**Temperature-gradient-induced charge and spin currents in graphene with resonance levels**

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## Abstract

Charge and spin caloritronic effects attracted recently a lot of attention as a new step in enhancing functionality of spintronic devices [1,2]. From this point of view, graphene is probably the most important material for investigations, that has been already proved by studying its numerous very unusual electronic and transport properties. Not only 'classical' one-layer graphene but also two-layer [3,4], three- and multi-layer [5] graphene structures have been already studied as new perspective thermoelectric materials [6,7].

In our work we consider charge and spin thermoelectric effects in a one-layer graphene with certain choice of impurities creating resonance levels. We use the model with a short-range impurity potential characterized by parameter $V_0$ related to the type of impurity in the graphene lattice or at the surface of graphene. Especially important for the characterization of impurity states are spin-orbit interaction effects, even in the case when they are rather weak [9]. In our calculations of impurity states we used a standard T-matrix approach for the resonant states near K and K' Dirac points in the Dirac energy spectrum of low-energy electron excitations. To calculate the charge and spin thermoelectric current we use the kinetic equation method, correspondingly modified to account for pseudospin and spin-dependence of the electron distribution function. The key point of are calculation is the electron relaxation time, which includes the effect of resonant scattering from impurities. It strongly modifies both momentum and spin relaxation in graphene. Figure 1 demonstrates the variation of electron relaxation time $\tau(\varepsilon)$ for different values of the parameter $V_0$ and different impurity density $N$.

Impurities influence the thermoelectric Seebeck constant α and thermoelectric current induced by the temperature gradient [8]. As we show in Fig. 2, the localized states affect significantly the thermoelectric constant $\alpha$. For positive chemical potential $\mu$, only resonant states with positive energies (correspondingly, negative impurity potential, $V_0 < 0$) increase the Seebeck current. The value of constant α depends on temperature, and for $T$ = 10K it is smaller, whereas at $T$ = 300K it can be as high as α > 0.15 V/K. We also show the charge current (Fig.3) as a function of chemical potential $\mu$ for different temperatures T and impurity concentration N. We find that the thermoelectric constant $\alpha$ can be larger than it was reported before [6]. Taking into account heat conductivity by electrons without phonons, we evaluated the figure of merit $ZT$. We also take into account intrinsic spin-orbit interaction which modifies resonant states in graphene [8]. This interaction gives us a possibility of generation of the spin-polarized current in graphene by the temperature gradient.

Another problem which we consider in this work is the magnetization induced by the temperature gradient in graphene with Rashba spin-orbit interaction. Strong Rashba interaction is possible for graphene on substrate In this case we use Green's function formalism to find the magnetization. Also, in this case we take into account resonant state generating by impurities for the calculations of relaxation times. We find an influence of resonant states on the magnetization in graphene. This influence is especially strong when impurities enhance the local spin-orbit interaction.

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## References

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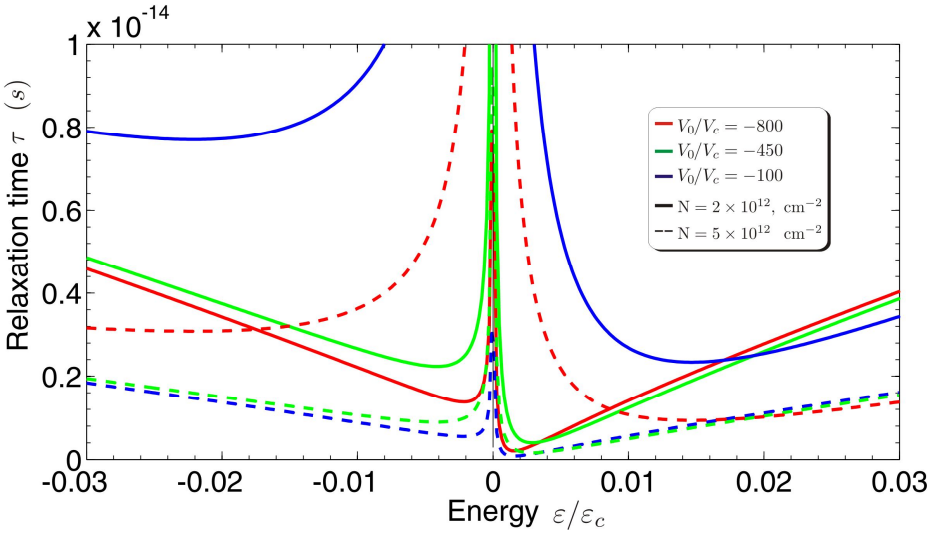


