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10 ANNIVERSARY

Phase Dependent Quantum Dynamics of Andreev States in a Ballistic Graphene-based Josephson Junction

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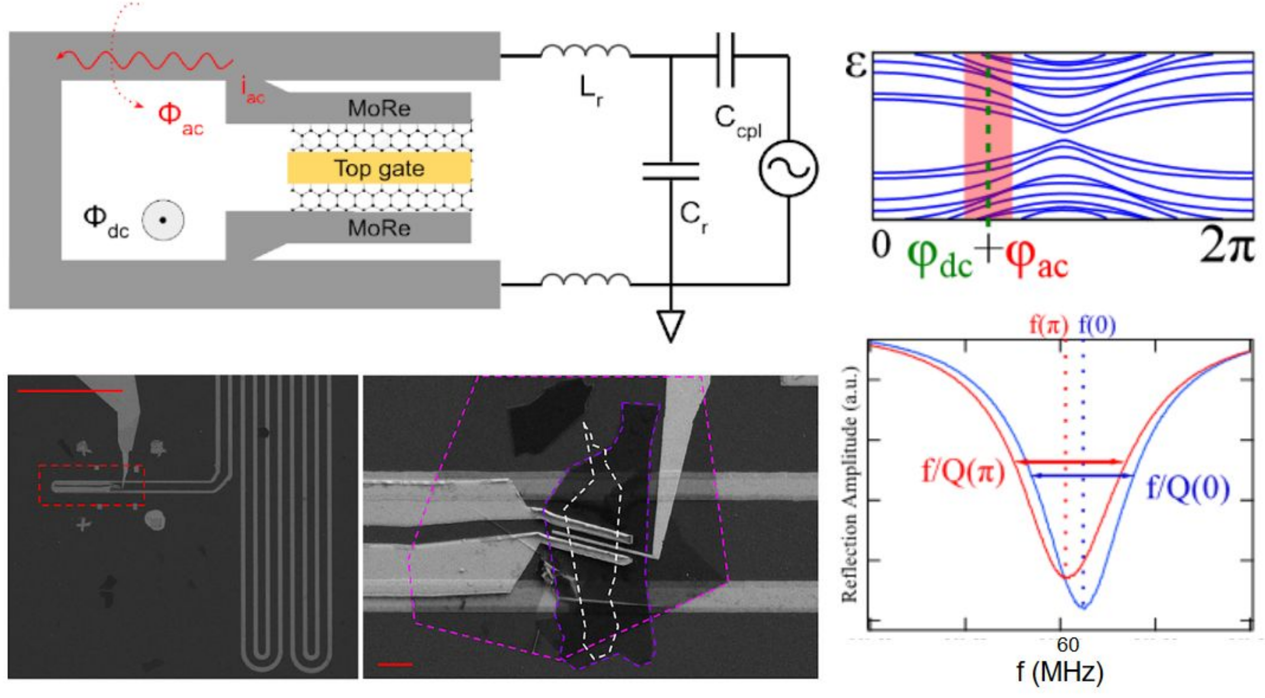
Introduction: A constant phase difference (φ) between two superconductors coupled by a weak link leads to a dissipationless supercurrent periodic in φ. The exact current-phase relation (CPR) is closely related to the Andreev bound states (ABSs) in the weak link, and measuring it is in itself a feat which has in the recent past revealed the ballistic transport in graphene [1,2] and topological materials [3,4]. If φ acquires a time-dependent ac component (δφ), the dynamics of ABSs causes delay in the current response and consequently a counter-intuitive dissipation [5]. Besides the equilibrium CPR, these dynamical responses can shed further light on the properties of the Andreev levels such as the topologically protected level crossings in a SNS junction based on topological materials [6]. While the previous work focuses on the weakly driven regime ($\delta\varphi \ll 2\pi$), a strong driving power can significantly modify the distribution function from the thermal equilibrium [7,8]. Here we present a systematic study of CPRs and the dynamical dissipations over the complete phase range under different drive frequencies and powers.

1 Susceptibility measurement



Setup: (a) The SNS is coupled to a superconducting resonator (L_r and C_r) with resonance frequency f_0 = 60 MHz. The coupling inductance from the ring L_r = 355 pH. (b) The graphene flake is encapsulated by BN and the junction W = 5 μm and L = 950 nm (only 330 nm covered by gate).

