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

Pedro C. Feijoo, Ferney A. Chaves, D. Jiménez

POLITÉCNICA

UAB
Universitat Autònoma
de Barcelona

Outline

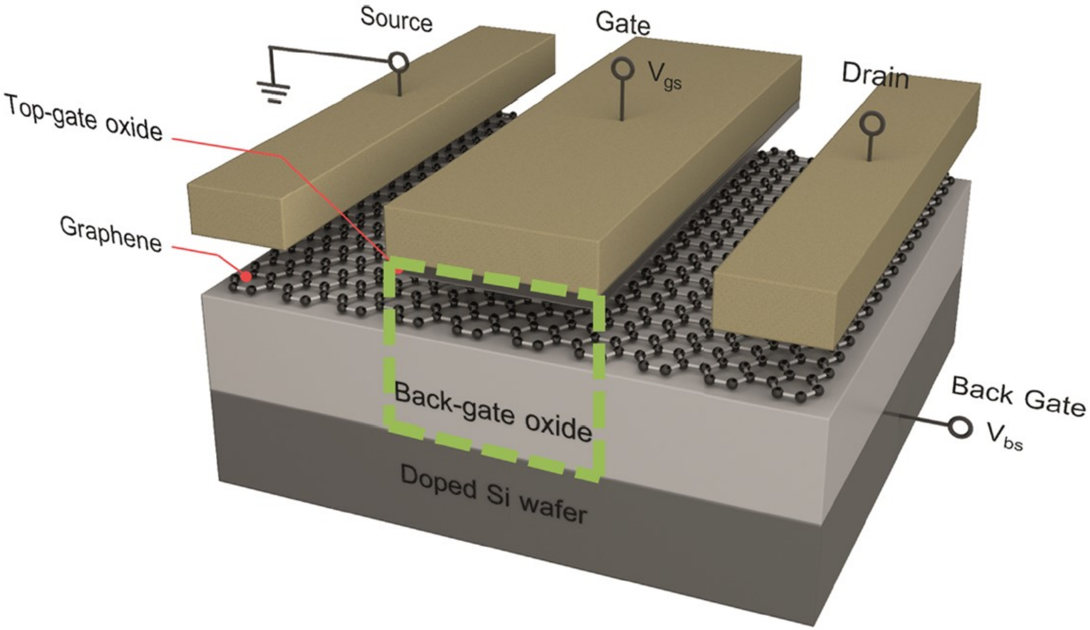
- Introduction
- Mathematical model
- Results
- Conclusions

