

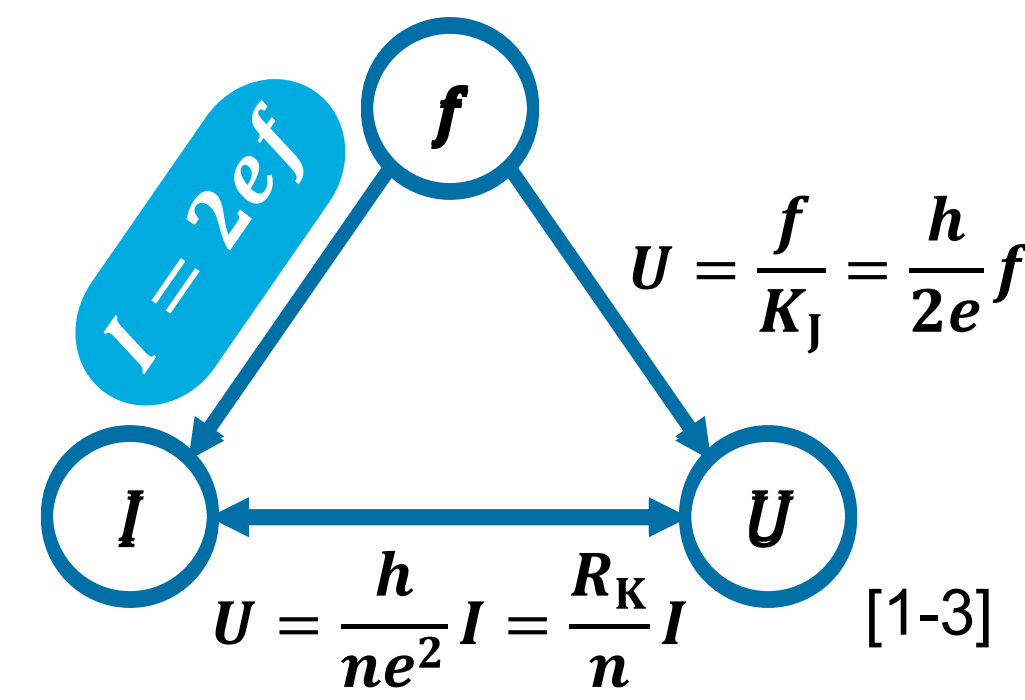
Quantized currents at $2ef$ - studying the potential of dual Shapiro steps for a quantum current standard

Introduction

The well-known Shapiro-steps, which form the basis of today's voltage standard, rely on synchronization of Josephson oscillations with external rf drives. In 1985 the dual to this effect, quantized current steps at $I = 2ef$, was theoretically predicted [1,4].

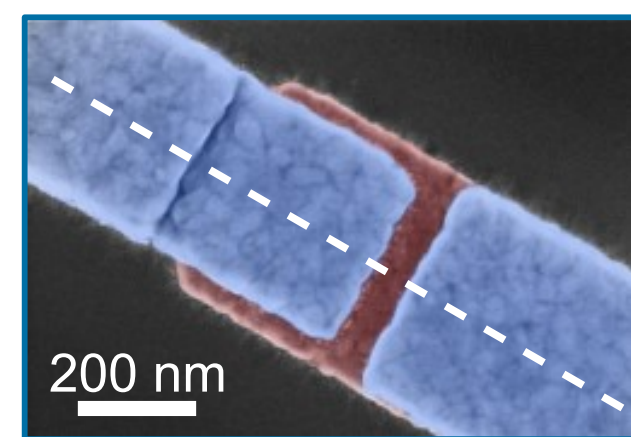
Realizing a current standard based on these so-called dual-Shapiro steps would make use of frequencies in the GHz-range for synchronization, and result in current steps in the nA-range. Furthermore, such devices are technologically compatible with Josephson voltage standards and might allow realizing voltage and current standards in one device.

To observe dual-Shapiro steps, a Josephson junction has to be embedded in an environment with impedance $Z_{\text{env}} > h/4e^2 \approx 6.4 \text{ k}\Omega$ to suppress quantum fluctuations of charge. Until recently this technological challenge had rendered the observation of quantized current steps elusive [5-7]. Here, we present our work to show pronounced steps at up to 2 nA [8,9] and present future perspectives.



Bloch oscillations in small Josephson junctions

A Josephson tunnel junction (JJ) is formed by two superconducting electrodes separated by a thin insulating barrier, which also gives rise to a junction capacitance.



