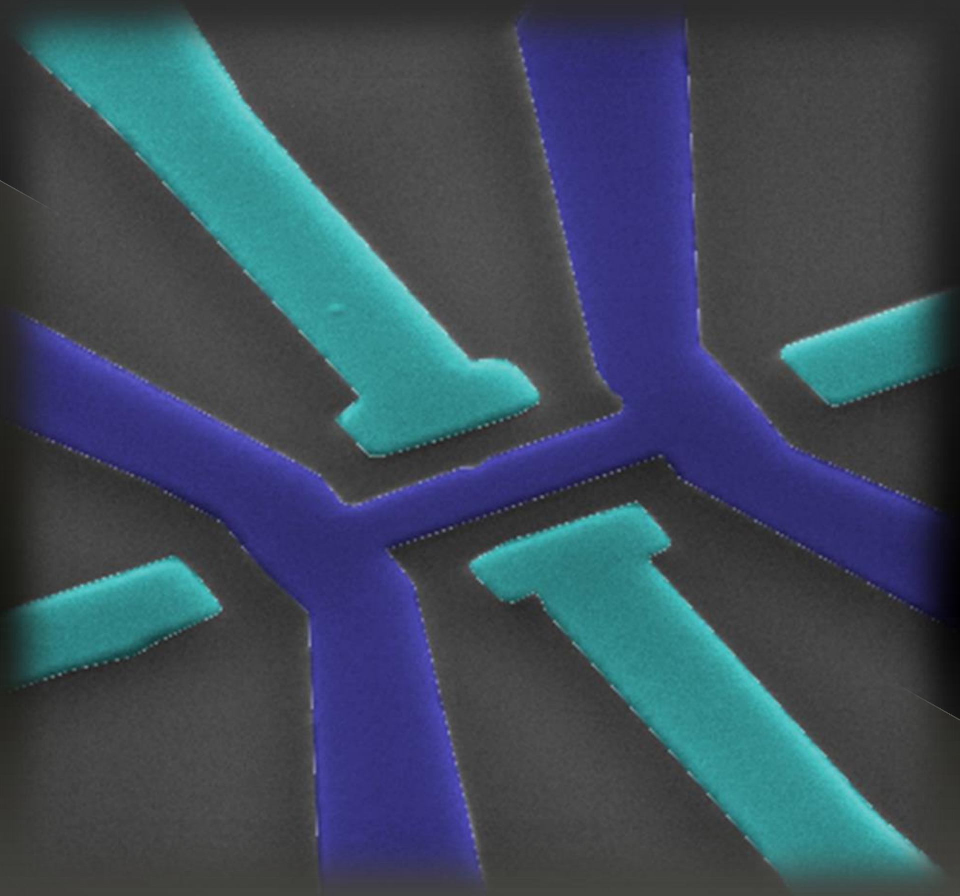
Can the electrostatic field affect a superconductor?



Claudio Puglia

Dipartimento di Fisica dell'Università di Pisa, Pisa, Italy

Ph.D. seminar

September 16, 2019

superconducting quantum electronics lab

Outline

- Superconductivity in the presence of external electrostatic fields *E*: what is known
- The BCS supercurrent field-effect transistor: Aluminium and Titanium devices
- **Towards the 4K barrier: a Vanadium device**
- **Exploring a new type of junction: Superconductor/Normal metal/Superconductor (SNS)**
- **Stochastic behaviour of the switching current**
- **How change the Switching Current Probability Distributions (SCPD) with the electric field?**
- **Perspectives & conclusions**

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Superconductivity in the presence of electrostatic fields $\boldsymbol{E}$

- London brothers (1935): exponential suppression of $E \rightarrow \nabla^2 \vec{E} = \frac{1}{\lambda_L} \vec{E}$
  [London & London (1935)]

- Conventional BCS predictions estimate sub-atomic electrical penetration $\equiv \lambda_{\mathrm{TF}}$
  [Larkin & Migdal (1963)]

- Recent theories: E remains localized at the surface but manifesting itself non-locally deep inside the superconductor $\sim \xi_0$ or larger
  [Jakeman *et al*. (1967); Blatter *et al*. (1996); Lipavsky *et al*. (2006)]

- So far no clue on the possibility to manipulate BCS superconductors via field-effect

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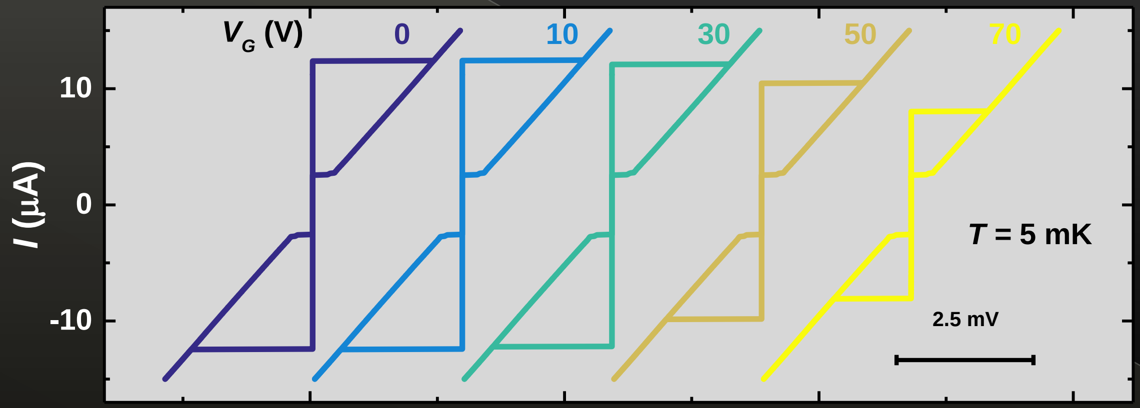
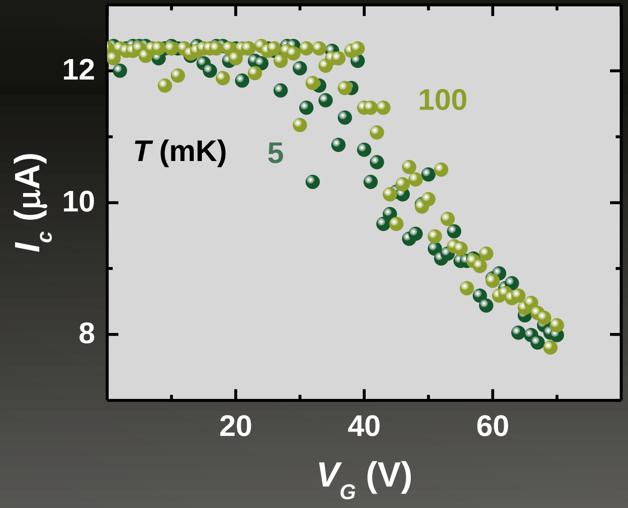
The dawn of the field-effect