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

INTRODUCTION

Introduction

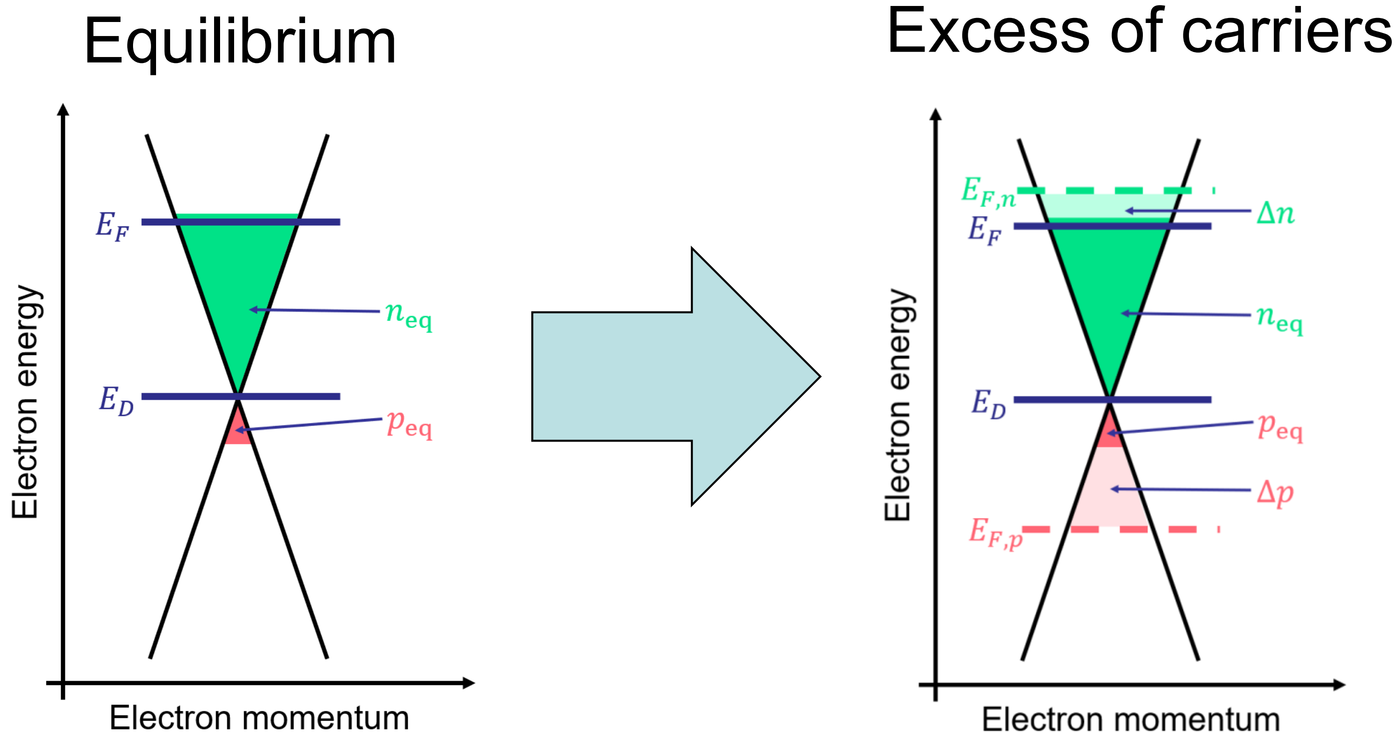
- Graphene Field-Effect Transistor (GFET)
  - High mobility and saturation velocity
  - Applications in radiofrequency and photonics