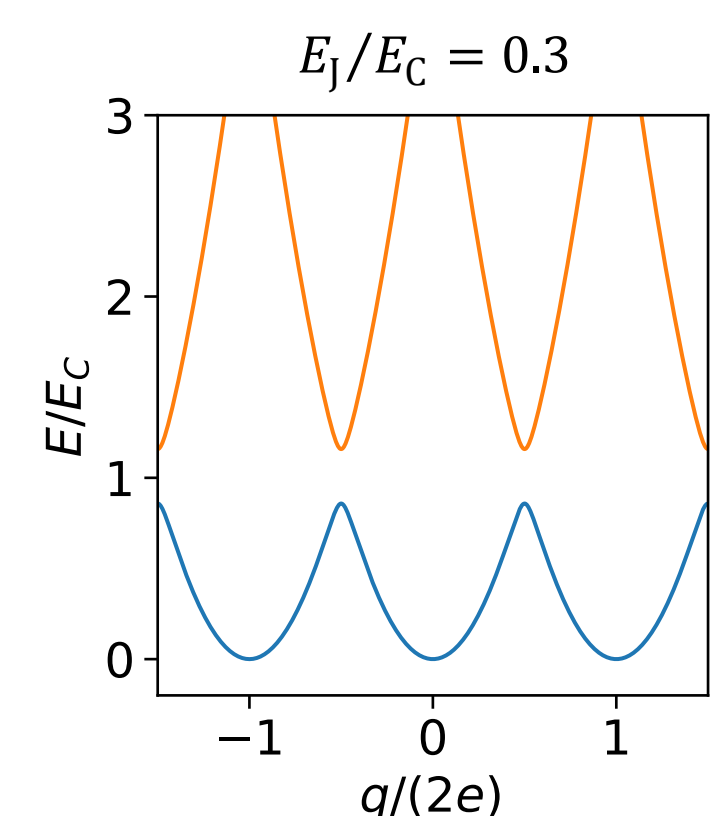
Sketched line cut along the dashed line:



Blue, red: Al electrodes, black: AlOx barrier

Quantum mechanical description: $H = \frac{Q^2}{2C} - E_J \cos(\varphi)$, with $E_J = \frac{h I_c}{4\pi e}$, $E_C = \frac{e^2}{2C}$

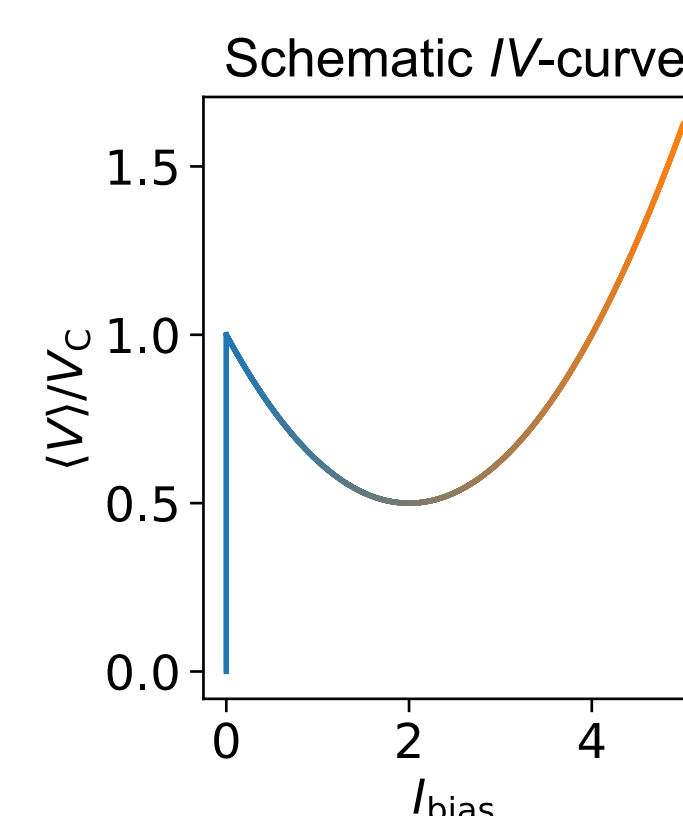
First two eigenstates govern the dynamics of a quasi-charge particle in a biased JJ [1]



