Towards perfect quantum sensing: gate-controlled bi-superconducting quantum interference devices

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Introduction

- Superconductivity + Josephson effect = Superconducting QUantum Interference Devices (SQUIDs)
- Ultra-high precision magnetic flux-to-voltage transducers
- Applications spanning medical imaging, remote sensing, geophysical surveying, quantum metrology
- DC SQUIDs currently see significant commercial and laboratory usage

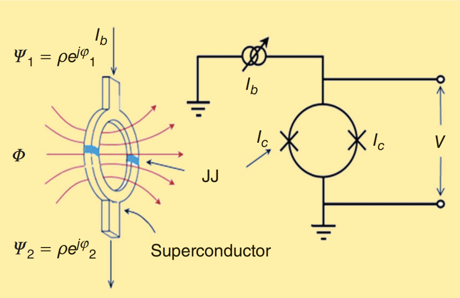

Figure: DC SQUID schematic

bi-SQUIDs

- DC SQUIDs suffer from poor response linearity
- See improvements by connecting many devices in an array structure
- Alternatively investigate a new single-cell device geometry: the bi-SQUID
- Theoretically predict a drastically better performance compared to a typical DC SQUID
- Obtaining this theoretical improvement in practice has been elusive

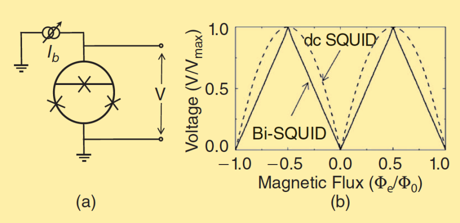

Figure: (a) bi-SQUID schematic. (b) bi-SQUID voltage-flux response vs. DC SQUID for comparison.[a]

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[a] O. Mukhanov, G. Prokopenko, and R. Romanofsky, “Quantum sensitivity: Superconducting quantum interference filter-based microwave receivers,” *Microwave Magazine, IEEE* 15, 57–65 (2014).

Superconducting Field Effect?

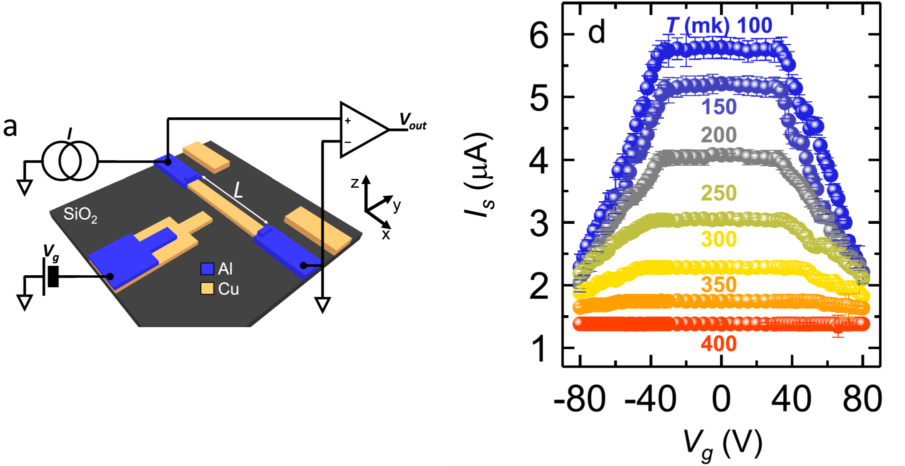

Figure: Left: Gated (Al-Cu-Al) SNS junction. Right: Gate-driven suppression of junction critical current. Adapted from: G. De Simoni, F. Paolucci, C. Puglia, and F. Giazotto, "Josephson field-effect transistors based on all-metallic Al/Cu/Al proximity nanojunctions," *ACS Nano* 13, 7871–7876 (2019).

Gate-Controlled bi-SQUIDs

- Idea: exploit the superconducting field effect to precisely tune the behaviour of a bi-SQUID[a]
- Collaboration with Superconducting Quantum Electronics Lab (SQEL) in Pisa, Italy[b]

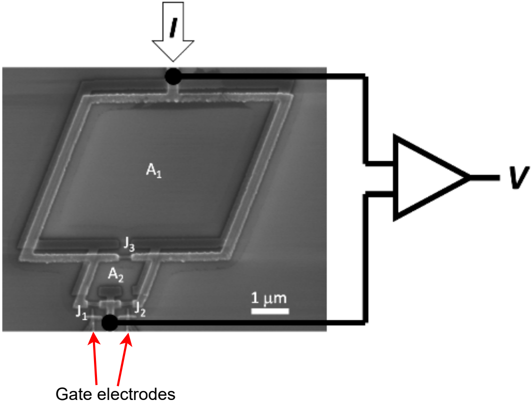

Figure: Gated SNS bi-SQUID

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[a] G. C. Tettamanzi, I. Nakone, F. Giazotto, and P. Atanackovic, "A quantum magnetic field receiving device," Australian Provisional Patent Application 2021903616 (2021).