Introduction

Recombination time in graphene

$\tau \approx 1 - 100\ \mathrm{ps}$ have been reported



$$U = \frac{\Delta n}{\tau}$$

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

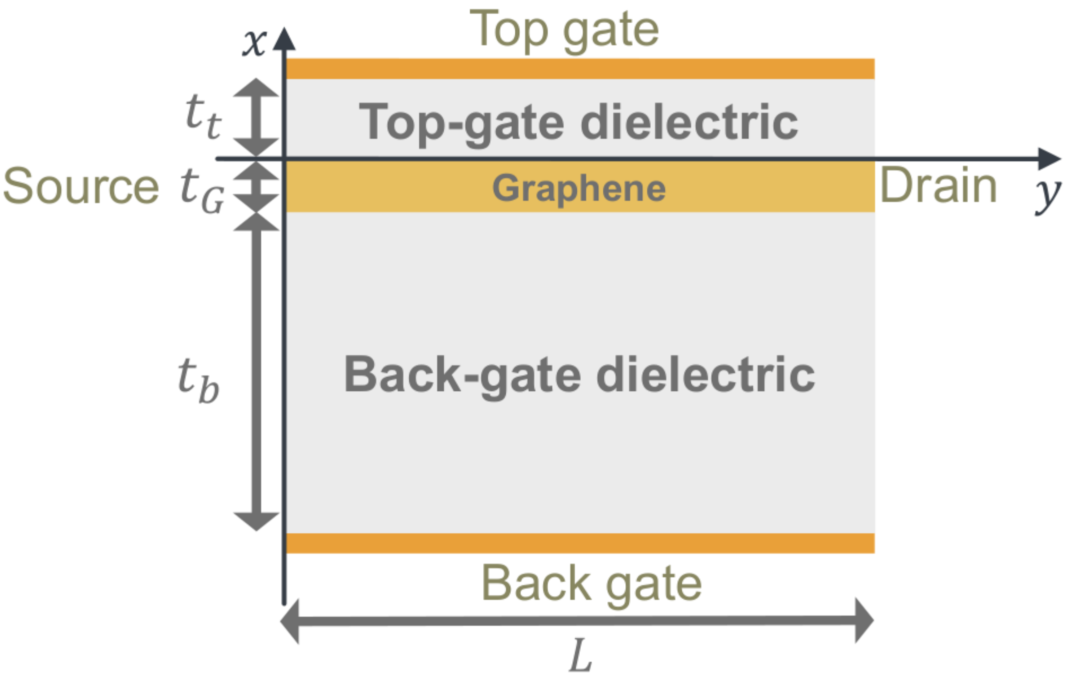
MATHEMATICAL MODEL

Mathematical model

- Poisson's equation

$$\nabla \cdot [\epsilon(x,y)\nabla\phi(x,y)] = \rho_{\mathrm{free}}(x,y)$$

$$\rho_{\mathrm{free}}(x,y) = \frac{q[p(y)-n(y)]}{t_G}$$



Boundary conditions

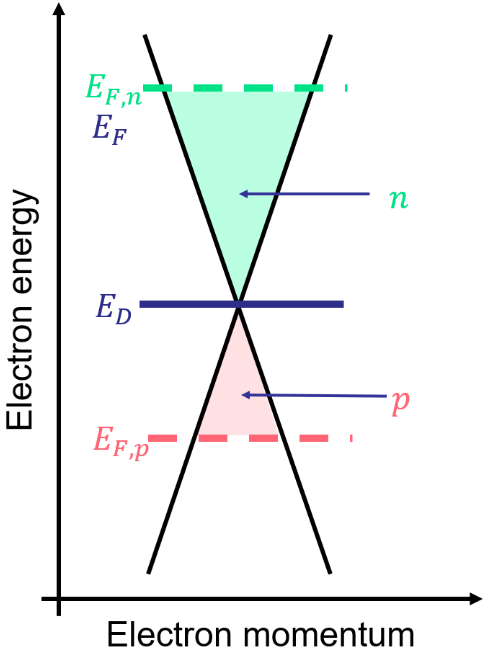
$$\phi(t_t, y) = V_G - V_{gs0}$$

$$\left.\frac{\partial\phi}{\partial y}\right|_{y=0} = \left.\frac{\partial\phi}{\partial y}\right|_{y=L} = 0$$

$$\phi(-t_G - t_b, y) = V_B - V_{bs0}$$

Mathematical model

- Carrier concentration



$$n = \sigma_0 + \frac{2}{\pi}\left(\frac{kT}{\hbar v_F}\right)^2 \mathcal{F}_1\left[\frac{E_{F,n} - E_D}{kT}\right]$$

$$p = \sigma_0 + \frac{2}{\pi}\left(\frac{kT}{\hbar v_F}\right)^2 \mathcal{F}_1\left[\frac{E_D - E_{F,p}}{kT}\right]$$

$$E_D(y) = -q\phi\left(x = -\frac{t_G}{2}, y\right).$$

Electron and hole concentrations are deduced from the linear dispersión relation and the Fermi-Dirac statistics.

Mathematical model

- Current continuity equation

$$J_n(y) = n(y)\mu_n(y)\frac{\mathrm{d}E_{F,n}(y)}{\mathrm{d}y}$$

$$J_p(y) = p(y)\mu_p(y)\frac{\mathrm{d}E_{F,p}(y)}{\mathrm{d}y}$$

$$\frac{\mathrm{d}J_n(y)}{\mathrm{d}y} = qU(y)$$

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

$$J_{DS} = J_n(y) + J_p(y)$$

$$\mu_n(y) = \mu_p(y) = \mu(y) = \frac{\mu_{LF}}{\sqrt[\beta]{1 + \left(\frac{\mu_{LF}}{v_{\mathrm{sat}}}\left|-\frac{\partial \phi}{\partial y}\right|_{x=-\frac{t_G}{2}}\right|\right)^{\beta}}}$$

