Field-Effect Controllable Metallic Josephson Interferometer

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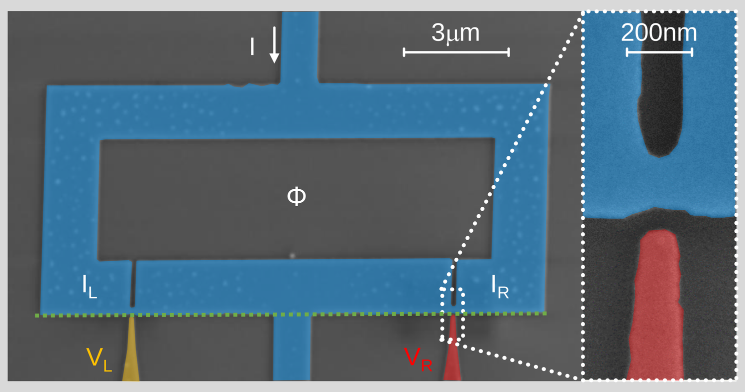
Motivations

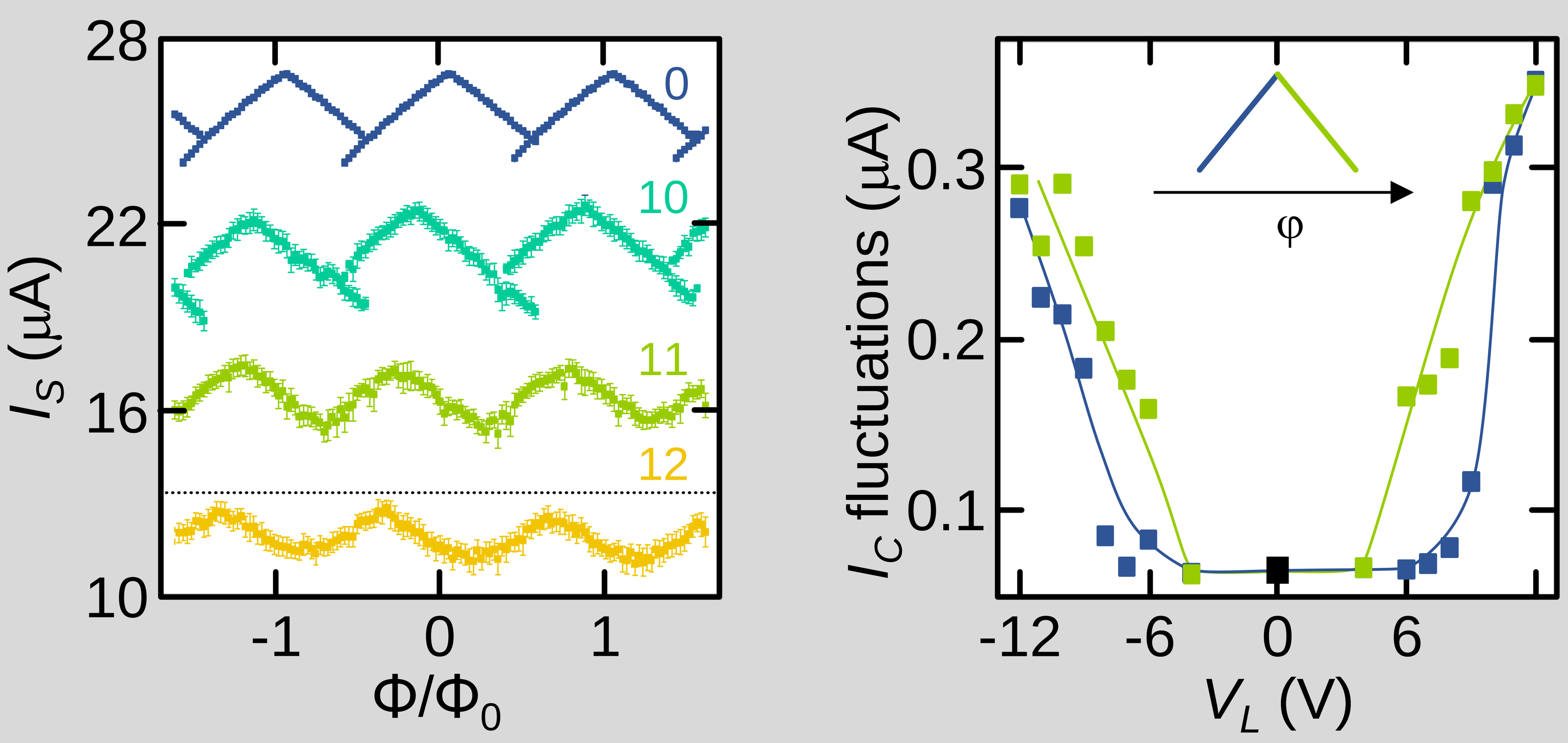
Recently, strong static electric fields have been shown to modulate the critical supercurrent in metallic wires [1-3] and Josephson junctions (JJs) [4], down to full suppression. Here, we lay down a fundamental brick for both the insight and the technological application of this unorthodox field-effect by realizing a titanium-based monolithic Superconducting Quantum Interference Device (SQUID) [5], which can be tuned by applying a gate bias to the JJs independently.