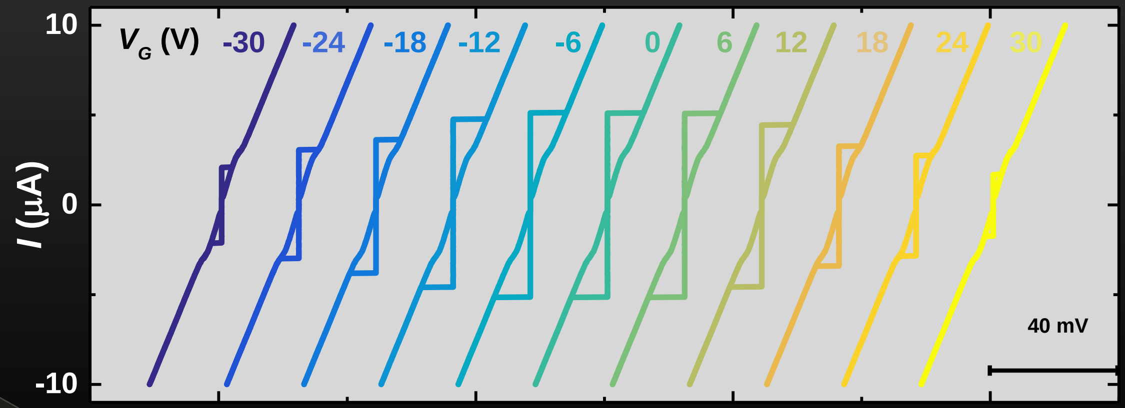
Al supercurrent FET

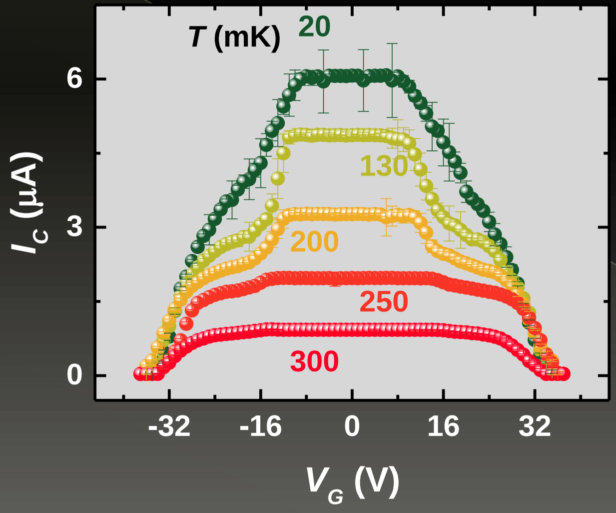


Parameters:
T_c = 1.2 K
B_c > 110 mT
V_G > 70V



Ti supercurrent FET





Parameters:
T_c = 0.34 K
B_c = 90 mT
V_G > 33 V

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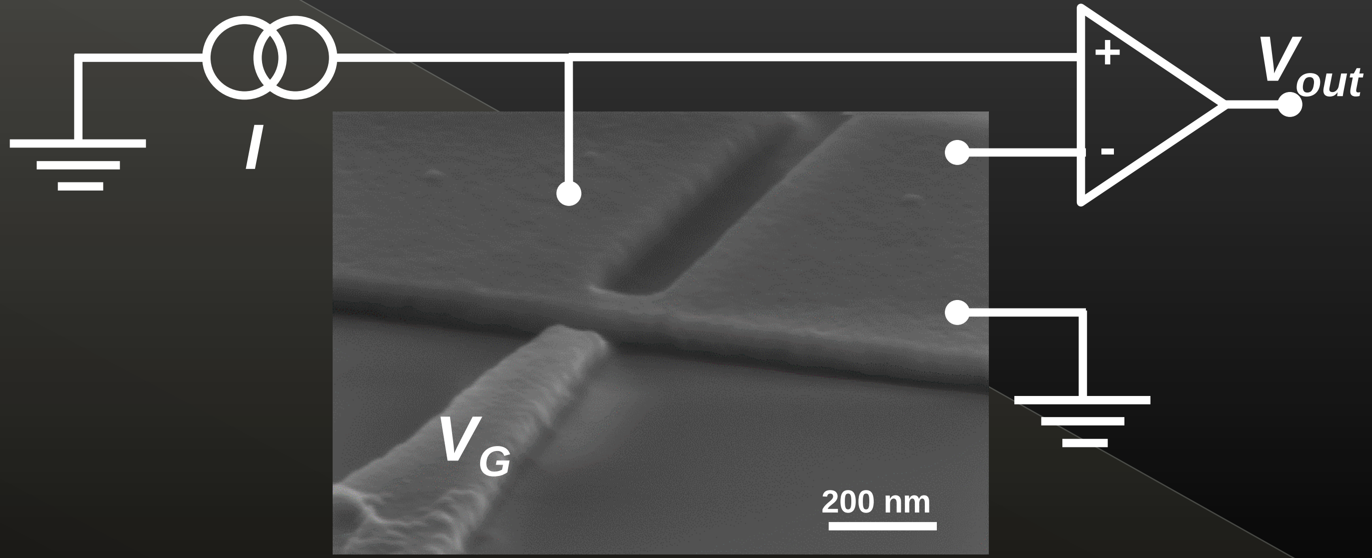
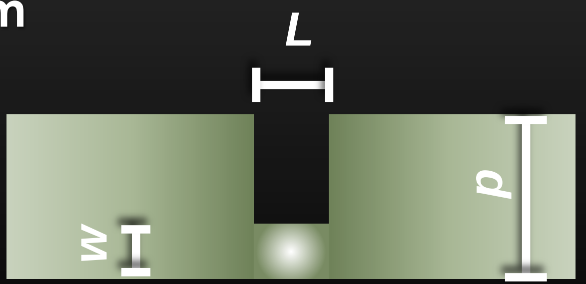
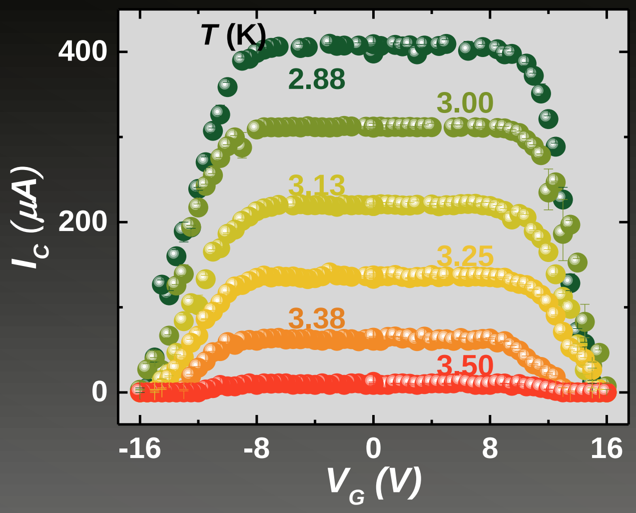
Towards the 4K barrier: vanadium