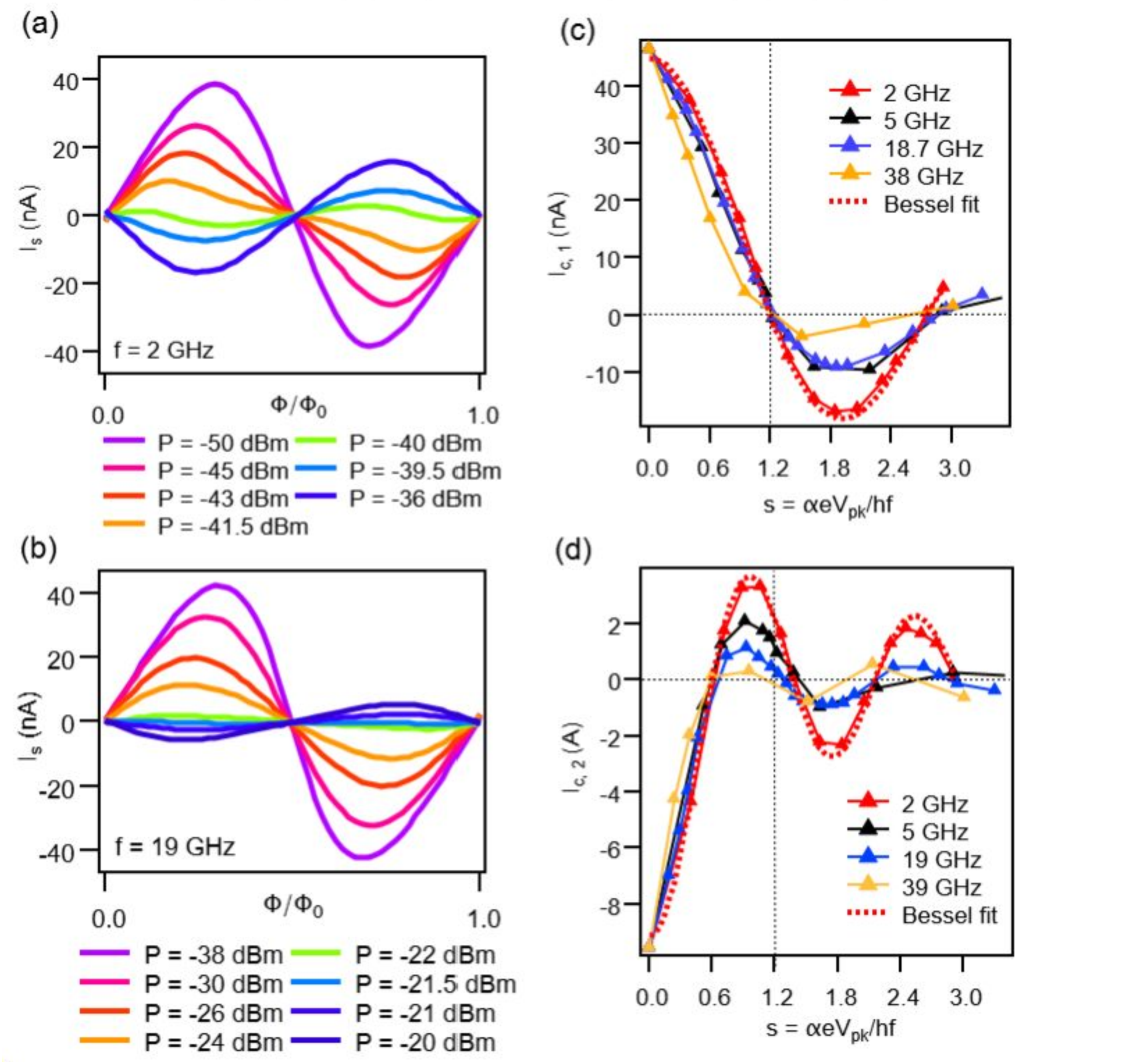
Principles [5]: (c) The SNS junction is phase biased by a dc flux modulated by a small ac flux from the resonator. The current response is the susceptibility

$$\chi = \delta i_{ac}/\delta\Phi_{ac} = (2\pi/\Phi_0)\delta i_{ac}/\delta\varphi$$