Boundary conditions

$$E_{F,n}(L) = E_{F,p}(L) = -qV_D$$

$$E_{F,n}(0) = E_{F,p}(0) = -qV_S$$

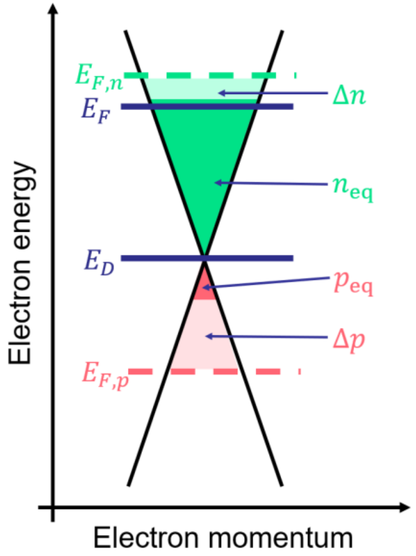
Our model solves self-consistently Poisson’s equation and current continuity.

Mathematical model

- Recombination model

$$\frac{\mathrm{d}J_n}{\mathrm{d}y} = -\frac{\mathrm{d}J_p}{\mathrm{d}y} = qU$$

$$U = \frac{\partial\,\Delta n}{\partial t} = \frac{\partial\,\Delta p}{\partial t} = -\frac{\Delta n}{\tau} = -\frac{n - n_{\mathrm{eq}}}{\tau}$$



We consider band-to-band recombinations and charge neutrality.

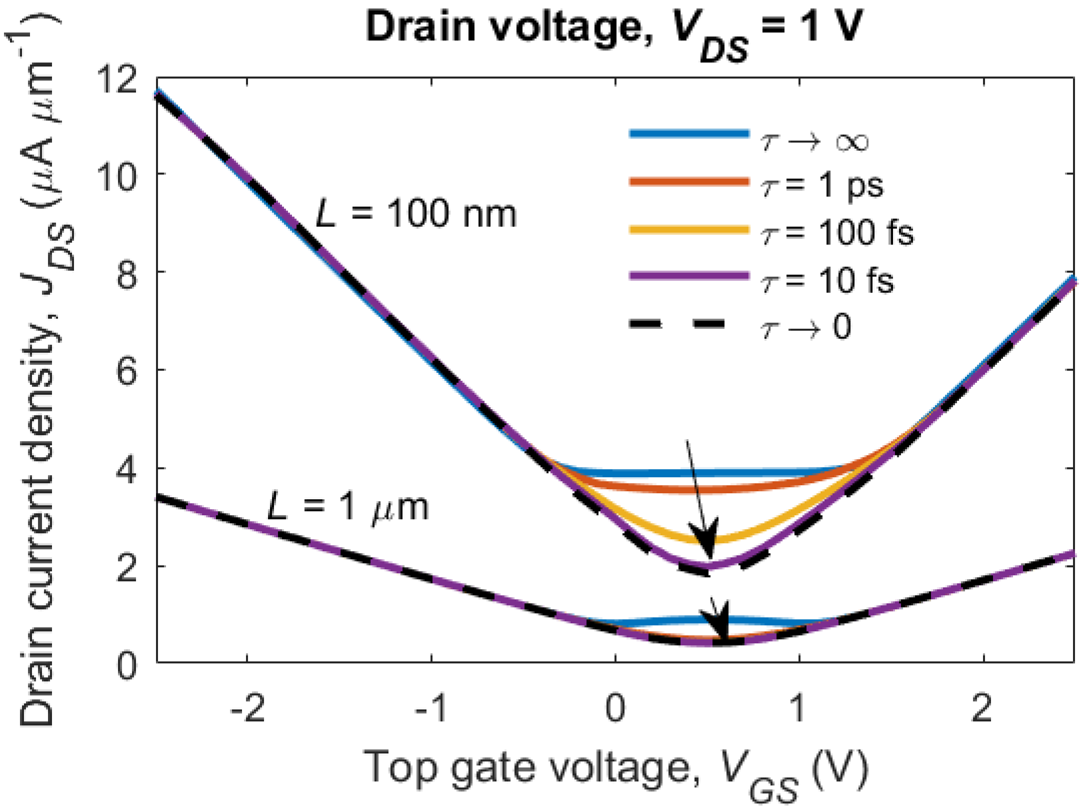
$$U \propto -\Delta n \qquad \Delta p \approx \Delta n$$