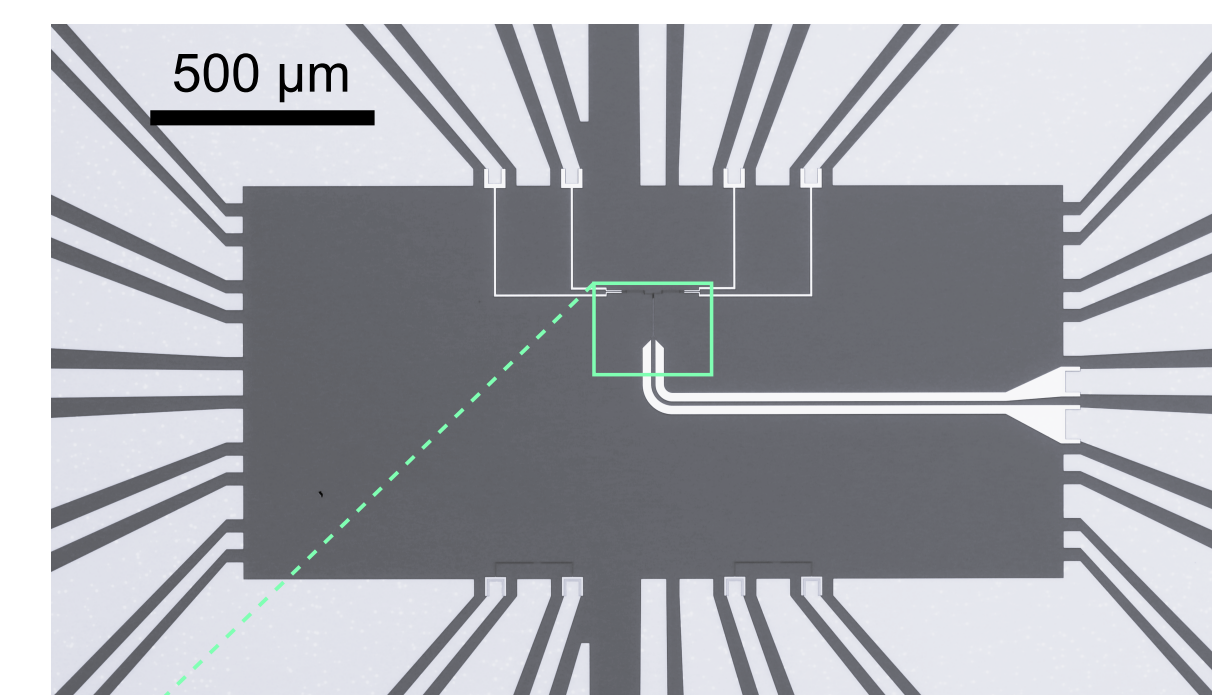
$I_{\text{bias}} = 0$: Coulomb blockade

$I_{\text{bias}} > 0$: Bloch oscillations, i.e. coherent Cooper-pair transport; shows as negative differential resistance in IV-curve.

$I_{\text{bias}} \gg 0$: Landau-Zener tunneling to higher eigenstates destroys the coherent Cooper-pair transport of Bloch oscillations.



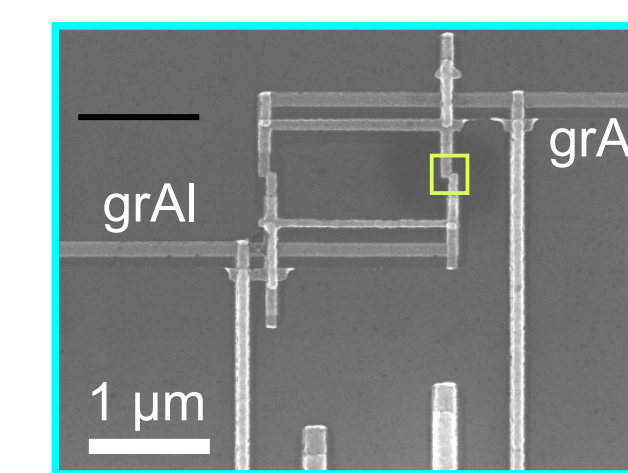
Experimental realization



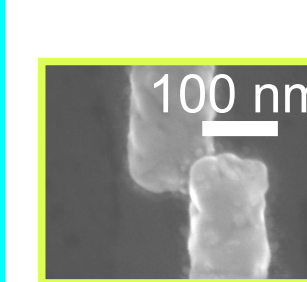
Four probe measurement setup (top middle) to measure IV-curves. Slot line (right) to feed the rf-drive for locking of Bloch-oscillations and generation of quantized current steps.



To enable quantized current steps an environment with impedance $Z_{\text{env}} > 6.4 \text{ k}\Omega$ is needed. We realize this using oxidized titanium (TiOx [10]) and granular aluminium (grAl [11]) in the leads.