(d) The in-phase/out-of-phase components (χ' and χ'') is related to the resonance frequency and the quality factor of the resonator:

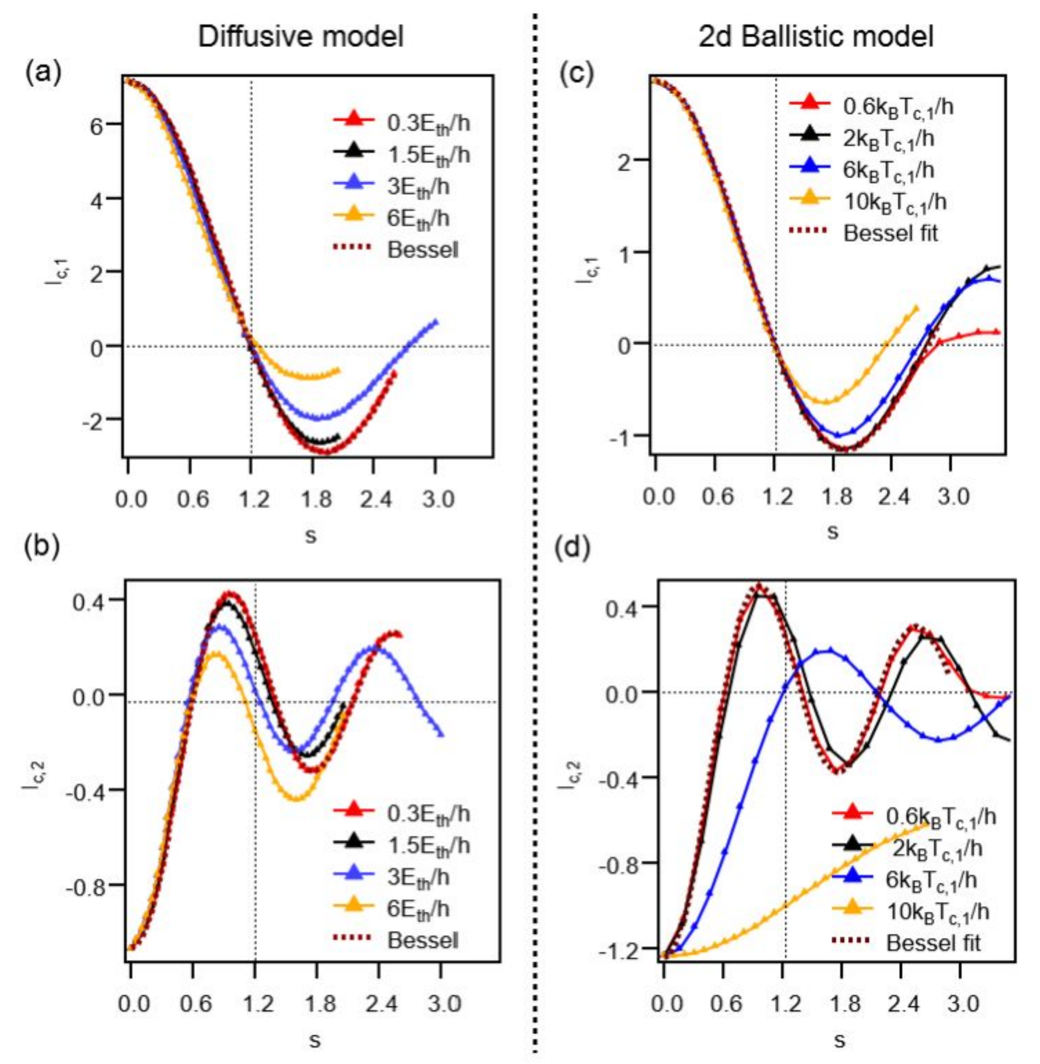
$$-2\frac{\delta f}{f} = \frac{L_c^2}{L_r}\chi' \qquad \delta\left(\frac{1}{Q}\right) = \frac{L_c^2}{L_r}\chi''$$

3 Measured CPR with irradiation



(a) CPR (T = 12mK) at f_{irrad} = 2 GHz and (b) at f_{irrad} = 19 GHz (c) First CPR harmonic $I_{c,1}$ against the normalised power s for different F. (d) Second CPR harmonic $I_{c,2}$ against s (the peak voltage V_{pk} of the irradiation normalised by f_{irrad})The lowest frequency curve (2 GHz) can be fitted to the Bessel function corresponding to the adiabatic ac Josephson effect.