$$U = -\frac{n - n_{\mathrm{eq}}(n, p, E_D)}{\tau}$$

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

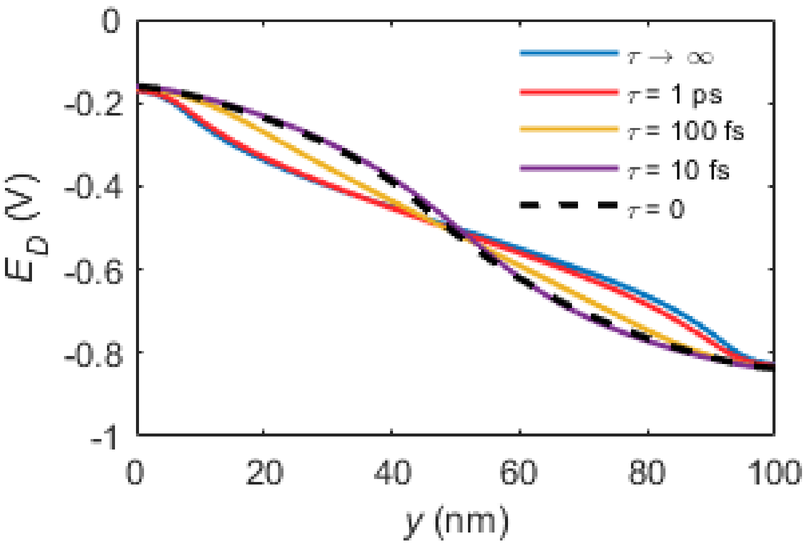
RESULTS

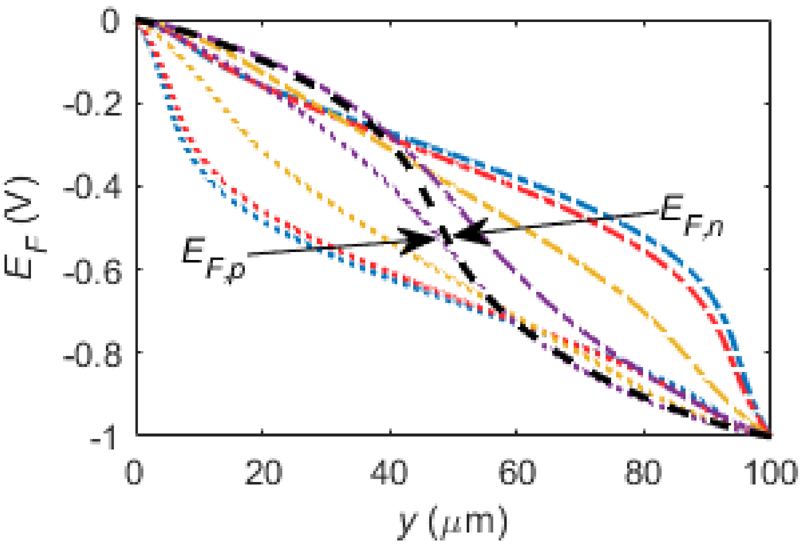
Transfer curves

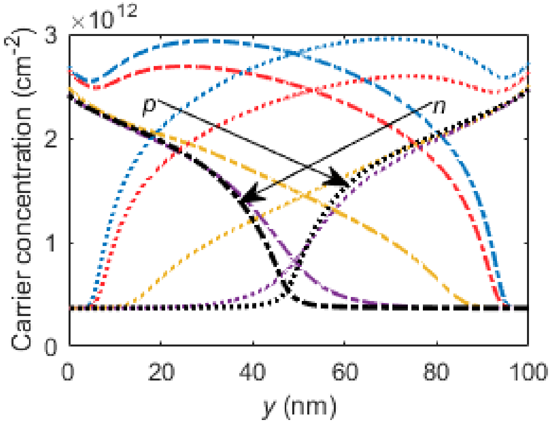


Recombination mainly affects at biases close to Dirac point.

