\,W/K^2)T$ represents the maximum possible value of energy transported per phonon mode and does not depend on particle statistics being universal for fermions, bosons, and anyons.

Expression for conductance above is known as the Landauer equation which is valid in 1D, 2D, and 3D resistors, if we use the appropriate expressions for number of modes $M_{el}(E)$. Conductivity of any material depends on its density of states in the Fermi conductance window with width of $\approx \pm 2kT$ around the equilibrium value of electrochemical potential E_{F0}. In the same way the phonon window determines which phonon modes carry the heat current. These two window functions are very similar in shape and play a key role in determining the electrical and thermal conductances.

[1] Yuriy Kruglyak, J. Nanoscience, vol. 2014, Article ID 725420, 15 pages, 2014; DOI: 10.1155/2014/725420.