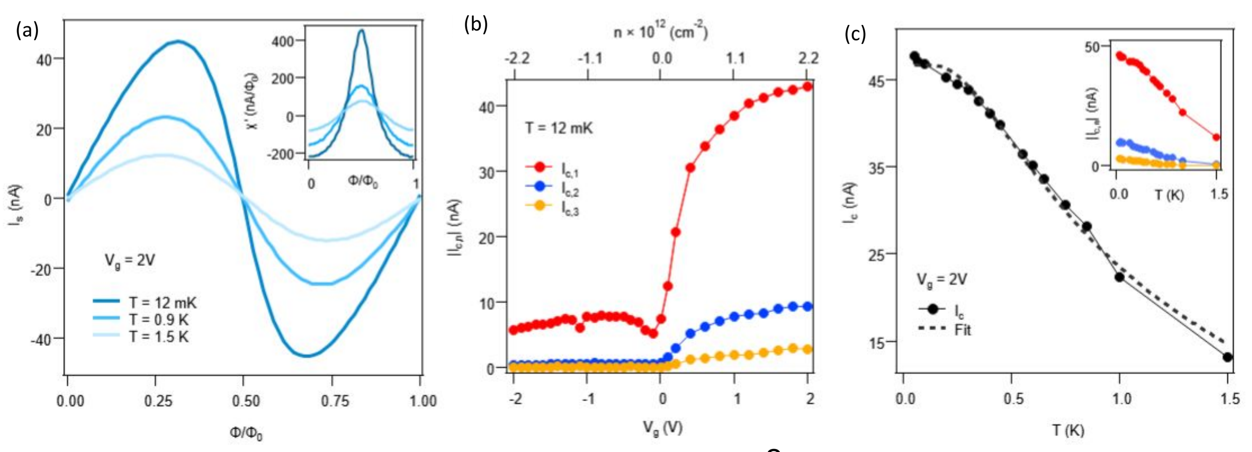
Green's function calculation



Diffusive:(a) and (b) the CPR harmonics $I_{c,1}$ and $I_{c,2}$ versus s. T = 0.005E_{th}/k_B. The inelastic scattering rate Γ = 1.2E_{th}.
Ballistic:(c) and (d) $I_{c,1}$ and $I_{c,2}$ - s. T and Γ same as (a,b)