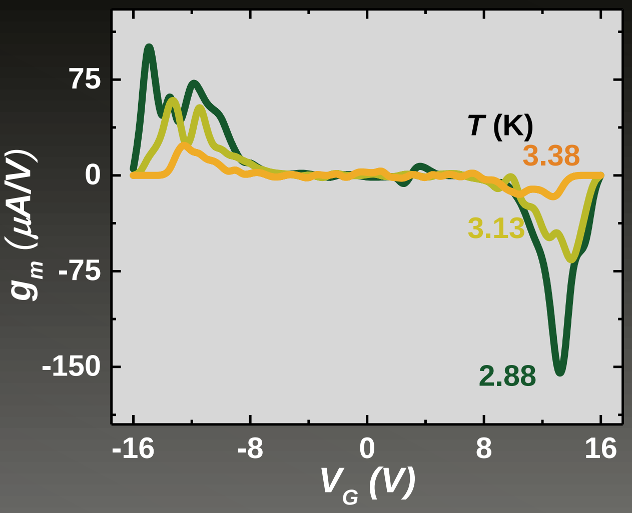


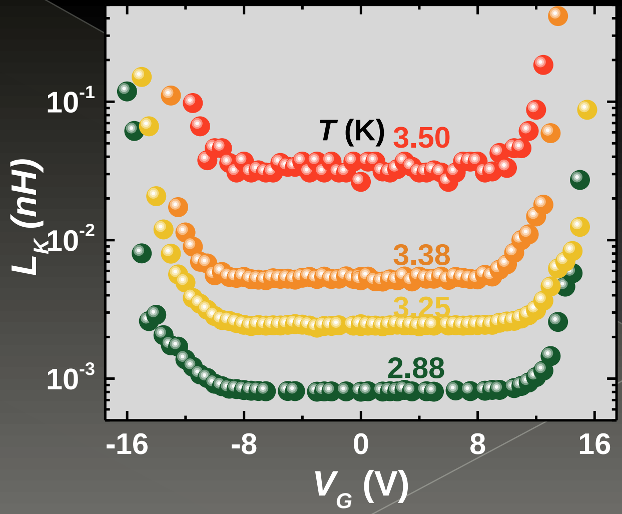
Characteristic parameters:

L = 150 nm
w = 120 nm
d = 2000 nm
T_c = 3.65 K
B_c > 1 T
R_N = 32Ω









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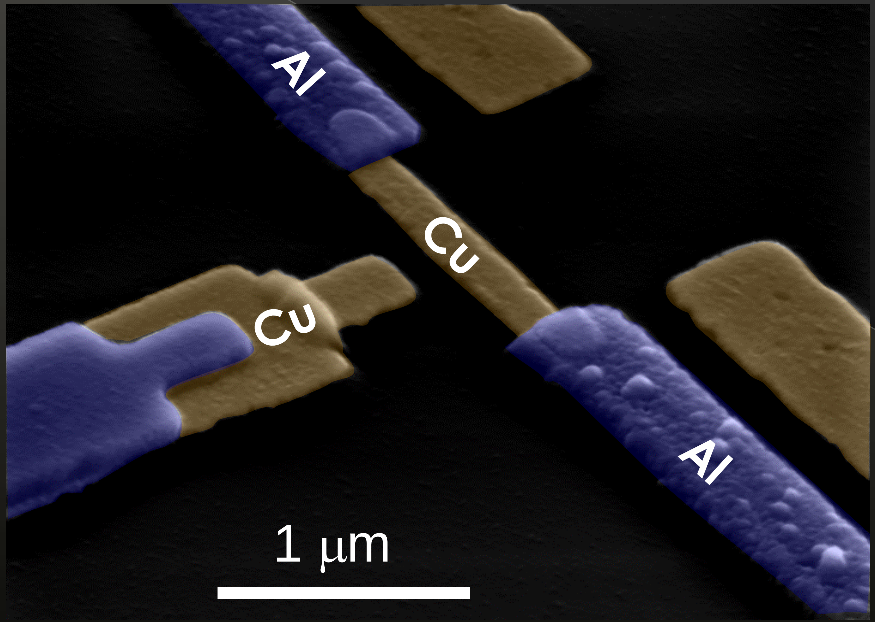
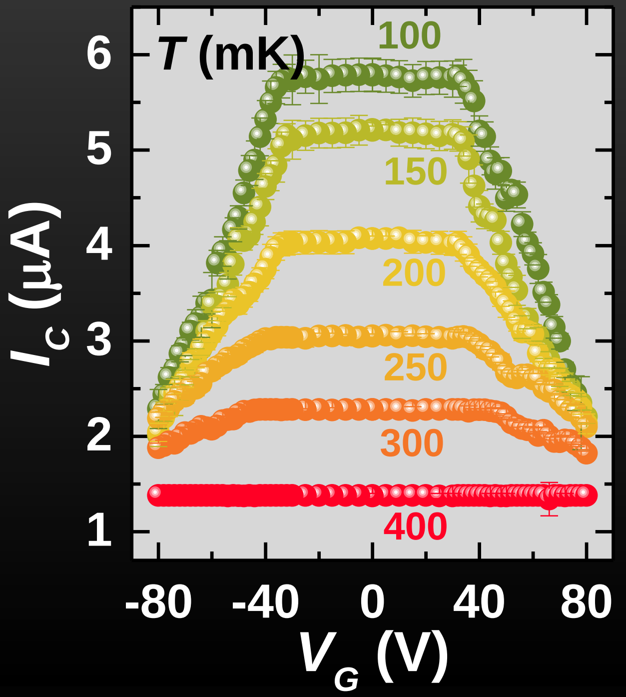
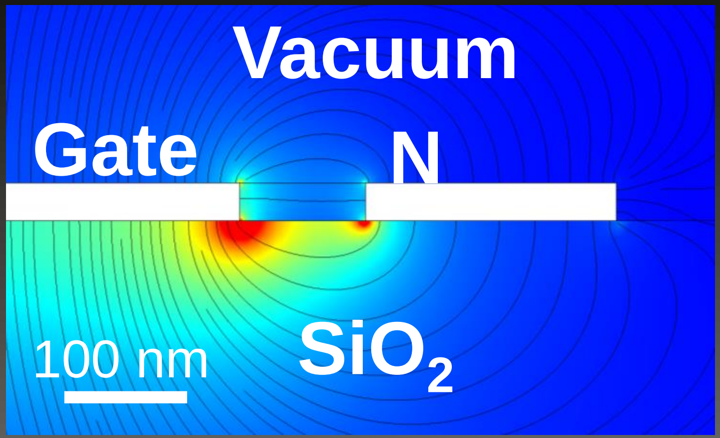
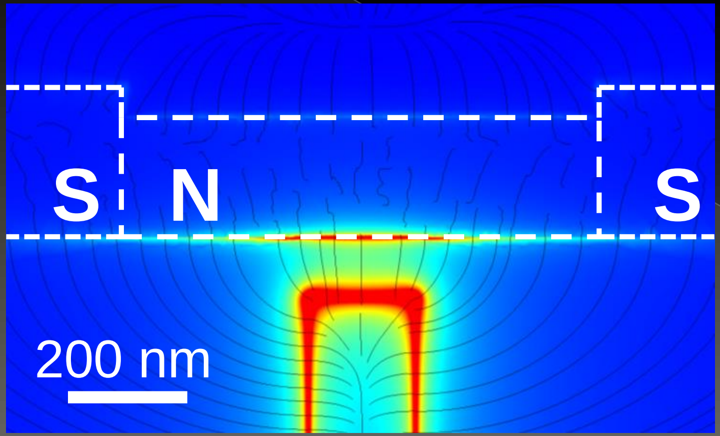
Exploring a new type of junction
Superconductor/Normal metal/Superconductor (SNS)



Characteristic parameters:
l = 1150 nm
w = 180 nm
t = 20 nm
T_c = 1.5 K
B_c = 30 mT
R_N = 10Ω







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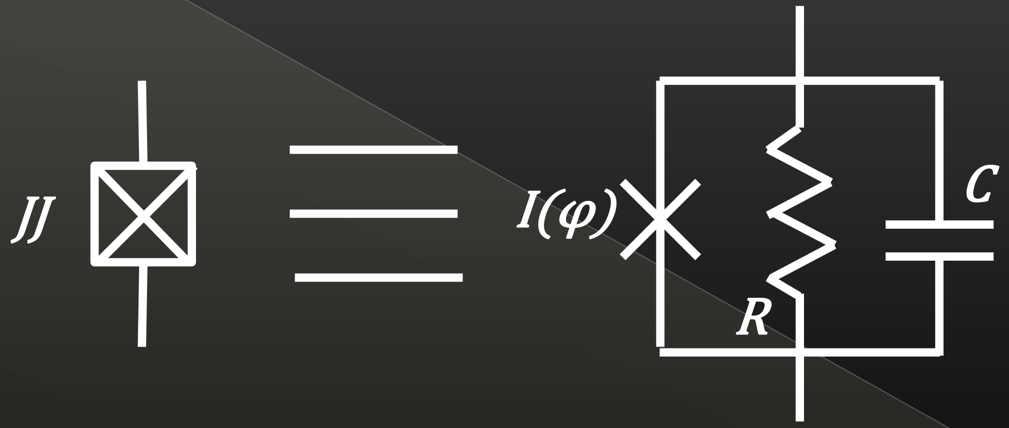
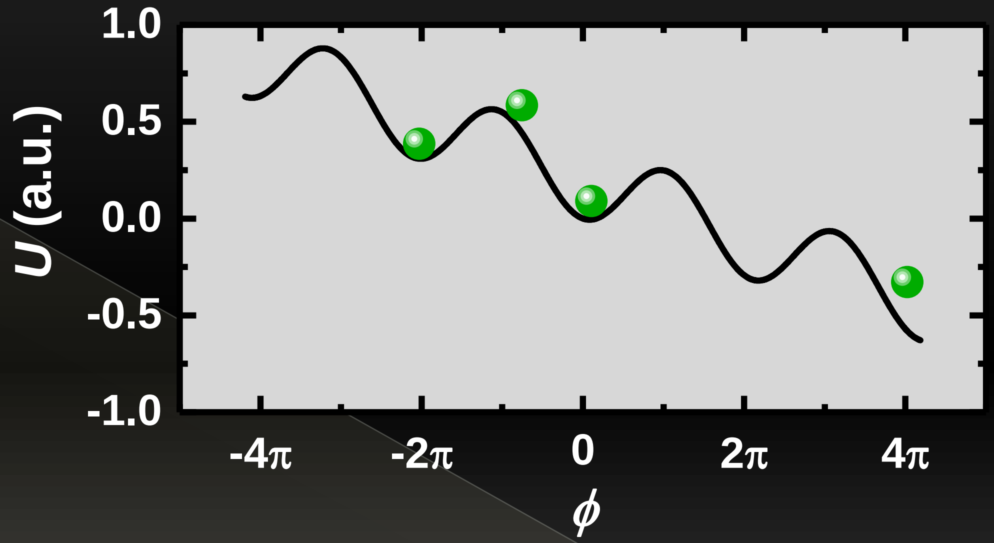
De Simoni, G.; Paolucci, F., **Puglia, C.**; Giazotto, F.; *ACS Nano* 2019,13,7, 7871-7876