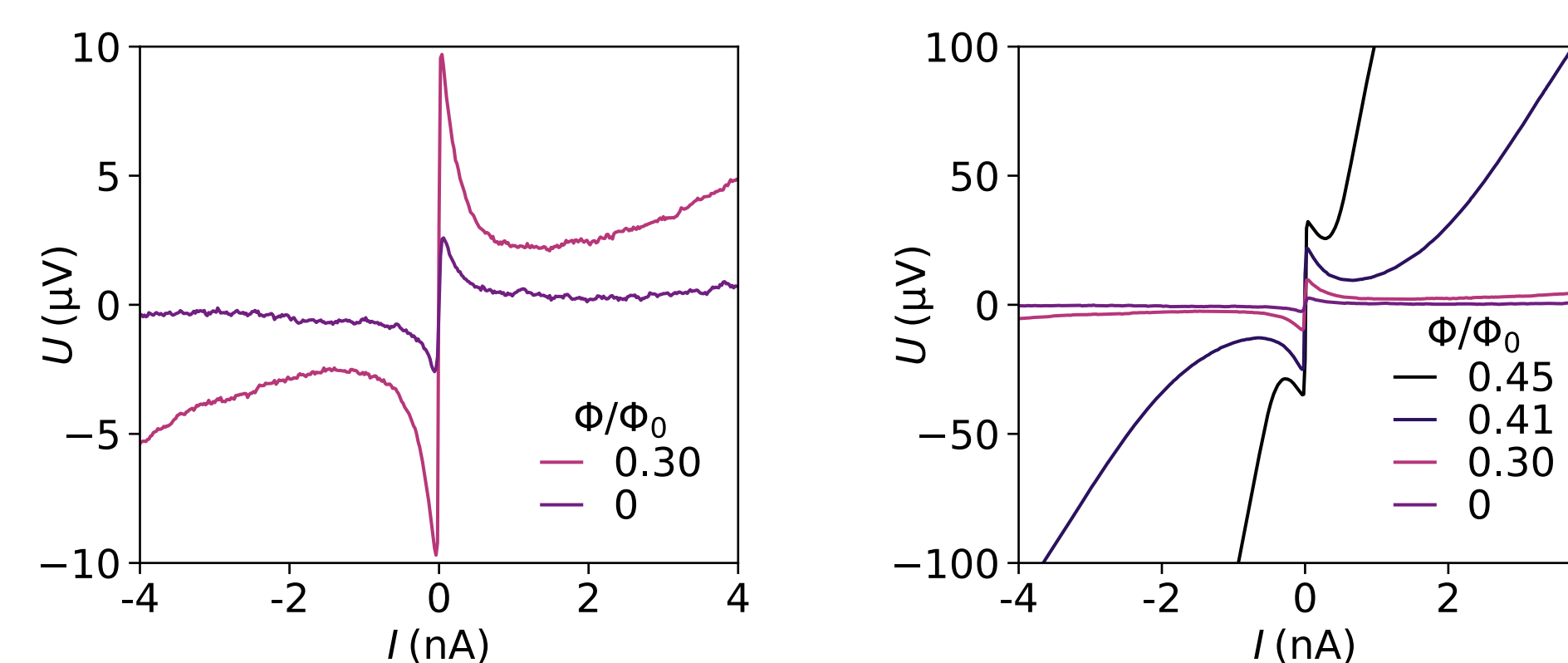


A DC-SQUID allows to tune the effective E_J with an external magnetic field.



The Al/AIOx/Al Josephson junctions of size $\sim 20 \times 30 \text{ nm}^2$ have a critical current $I_c = 15 \text{ nA}$