The diffusive model agrees better with data

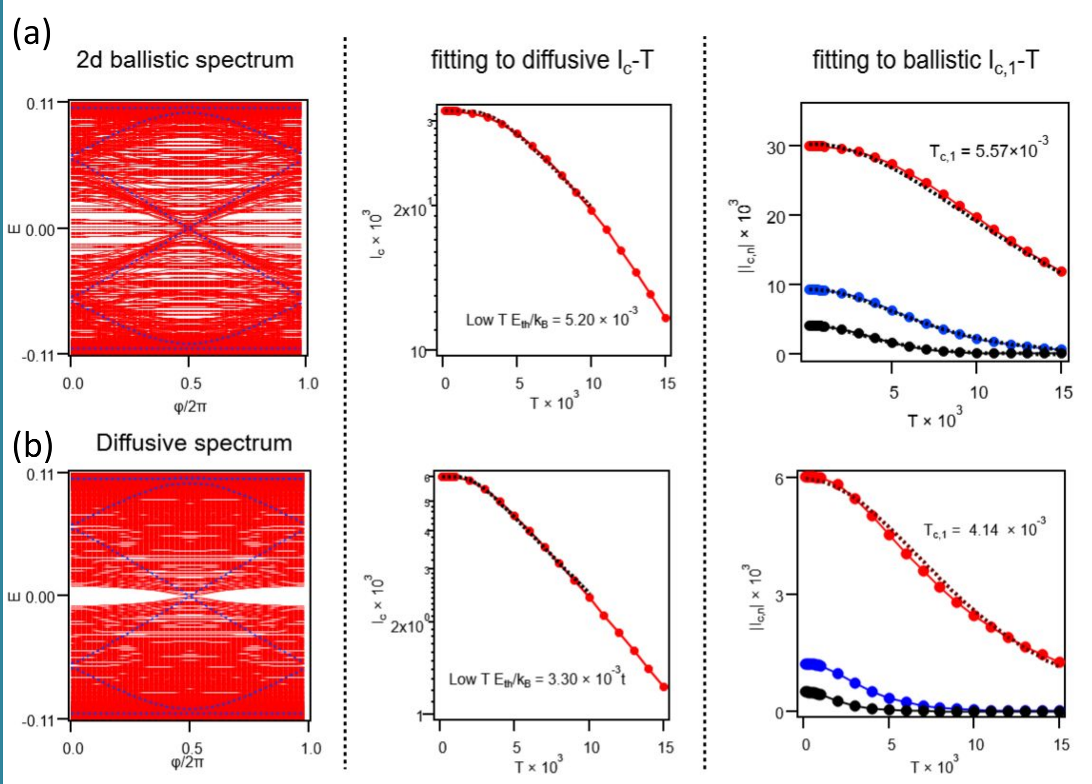
2 Measured CPR without irradiation



(a) CPR at T = 12mK, 0.9K,1.5K (by integrating χ' in the inset) (b) CPR harmonics $|I_{c,n}|$ versus gate voltage V_g. (c) critical current I_c ($|I_{c,n}|$ in inset) versus T.

Diffusive model [9]: $E_{th}/k_B = \hbar v_F l_e/2L^2$ = 400 mK. l_e ~ 100 nm.
Ballistic model [10]: $T_{c,1}$ = 450 mK. Theoretical $T_{c,1} = \hbar vF/2\pi(L+\xi)$ = 530 mK