Stochastic behaviour of the switching current



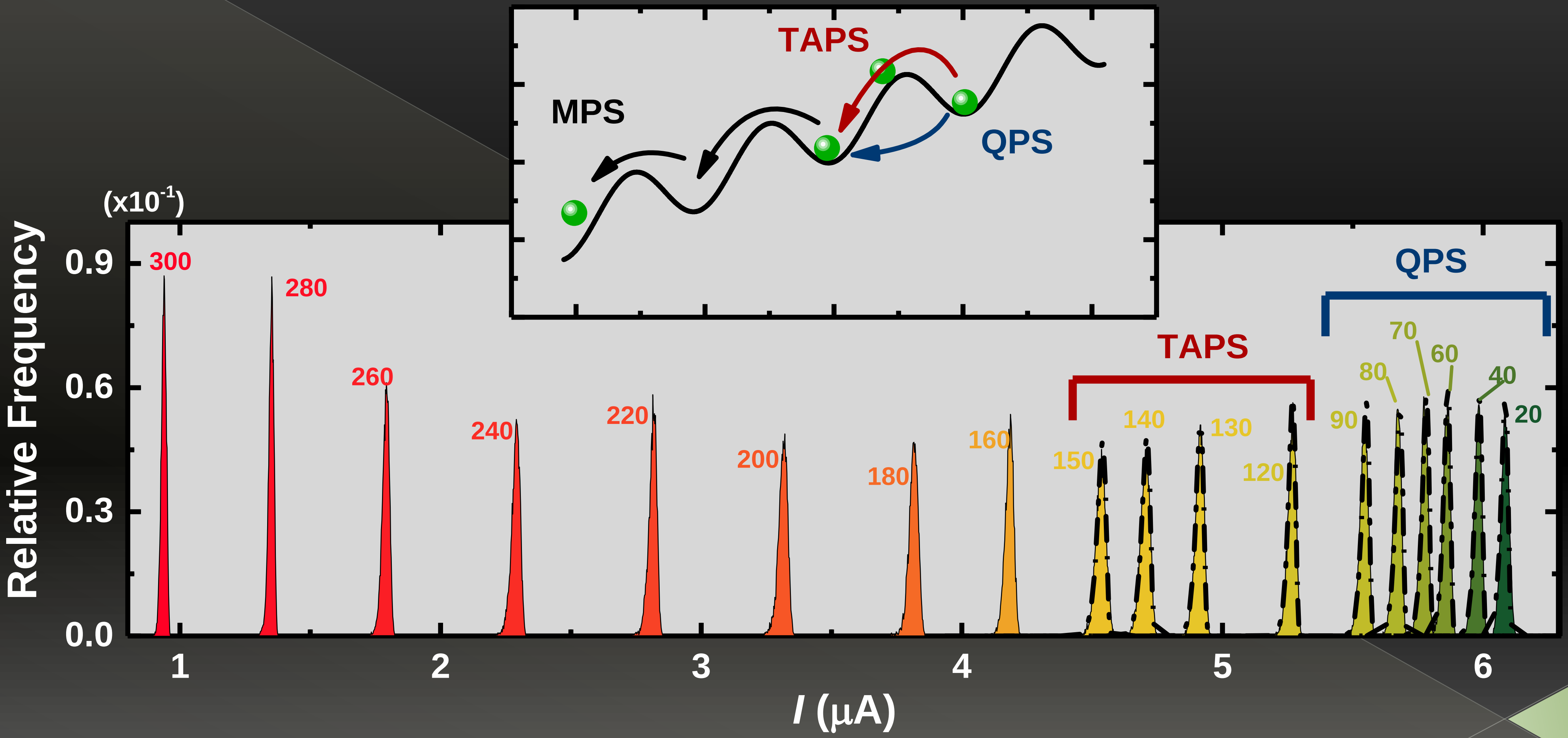
$$m_P\ddot{\phi} = -\eta\dot{\phi} - \left(\frac{I_C\hbar}{2e}\right)\sin\phi + I\frac{\hbar}{2e}$$

$$U_{WB} = E_J\left[(1-\cos\phi) - \frac{I}{I_C}\phi\right]$$



Critical current: the minimum current that has a 100% probability of switching the superconductor to its normal state.