[b] G. De Simoni *et. al.* "Ultrahigh linearity of the magnetic-flux-to-voltage response of proximity-based mesoscopic bi-SQUIDs," *Phys. Rev. Applied* 18, 014073 (2022).

Circuit-theoretic SQUID modelling

- Lumped element circuit approximation + RCSJ model[a][b]

$$I_k = I_{c_k} \sin(\varphi_k) + \frac{\hbar}{2eR_k}\frac{\mathrm{d}\varphi_k}{\mathrm{d}t} + \frac{\hbar C_k}{2e}\frac{\mathrm{d}^2\varphi_k}{\mathrm{d}t^2} \quad (1)$$

- Derive a system of ODEs in the Josephson phases φ_k
- Compute voltage response of SQUID via

$$V(t) = \frac{\hbar}{2e}\left(\frac{\dot{\varphi_1} + \dot{\varphi_2}}{2}\right) \quad (2)$$

- Numerically solve ODEs to simulate characteristic behaviour of the device

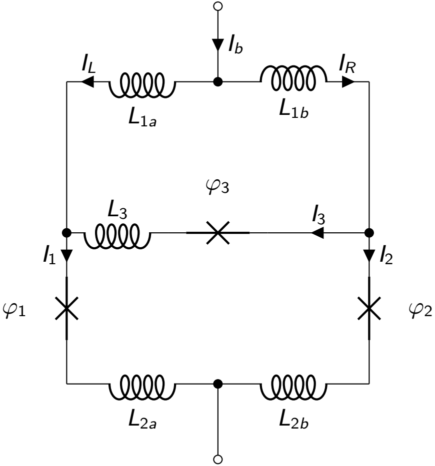

Figure: bi-SQUID circuit approximation

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[a] P. Longhini *et. al.* "Voltage response of non-uniform arrays of bi-superconductive quantum interference devices," *Journal of Applied Physics* 111, 093920 (2012).

[b] G. C. Tettamanzi, I. Nakone, F. Giazotto, and P. Atanackovic, "A quantum magnetic field receiving device," Australian Provisional Patent Application 2021903616 (2021).

Minimal extensions to capture gate effect

- Add gate voltage-dependent terms to model
- Promote junction critical current to a function of the gate voltage V_g based on observed experimental behaviour
- Add phase offset term $\varphi_0(V_g)$ to the current-phase relation of the gated junctions

$$I_{c_k}\sin(\varphi_k) \longrightarrow I_{c_k}(V_g)\sin(\varphi_k + \varphi_0(V_g)) \tag{3}$$

- Obtain model parameters via fits to experimental data (V-I curves)

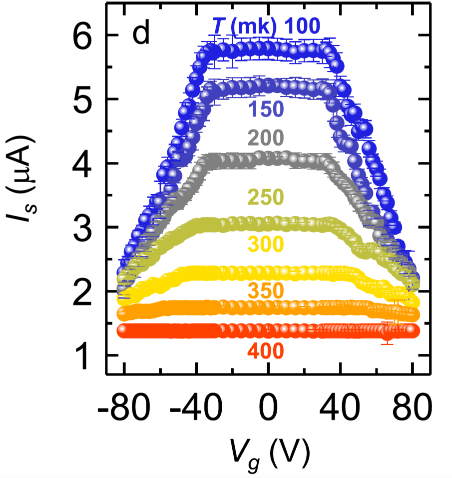


Figure: Junction critical current vs. applied gate voltage.

Fits to Model

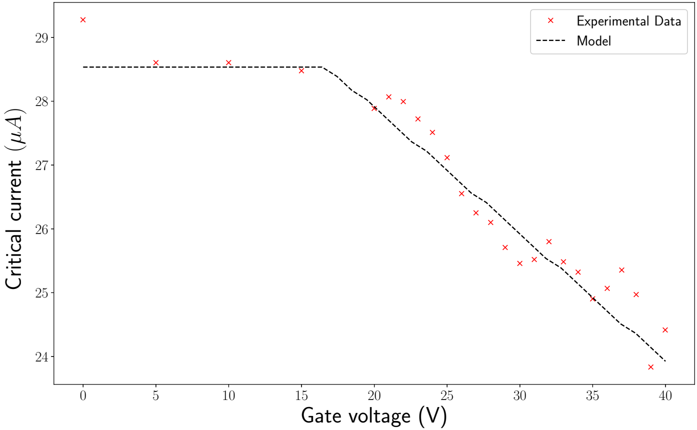


Figure: Device critical current vs. gate voltage at 30 mK; experiment and simulations.