Dirac point:
$V_{GS} = 0.5\ \mathrm{V};\ V_{DS} = 1\ \mathrm{V}$

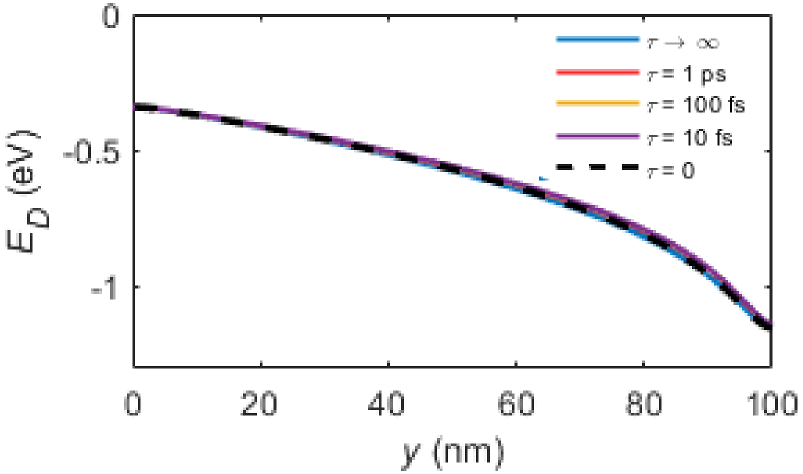


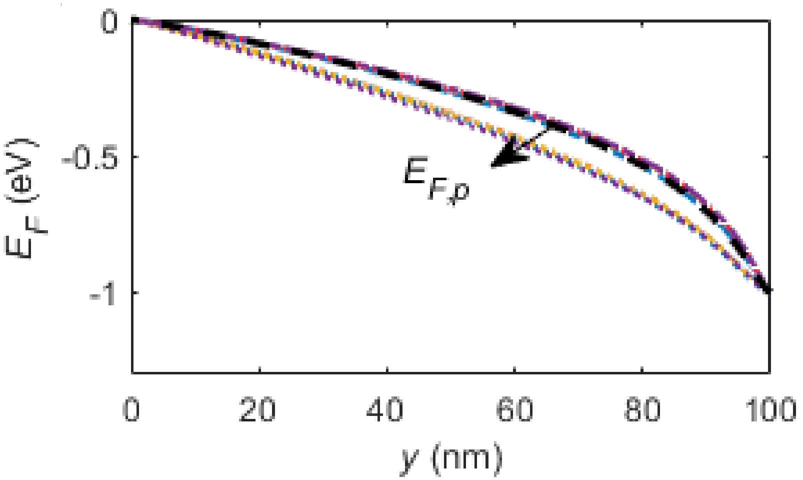




$L = 100\ \mathrm{nm}$

Far from Dirac point:
$V_{GS} = 2\text{ V};\ V_{DS} = 1\text{ V}$



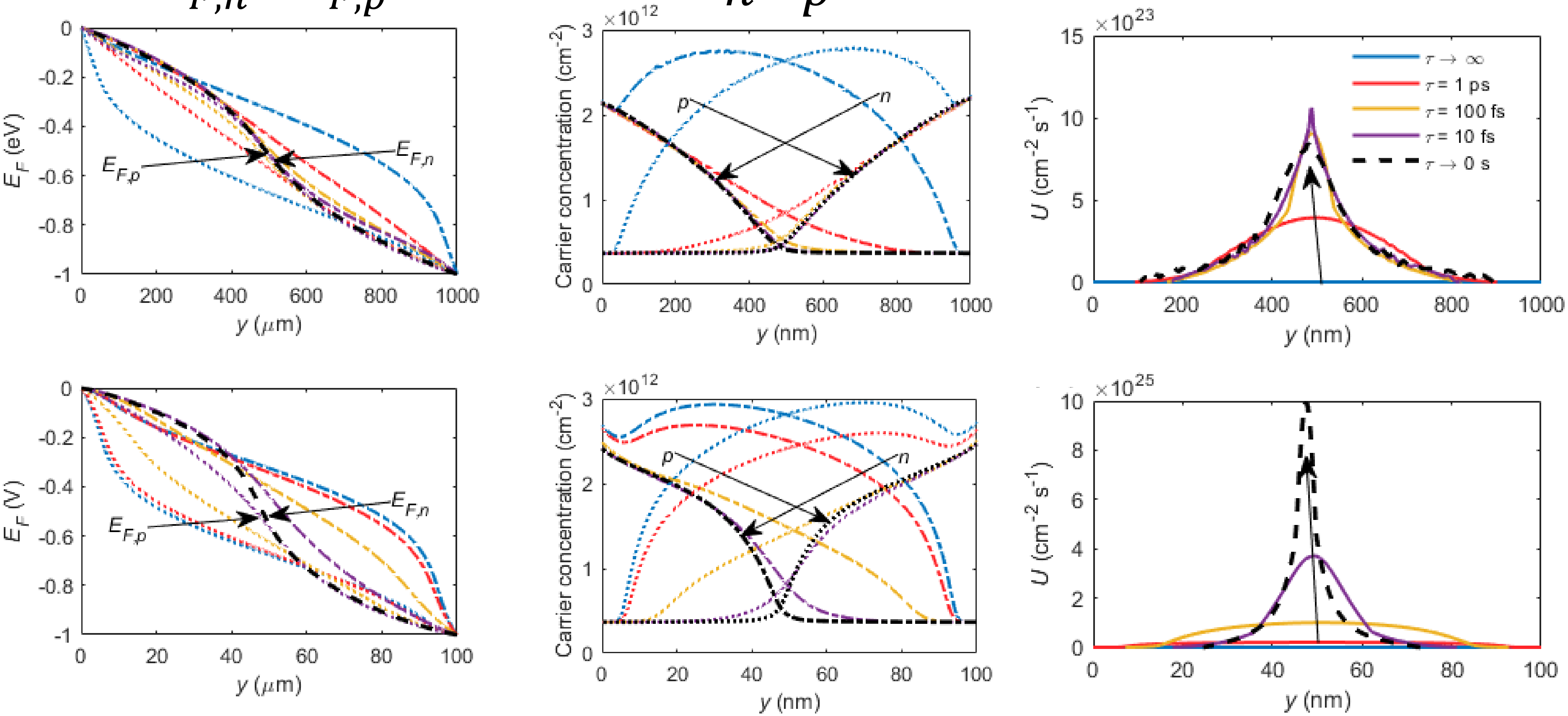


$L = 100\text{ nm}$

Different channel lengths

$L = 1\ \mu\text{m}$

$E_{F,n}$ $E_{F,p}$ n p U



$L = 100\ \text{nm}$

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

CONCLUSIONS

Conclusions

- Effect of recombination in GFETs. We considered band-to-band recombination with charge neutrality
- Recombination affects mainly around the Dirac bias, where charge transport is ambipolar
- For a 100 nm channel,
  - $\tau < 10\text{ fs} \rightarrow$ single quasi-Fermi level approximation ($\tau \rightarrow 0\ s$)
  - $\tau > 1\text{ ps} \rightarrow$ null recombination rate ($U = 0$)
- These limits are larger for longer channels

Acknowledgements

- **European Union**’s Horizon 2020 Research and Innovation Programme under Grant Agreement No. GrapheneCore3 881603.
- **Spanish Government** under the project RTI2018-097876-B-C21 (MCIU/AEI/FEDER, UE)
- European Union Regional Development Fund within the framework of the ERDF Operational Program of Catalonia 2014–2020 with the support of the ***Departament de Recerca i Universitat***, with a grant of 50% of total cost eligible. GraphCAT project reference: 001-P-001702.

Thanks for your attention!