Tight binding simulations

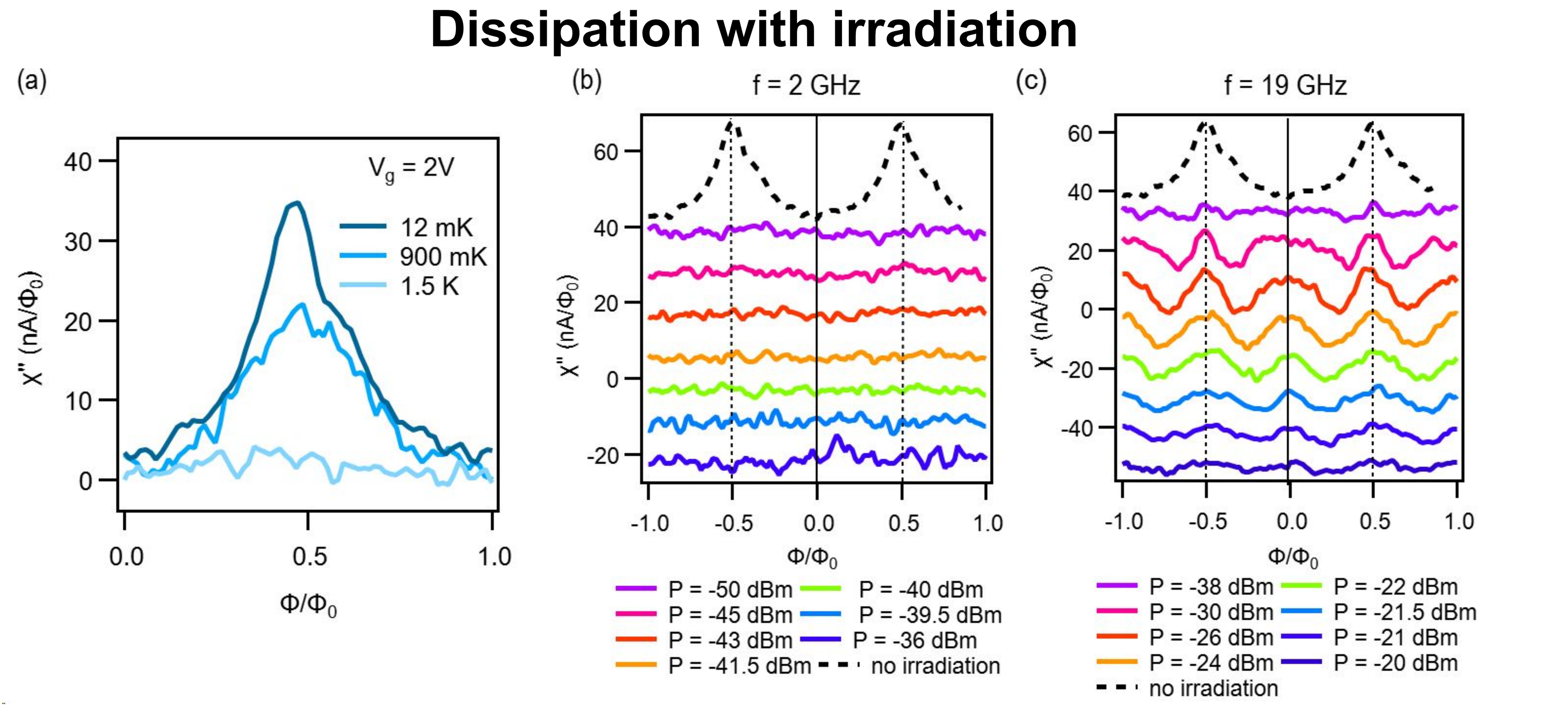


W = 120, L = 30, $\hbar v_F$ = 2.
(a) **2d ballistic** with doping inhomogeneity. (Left to right): Spectrum;I_c-T; $|I_{c,n}|$-T. By diffusive model [9]: E_{th}/k_B =0.005. By ballistic model [10]: $T_{c,1}$=0.005. (Theoretical $T_1=\hbar vF/2\pi(L+\xi)$=0.006)
(b) **diffusive** with doping inhomogeneity. By diffusive model [9]: E_{th}/k_B = 0.003t. By ballistic model [10]: $T_{c,1}$ = 0.004t. (Theoretical $E_{th} = E_g/6.2$ = 0.003t)

Blue dashed lines: 1d ballistic spectrum

Both ballistic and the diffusive model yield similar and reasonable energy scales of the junction (~ 500 mK).
This is also the case reproduced by the tight-binding simulations.

4 Dissipation with irradiation



(a) Dissipative χ'' versus flux without irradiation at 12 mK, 0.9K and 1.5K. The peak at phase π due to higher possibility of interlevel transition as the minigap closes.
(b) χ''(Φ) with irradiation same as CPR measurement: (b) f = 2GHz. No flux dependence with higher power. (c) f = 19 GHz.

Doubling of periodicity with higher power. Only observed with F > 10 GHz.

Conclusion

1. We systematically measure the CPR and dissipation with different temperature, carrier density, irradiation frequency and power in a graphene SNS junction.
2. Comparing the tight-binding model with the unirradiated measurement, the Andreev spectrum can be approximated by the diffusive model but with a soft minigap, in agreement with previous works [11]. The Thouless energy of the junction as 34 μeV (400 mK or 8 GHz).
3. From the Green's function calculation of the irradiated junction, the CPR harmonics evolution with the power agrees better with the diffusive model. The departure from the Bessel function dependence with irradiation frequency higher than 5 GHz signals the onset of nonequilibrium state.
4. The nonequilibrium states manifests more clearly in dissipation as a doubled periodicity, observed only with irradiation frequency higher than 10 GHz

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REFERENCES

[1] Nanda et al. Nano Lett., 17, 6, 3396–3401 (2017)
[2] Indolese et al. Nano Lett. preprint (2020)
[3] Murani et al. Nat. Comm. 8, 15941 (2017)
[4] Li et al. Phys. Rev. Lett. 123, 026802 (2019)
[5] Dassonneville et al. Phys. Rev. B 97, 184505 (2018)
[6] Murani et al. Phys. Rev. Lett. 122, 076802 (2019)
[7] Virtanen et al. Phys. Rev. Lett. 93, 247005 (2010)
[8] Basset et al. Phys. Rev. Research 1, 032009(R) (2019)
[9] Dubos et al. Phys. Rev. B 63, 064502 (2001)
[10] Cayssol et al. Phys. Rev. B 67, 184508 (2003)
[11] Bretheau et al. Nat. Phys. 13, 756–760 (2017)