Stochastic behaviour of the switching current: Phase Slips



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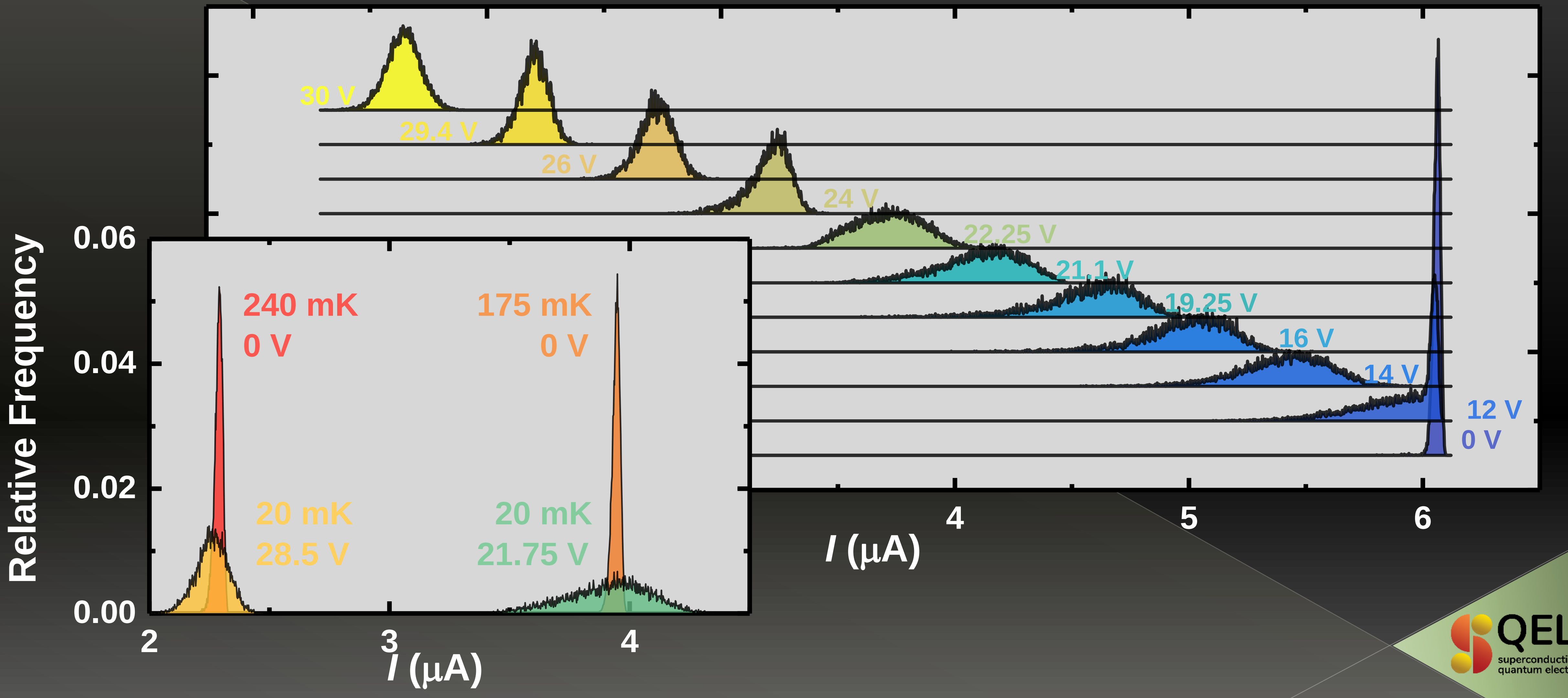
Electric field and Switching Current Probability Distributions



Ongoing & future experiments

- Detailed investigation of Nb Dayem bridge JJs (high T_C , realization of qbits)
- Investigation of thermal transport, complementary understanding of microscopic mechanisms, FE-controlled phase-coherent caloritronics (thermal transistors, etc.)
- Realization of Dayem bridge-based FE SQUIDs, impact of FE on interference, phase rigidity & phase fluctuations induced by EFs
- Spectroscopy (SSQUID, SGM, STM) to investigate this possible inhomogeneous state
- “Advanced” electronic devices: flip-flop, logic gate (NOT, AND etc.)

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Conclusions

- Demonstrated for the first time FE on films made by different BCS superconductors (Al, Ti, V)
- FE is present in fully-superconducting & proximized N metals
- Study of the stochastic behaviour of the switching current in a Dayem bridge device
- Observation of the field-effect on switching current probability distributions
- Quantum information architectures based on JoFETs (i.e., metallic gatemons)
- Remarkable tool to envision novel-concept devices: tunable weak links, interferometers, SP detectors, Coulombic & phase-coherent caloritronic structures

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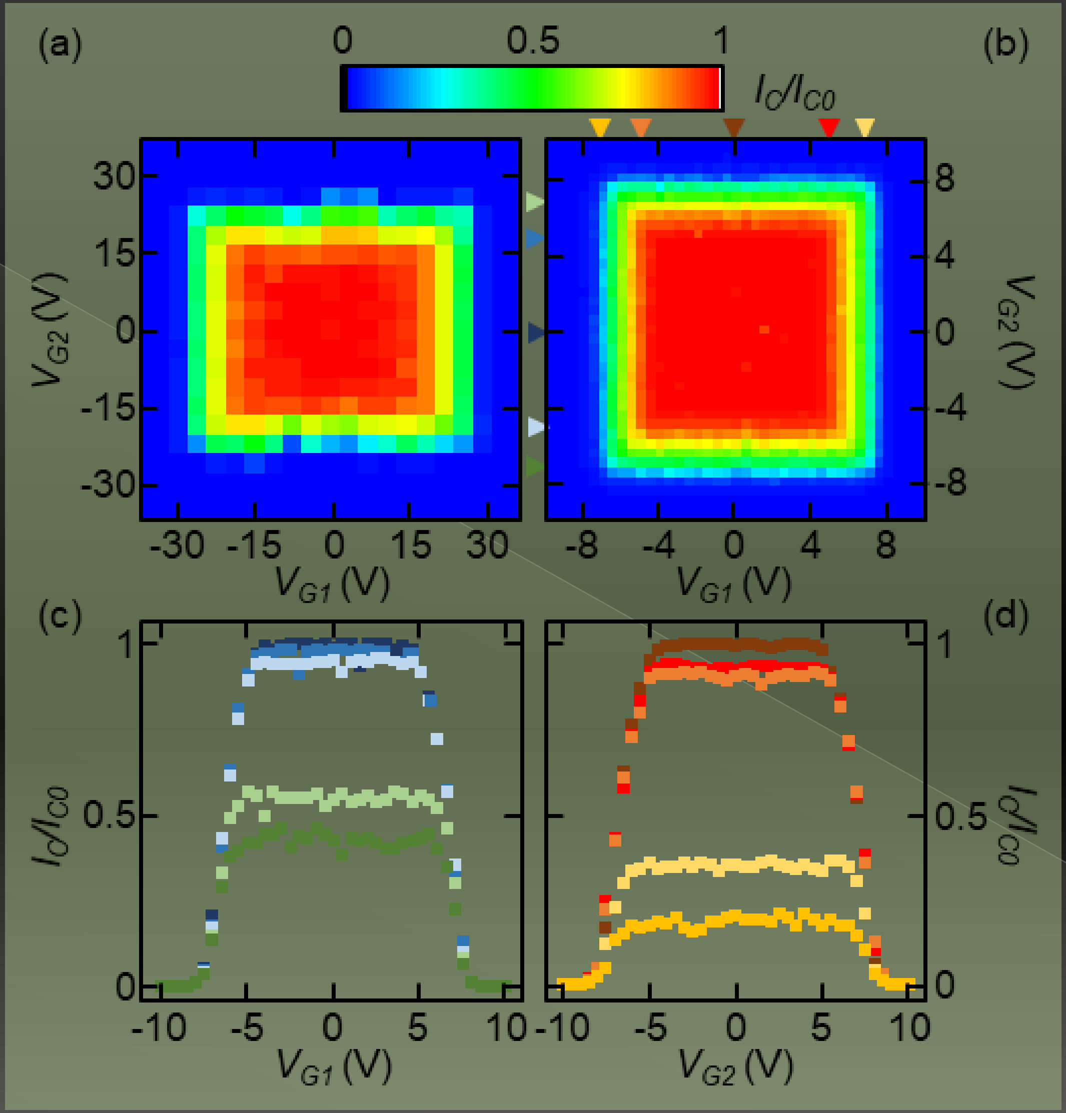
Manifestation of bipolarity