I. Device



The SQUID is realized with a single-step electron beam lithography and 30 nm-thick evaporation of Titanium. The two junctions consist in two constrictions (Dayem bridges) 150 nm x 150 nm. Each junction is gated by a correspondent electrode, distant 30 nm and 50 nm from the right and left junction

III. High gate voltages



At higher voltages, the switching current interferes even below the single junction critical current. This effect cannot be explained within a SQUID model where the single junction critical current is suppressed by the electric field. In this case, indeed, a switching current independent on the flux (due to the ungated junction) is expected.

Another effect that appears at high voltage is the propagation of the fluctuations in both the branches.

Both the suppression and fluctuations in the two branches of $I_S(\Phi)$ indicate the presence of a local gate-dependent phase fluctuation able to affect the ungated junction by means of the fluxoid quantization. The electric field shows hence a coupling to the junction phase.

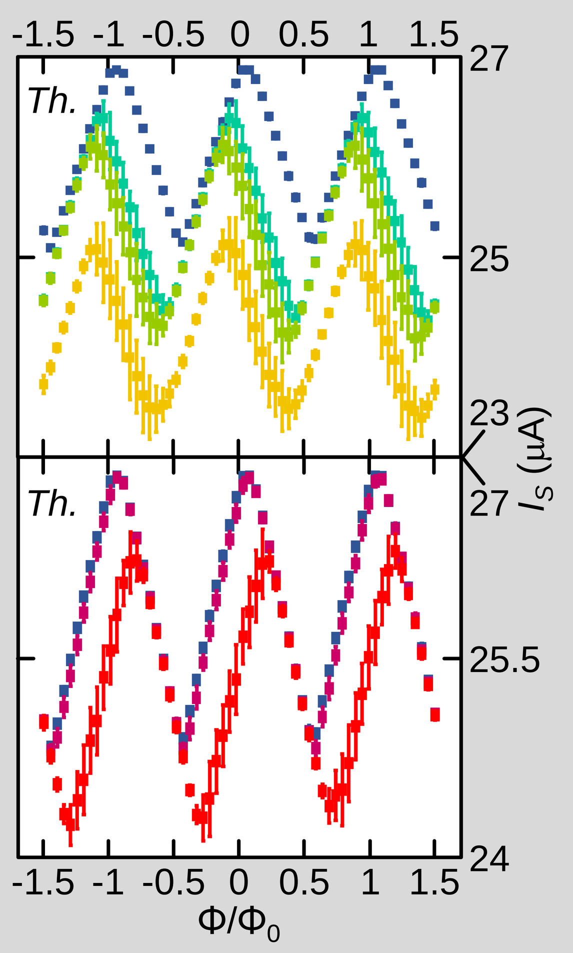
IV. Effective model

We used a RCSJ-based model to grasp the basic physics of the interferometer. The model has the purpose to give an insight to the dependence on the gate voltage of the noise and critical current of the single junction.

The model includes self inductance and thermal noise. It is moreover enriched with a gate-dependent Gaussianly-distributed, delta-correlated stochastic noise fluctuation of current.

