Mesoscopic Schwinger effect in ballistic graphene transistors

Bernard Plaçais[1]
Aurélien Schmitt[1], Pierre Vallet[2], Takashi Taniguchi[3], Kenji Watanabe[3], Jean-Marc Berroir[1], Erwann Bocquillon[1,4], Gwendal Fève[1], Christophe Voisin[1], Mark-Oliver Goerbig[5], Jérôme Cayssol[2,1], Jan Troost[1], Emmanuel Baudin[1]

1 *Laboratoire de Physique de l'Ecole normale supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université de Paris, 24 rue Lhomond, 75005 Paris, France.*
2 *Laboratoire Ondes et Matière d'aquitaine, 351 cours de la libération, 33405 Talence, France*
3 *Advanced Materials Laboratory, NIMS, Tsukuba, Ibaraki 305-0047, Japan*
4 *II. Physikalisches Institut, Universität zu Köln, Zülpicher Strasse 77, 50937 Köln*
5 *Laboratoire de Physique des Solides, CNRS, Université Paris-Saclay, F-91405 Orsay, France*

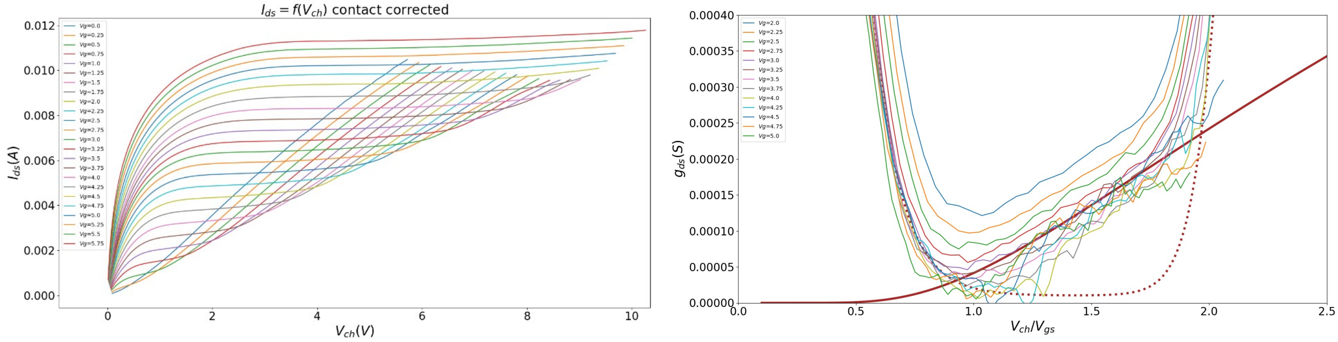
bernard.placais@phys.ens.fr

Vacuum breakdown by particle-antiparticle pair creation in a strong electric field, introduced by Sauter [1] and Schwinger [2], is a basic non-perturbative prediction of quantum electro-dynamics (QED). Its demonstration remains however elusive as Schwinger fields, $E_S = m^2c^3/e\hbar$, are beyond reach even for the light electron-positron pairs. Here we put a mesoscopic variant of Schwinger-effect to test in graphene, which hosts massless Dirac fermions with electron-hole symmetry. Using DC transport and RF noise, we report on universal 1d-Schwinger conductance at the pinch-off of long, hBN-encapsulated, graphene transistors [3]. In ballistic transistors the pinch-off electric fields are confined in a Klein junction of length λ~0.1µm at the transistor drain, inducing giant Klein-collimation at high bias and a transport gap set by the Fermi energy. They confer an apparent mass to Dirac fermions, leading to a Schwinger breakdown voltage, $V_S = E_S\lambda$, reaching pinch-off bias at large doping, while remaining smaller than the Pauli-blocked onset of Zener transport [4]. The ensuing Schwinger electron-hole conductance is measured in quantitative agreement with prediction (Figure). The mesoscopic Schwinger effect not only gives clues to current saturation limits in graphene electronics, but also opens new routes for QED experiments in the laboratory.

References

[1] F. Sauter, Z. Phys. 69 (1931) 742.
[2] J. S. Schwinger, Phys. Rev. 82 (1951) 664.
[3] A. Schmitt et al., (2022), in preparation
[4] W. Yang et al., Nature Nanotechnol. 13 (2018) 47.

Figure



Left: Current saturation by giant Klein collimation in a LxW=15x10µm, hBN-encapsulated, ballistic graphene transistor with a graphite gate. Gate voltages V_{gs} correspond to Fermi energies distributed in the range $0 \leq \mu \leq 0.2$eV. Ballistic pinch-off, at bias voltage $V_{ch}=V_{gs}$, is followed by a transition toward an ohmic Zener regime (conductivity σ_Z~1mS), which onset is rejected, by efficient Pauli blocking in long transistors, at twice the pinch-off voltage. **Right:** differential conductance scaling $g_{ds}(V_{ch}/V_{gs})$. It highlights the Klein-collimation, with a giant conductance suppression $g(1.5) \leq g(0)/5000$~1µS, leading to a broad conductance gap in the $V_{gs} \leq V_{ch} \leq 2V_{gs}$ range (dotted line) within which the Schwinger conductance, $g_S(x=V_{ch}/V_S) \approx 16e^2/\pi h \times (1.523x-0.943)$, is observed (solid line). Schwinger formula is fitted here to the V_{gs}=3.25V data for an onset at $V_{ch} \equiv 0.619V_S \approx 0.87V_{gs}$. Universality lies in the observation of a doping- and sample-independent zero-bias extrapolate of the linear dependence at $g_0 \approx$-0.18 mS.