Almost perfect bipolarity



Threshold gate voltages seem to be completely independent

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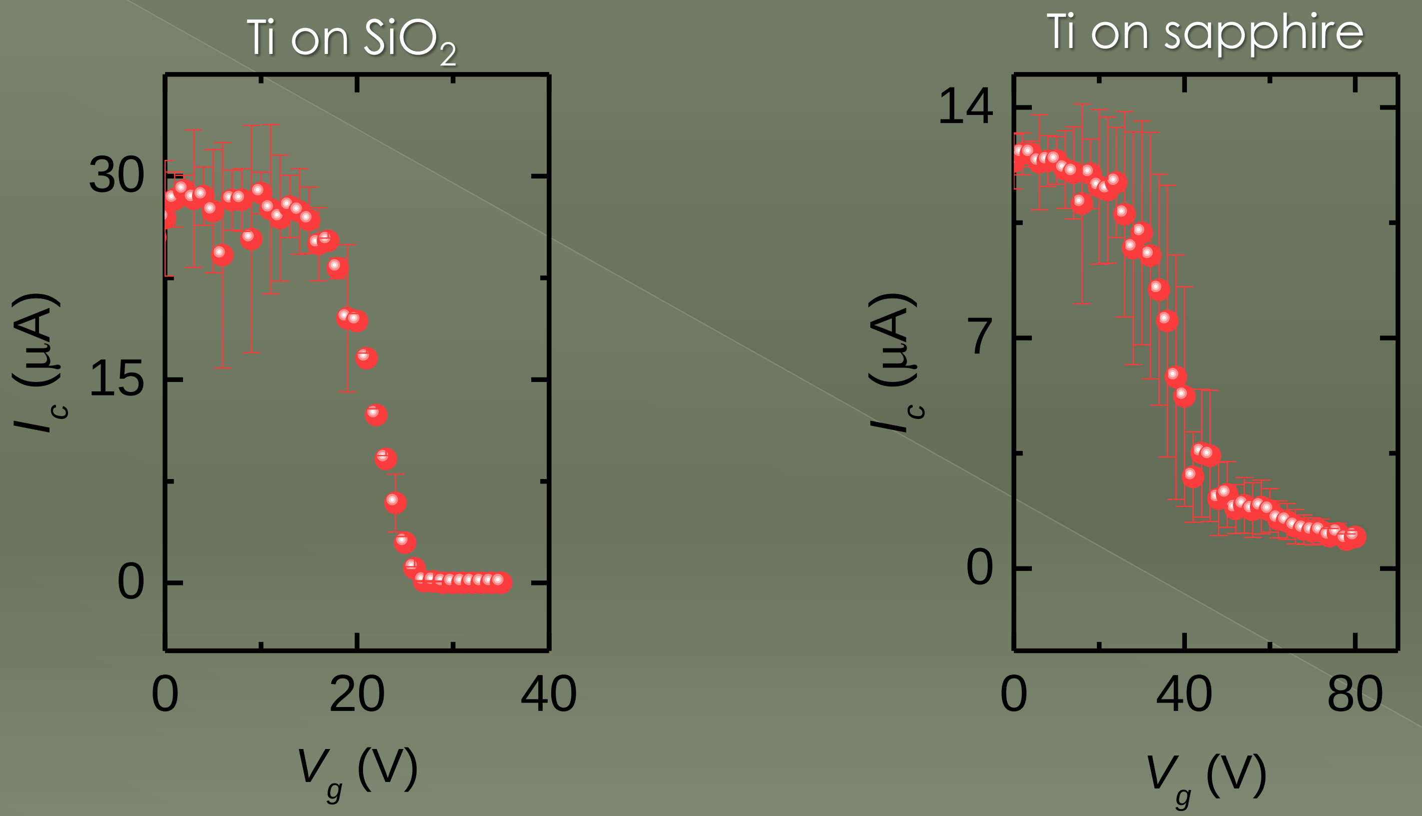
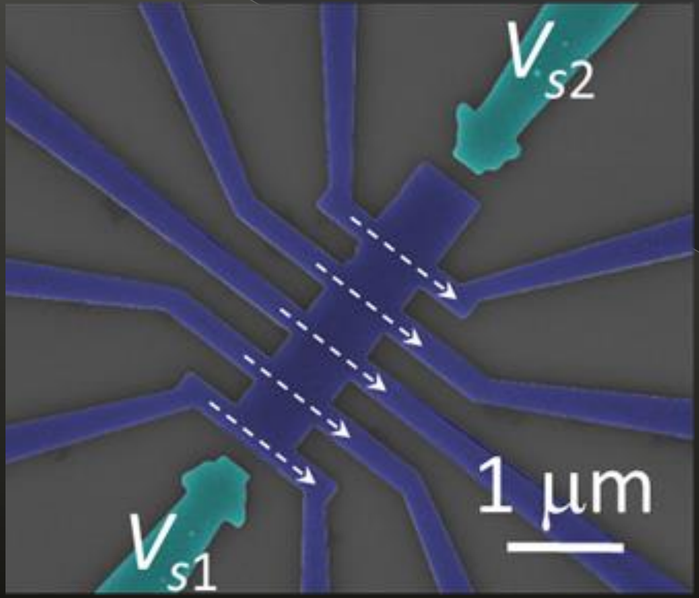
Independence of substrate on FETs performance