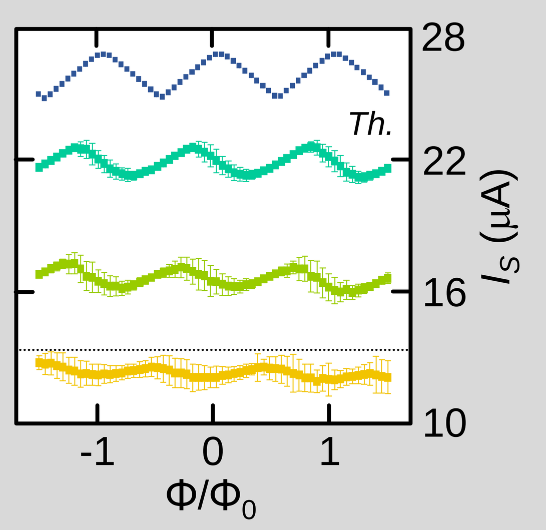
The model can reproduce the experimental results, yielding

- ***The sliding effect of the $I_S(\Phi)$ pattern***
- ***The behavior of the I_S fluctuations in the two branches***
- ***The suppression of I_S below the single junction critical current at high voltages***

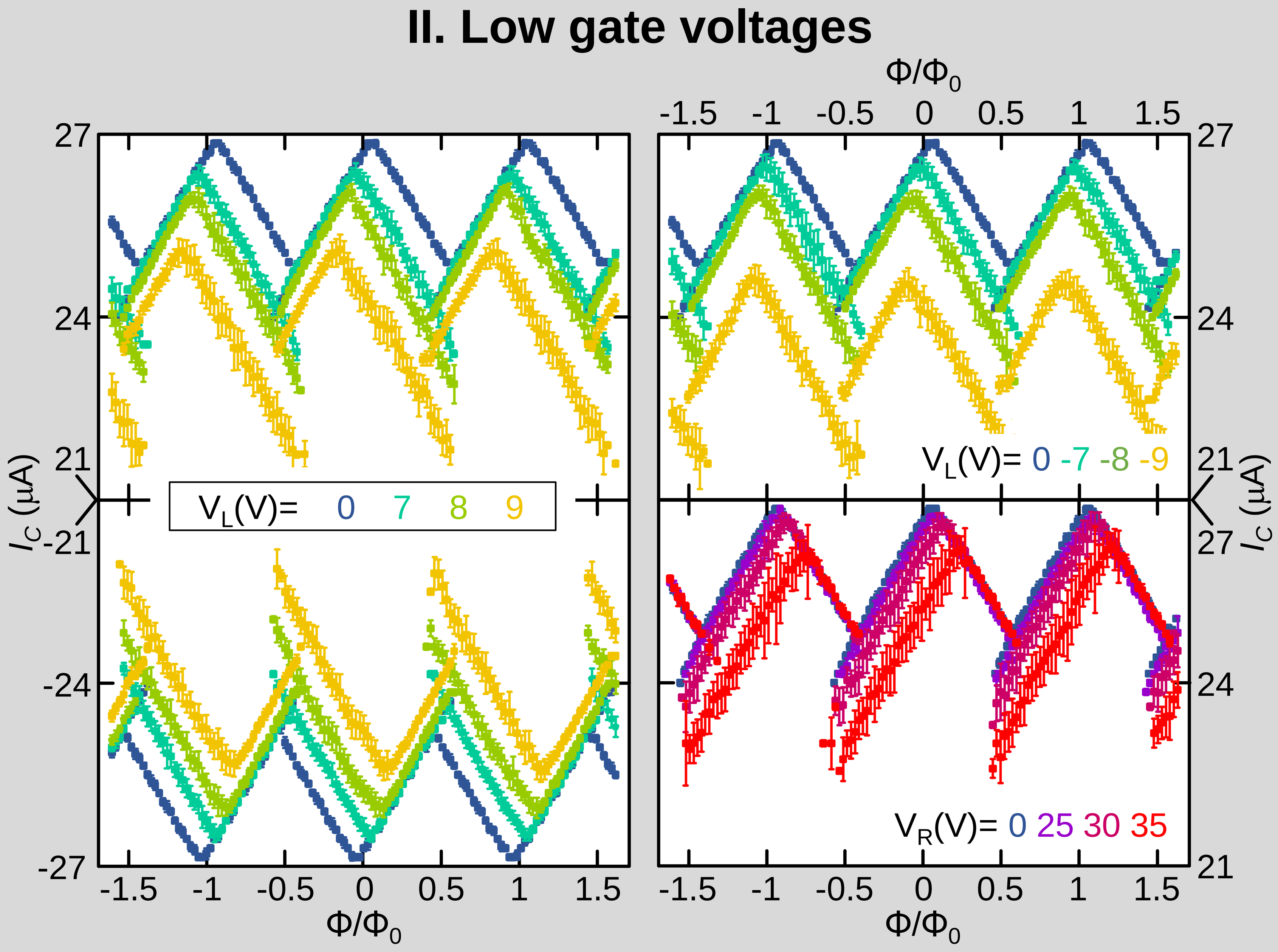


The model parameters indicate that

- ***A phase fluctuation of the gated junction is present and increases with the voltage***
- ***The critical current of the junction decreases with the gate voltage***
- ***The gate voltage affects also the critical current of the SQUID arm with slightly changing its kinetic inductance***



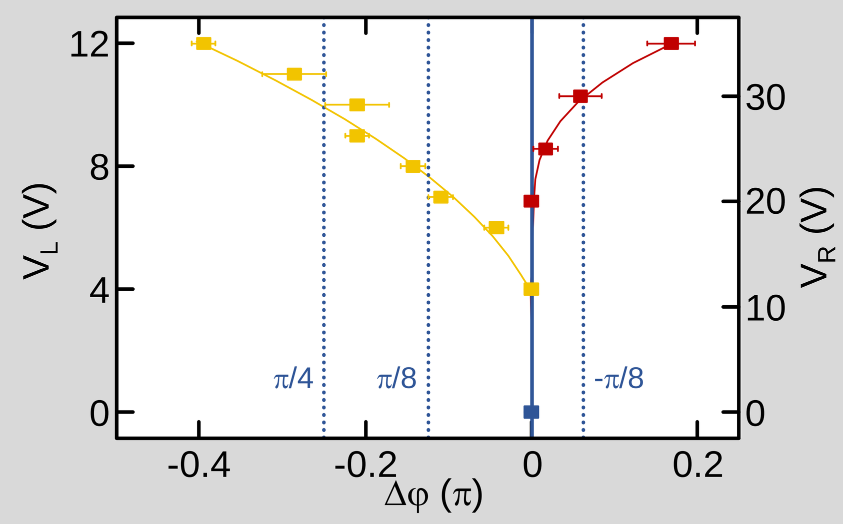
II. Low gate voltages



We demonstrated an unconventional presence of field-effect, affecting the switching current characteristic versus the magnetic flux $I_S(\Phi)$.

The behavior can be grasped by the following points:

- When ungated, the SQUID shows a triangular switching current modulation pattern $I_S(\Phi)$, typical of SQUIDs based on Dayem bridges;
- If one gate is charged, the switching current pattern $I_S(\Phi)$ slides along one of its branches, according to which gate is used;