Modelling of voltage-flux curves

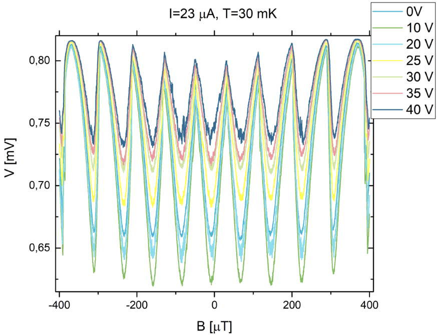


Figure: Experiment

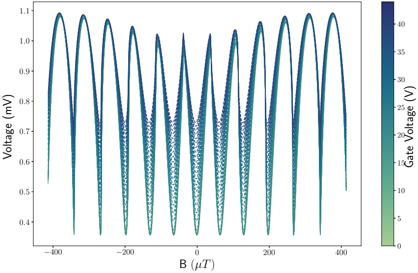


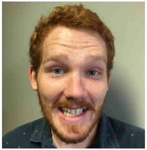
Figure: Model

Summary and Next Steps

- bi-SQUIDs have great potential to be engineered to be a highly performant magnetic sensor
- Electric field-induced suppression of Josephson junction supercurrent appears to arise from some kind of unconventional superconducting field effect
- Can obtain precise control of junction parameters in a SQUID driven by electrostatic gate electrodes
- Effect can be described at a phenomenological level in a lumped element circuit theory SQUID model, allowing for fast simulation of gate-driven SQUID structures
- Begin to explore whether new limits can be achieved in terms of response linearity with gate tuning

Acknowledgements

(a) G. C. Tettamanzi; UofA, Head of QuaNTeG



(b) J. Cruddas; UofA, Research Fellow

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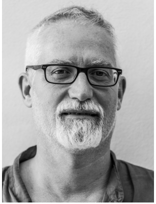
(d) G. De Simoni; CNR-Nano, Researcher



(e) F. Giazotto; CNR-Nano, Research Director

Supplementary Slides

A trivial explanation?

- Leakage current?
- Heating?
- Quasiparticle injection?

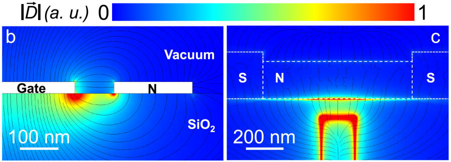


Figure: FEM simulation of electric displacement field around a gated SNS junction[a].

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[a] G. De Simoni, F. Paolucci, C. Puglia, and F. Giazotto, "Josephson field-effect transistors based on all-metallic Al/Cu/Al proximity nanojunctions," *ACS Nano* 13, 7871–7876 (2019).

Further experimental evidence

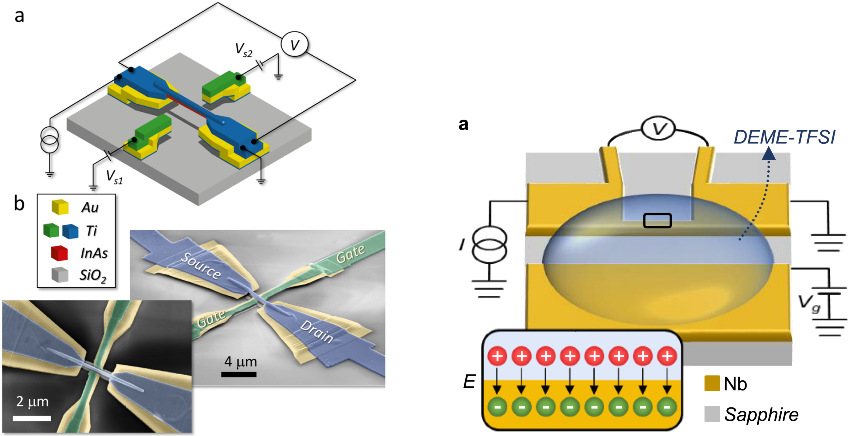

Figure: Left: Suspended SNS nanojunction[1]. Right: Ionic gated superconducting field effect transistor[2].

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[1] M. Rocci, *et. al.* "Gate-controlled suspended titanium nanobridge supercurrent transistor," *ACS Nano* 14, 12621–12628 (2020).

[2] F. Paolucci, *et. al.* "Electrostatic field driven supercurrent suppression in ionic-gated metallic superconducting nanotransistors," *Nano Letters* 21, 10309–10314 (2021).