T = 32mK

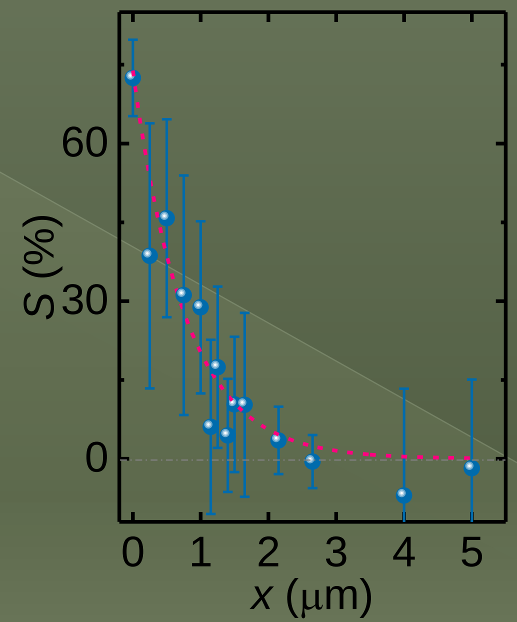


FE is independent of substrate type

Spatial extension of FE

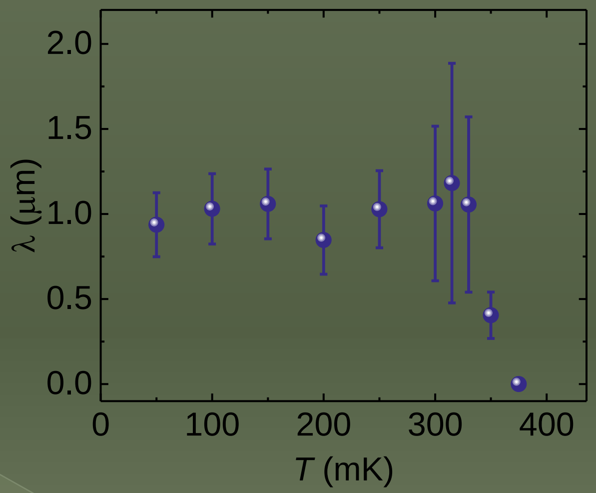


S = 100 ×[I_C(V_{si} = 0)-I_C (V_{si} = 90V)]/ I_C(V_{si} = 0)



λ ~ 770±150 nm

λ constant up to ~80% T_C



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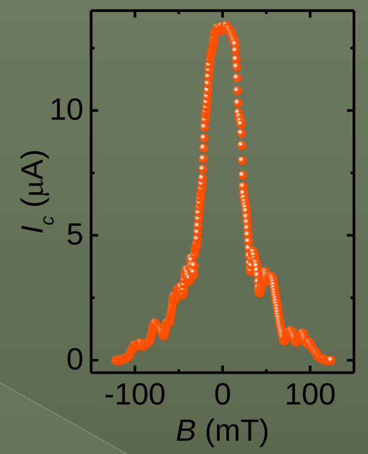
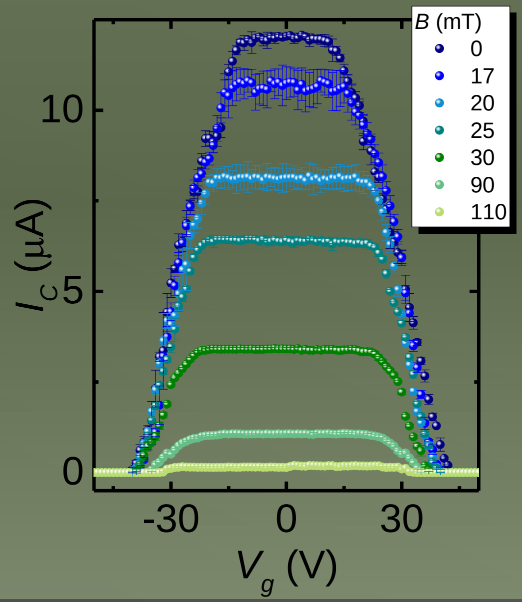
B-dependence of the supercurrent FET

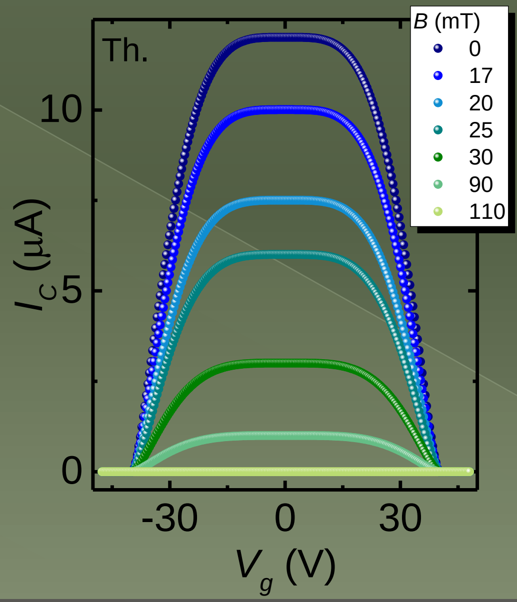


B_C ~ 127 mT @ 5 mK

Experiment



Theory



$V_g{}^c$ is weakly dependent on B

FE persists up to ~ B_c

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