- The maximum of $I_S(\Phi)$ is shifted. The shift defines the function $\Delta\varphi(V)$. The electrostatically tuned shift can have application in quantum computing in the form of tunable phase-shifters;



- At the same time, in the opposite branch, fluctuations of the switching current *Is* appear;
- The effect is symmetric in the polarity of the gate voltage;
- The time reversal symmetry $I_S^+(\Phi) = -I_S^-(-\Phi)$ between the positive and negative current patterns I_S^+ and I_S^- is preserved.

V. Future perspectives

Beyond the implications in fundamental physics, concerning the coupling between the electric field and the phase, gate-controllable metallic Josephson interferometer may have a wide range of possible applications.

In quantum information, the possibility to manipulate the phase can yield important implications in flux and phase qubits.

In superconducting electronics, electrostatically-tunable Rapid Single Flux Quantum (RFSQ) logic can be realized.

Bibliography

1. G. De Simoni *et al.* Nature Nanotechnology 13, 802 (2018)
2. F. Paolucci *et al.* Nano Lett. 18, 4195 (2018)
3. F. Paolucci *et al.* Phys. Rev. Applied 11, 024061 (2019)
4. G. De Simoni *et al.*, ACS Nano (2019), doi: 10.1021/acsnano.9b02209
5. F. Paolucci, F. Vischi *et al.* Arxiv 1904.08349