**Fig.1 Electron relaxation time $\tau(\varepsilon)$ for different impurity potential $V_0$ and different impurity concentrations N**

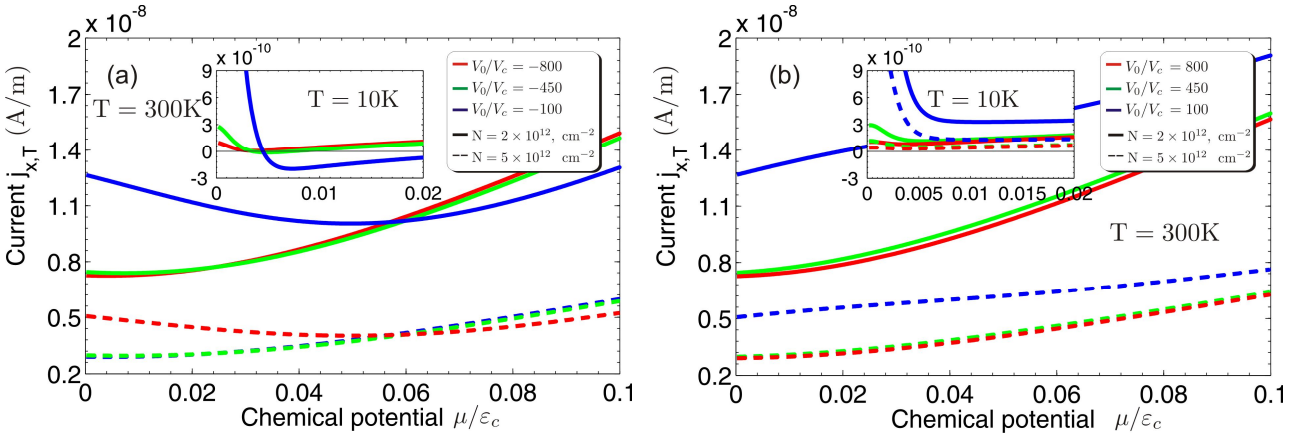


**Fig. 2 Thermoelectric current coefficient vs. chemical potential for different impurity potential $V_0$ - (a) $V_0$>0, (b) $V_0$<0.**

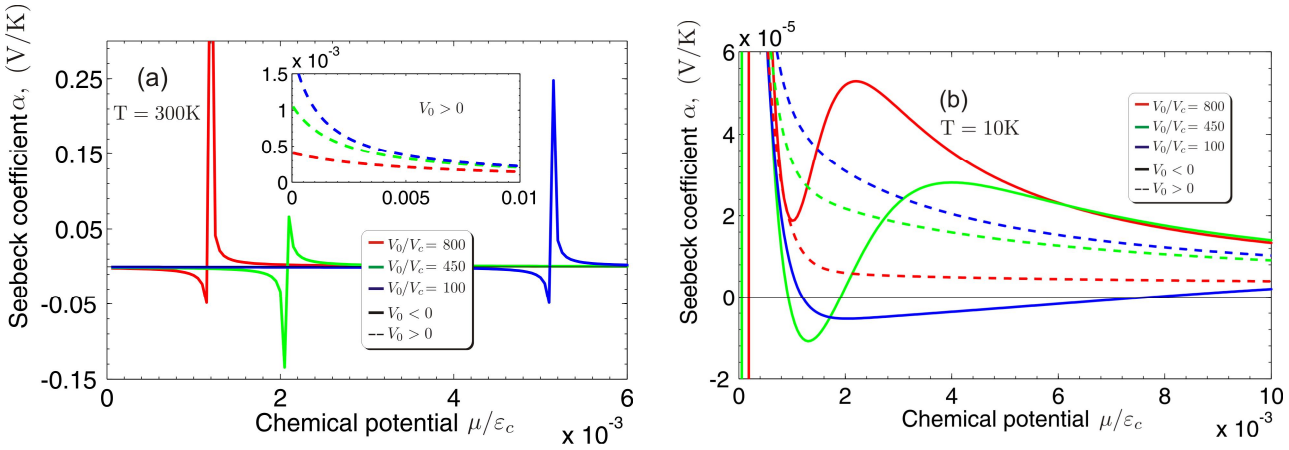


**Fig. 3 Seebeck coefficient vs. chemical potential for different impurity potential (a) T=300 K, (b) T=10 K.**