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Published in:
Physical Review. B: Condensed Matter and Materials Physics

DOI:
10.1103/PhysRevB.84.241408

Publication date:
2011

Resubmitted on December 9, 2011

(Supplemental material)

Nonlinear interaction of spin and charge currents in graphene

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(Dated: December 9, 2011)

PACS numbers: 72.25.Hg, 72.80.Vp, 75.76.+j, 85.75.-d

Here we present a derivation of Eq. (5), which is an analytical result to lowest (second) order for the nonlocal charge voltage generated by a nonlocal spin current.

The electrochemical potential for each spin channel $\mu_\pm = \mu_{\mathrm{avg}} \pm \Delta\mu$ is described by the spin-diffusion relations Eqs. (1) and (2). As mentioned in the article, we use the general solutions for $\mu_\pm$, $J_\pm$, and E for a homogeneous medium presented in Ref. 1. To find numerical solutions we divide the conducting system (graphene) into discrete regions and use the homogeneous solutions for each region, while keeping continuities of $\mu_\pm$ and $J_\pm$.

The nonlinear interaction between spin and charge is present due to the energy dependent conductivity $\sigma(\epsilon)$ of the system, which results in each region having a conductivity spin polarization β. Within this framework, the charge voltage variation ΔV across a discrete region of width Δx is

$$\begin{aligned}\Delta V &= V(x+\Delta x) - V(x) \\ &= \frac{\beta}{-e}[\Delta\mu(x+\Delta x) - \Delta\mu(x)] \ ,\end{aligned}$$

with β given by Eq. (4). By considering regions with infinitesimally small widths dx and describing the spin accumulation to first order via Eq. (3) we obtain

$$\begin{aligned}dV &= \frac{\alpha}{e}[\Delta\mu(x)]^2\frac{dx}{\lambda} \\ V_{\mathrm{nl}}(x_0) &= \int_{-\infty}^{x_0} dV = \frac{\alpha}{2e}[\Delta\mu(x_0)]^2 \ ,\end{aligned}$$

the latter is the result of Eq. (5) and it describes the nonlocal charge voltage shown in Fig. 1.

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[1] T. Valet and A. Fert, Phys. Rev. B **48**, 7099 (1993).