Recombination Time in Drift-Diffusion Models of Graphene Field-Effect Transistors

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1. Introduction

Graphene field-effect transistors (GFET) have been widely studied for applications in electronics, such as sensors or radiofrequency. Several physical models have been developed to explain the carrier transport in GFETs [1-3], but the way to introduce carrier generation-recombination is still in debate. Drift-diffusion models in graphene often use a single quasi-Fermi level for both electrons and holes as an approximation, assuming a very low recombination time, which is measured and calculated to be in the order of 1-100 ps [4]. This work presents a method to calculate the net recombination rate, adapted from semiconductor physics, which is applied to a self-consistent Poisson-drift-diffusion GFET model.

2. Methods

We study double-gate GFETs with a structure as presented in Fig. 1. Continuity equations for electron and hole current densities in the stationary state (J_n and J_p, respectively) can be expressed by the following equation:

$$\frac{\mathrm{d}J_n}{\mathrm{d}y} = -\frac{\mathrm{d}J_p}{\mathrm{d}y} = qU \qquad (1)$$

where U is the net recombination rate of electron-hole pairs [5]. The total drain current density J_{DS} is the sum of the electron and hole current densities. Considering only band-to-band generation-recombination in graphene, we write the net recombination rate with a relaxation form, depending on the recombination time τ:

$$U = \frac{\partial(\Delta n)}{\partial t} = \frac{\partial(\Delta p)}{\partial t} = -\frac{n - n_{\mathrm{eq}}}{\tau} \qquad (2)$$

To calculate carrier concentration in equilibrium n_{eq}, we must assume the quasi-neutral approximation (the excess of electrons must equal the excess of holes, $\Delta n = \Delta p$). The parameters for simulations are listed in Table 1.

3. Results and discussion

We explore how recombination time affects graphene carrier transport. Transfer characteristics in Fig. 2 show that the recombination time mostly affects drain current at biases close to the Dirac point. Quasi-Fermi levels for electrons and holes at the Dirac bias are represented in Fig. 3. For τ above 1 ps, the two levels show a large separation, which decreases as τ is reduced and eventually converge into the model of a single quasi-Fermi level for $\tau \to 0$. At the Dirac bias, electron and hole concentrations in the graphene channel are comparable, and their distribution as a function of τ can be observed in Fig. 4. The net recombination rate is represented in Fig. 5. This rate is null when the τ is large, as can be deduced from Eq. 2. However, for short times, the net recombination is maximum in the middle of the channel, where carrier concentration is minimum (see Fig. 4). The value of U at this point in the channel increases gradually as τ decreases.

4. Conclusions

This work confirms that a single quasi-Fermi level for electrons and holes is a good approximation when recombination times are small enough. However, a sizeable separation between quasi-Fermi levels might appear for longer recombination times being the increase of the conductivity at the Dirac voltage the expected fingerprint.

Acknowledgements

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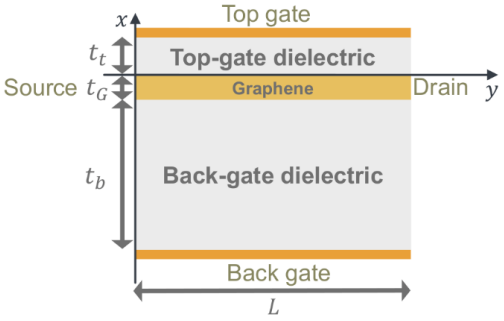

Fig. 1. Schematic of the active region of the GFET.

Parameter	Symbol	Values
Channel length	L	100 nm, 1 µm
Top dielectric thickness	t_t	10 nm
Bottom dielectric thickness	t_b	285 nm
Top dielectric permittivity	ϵ_t	9 ϵ_0
Bottom dielectric permittivity	ϵ_b	3.9 ϵ_0
Source bias	V_S	0 V
Drain bias	V_D	1 V
Bottom gate bias	V_B	0 V
Flatband voltages	V_{gs0} and V_{bs0}	0 V
Low-field carrier mobility	μ_{LF}	2000 $cm^2\ V^{-1}\ s^{-1}$
Saturation velocity	v_{sat}	$6.59 \cdot 10^5$ $m\ s^{-1}$
Saturation velocity parameter	β	1
Puddle concentration	σ_0	$3.67 \cdot 10^{11}$ cm^{-2}
Recombination times	τ	0, 10^{-14}, 10^{-13}, 10^{-12}, ∞ s
Temperature	T	300 K

Table 1. Main parameters used in the simulations.

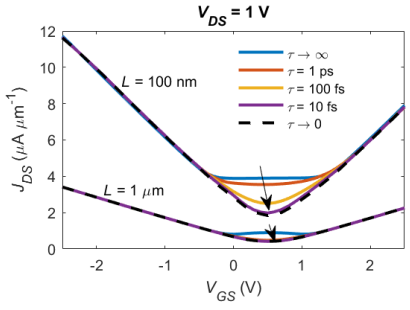

Fig. 2. Transfer curves for different recombination times in GFETs with two channel lengths.

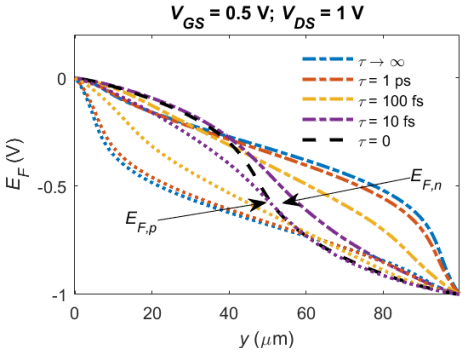

Fig. 3. Electron (dashed-dotted lines) and hole (dotted) quasi-Fermi levels at Dirac bias for different recombination times. As recombination time approaches 0 s, quasi-fermi levels converge to a single curve.

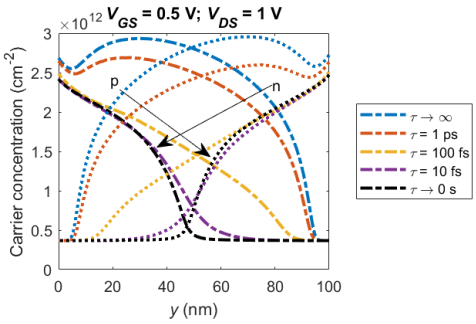

Fig. 4. Electron (dashed-dotted lines) and hole (dotted) concentrations in the channel at Dirac bias for different recombination times.

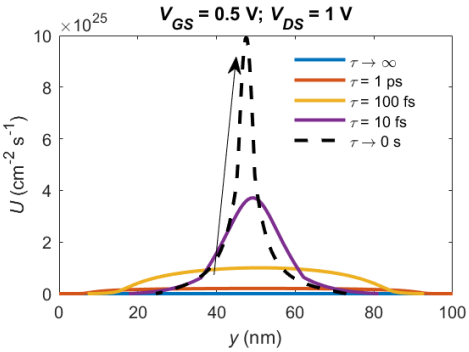

Fig. 5. Net recombination in the channel at Dirac bias for different recombination times.