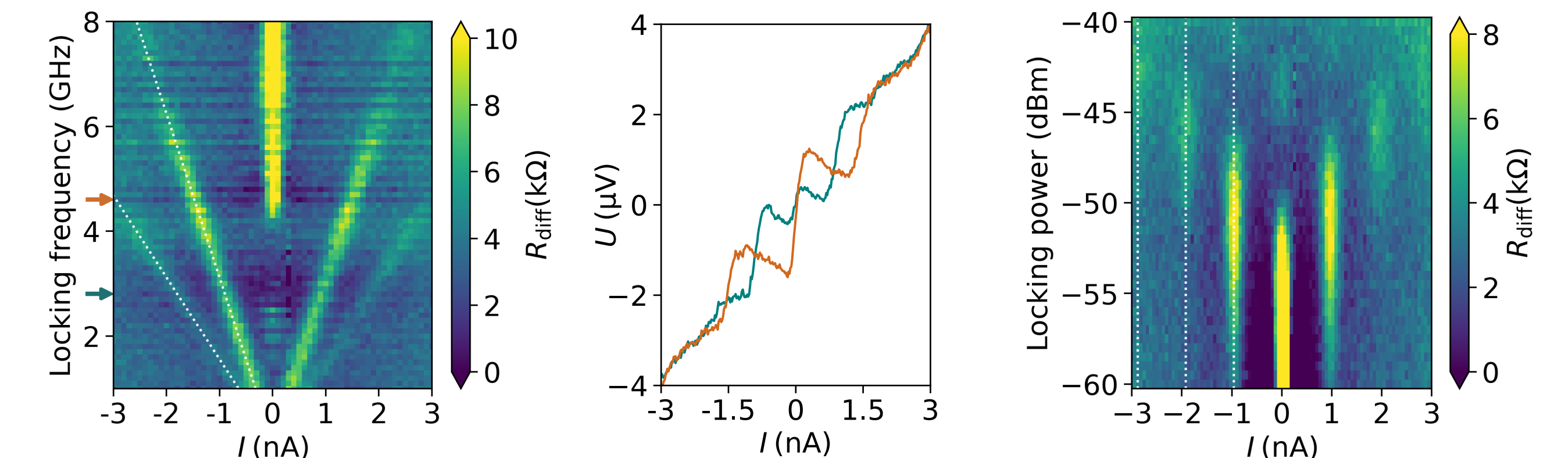
Measured Bloch oscillations



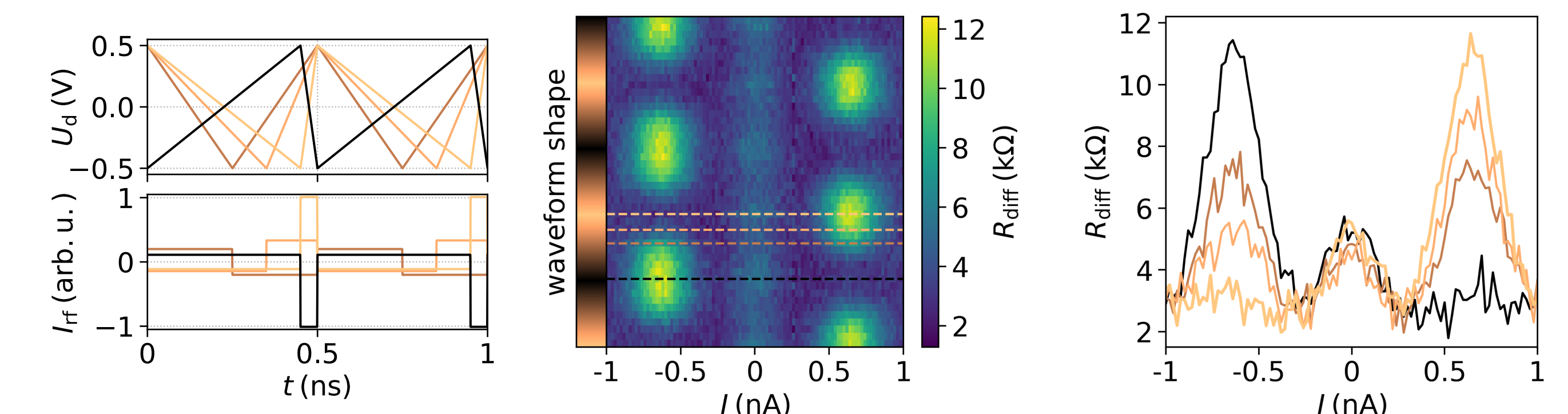
Zero magnetic flux through the loop of the DC-SQUID results in the largest Josephson energy E_J . The first two eigenstates (see bottom left box) have a smaller amplitude and are separated by a larger gap resulting in a small Coulomb blockade and vanishing Landau-Zener effect. Suppressing E_J by increasing the magnetic flux through the loop results in a larger blockade with the drawback of an increased Landau-Zener effect. Consequently, a trade-off is necessary for performing a dual-Shapiro step experiment [9].

Dual-Shapiro steps

By locking Bloch oscillations with an rf-drive we find steps, i.e. peaks in differential resistance R_{diff} , in IV-curves at the expected position $I = 2ef$, with e the elementary charge and f the drive frequency. With increasing power second and third order steps become visible.



Using a pulsed drive, we can select if current steps appear at positive or negative currents depending on the pulse polarity. Additionally, a pulsed drive leads to significantly increased peaks in differential resistance compared to a symmetric waveform.



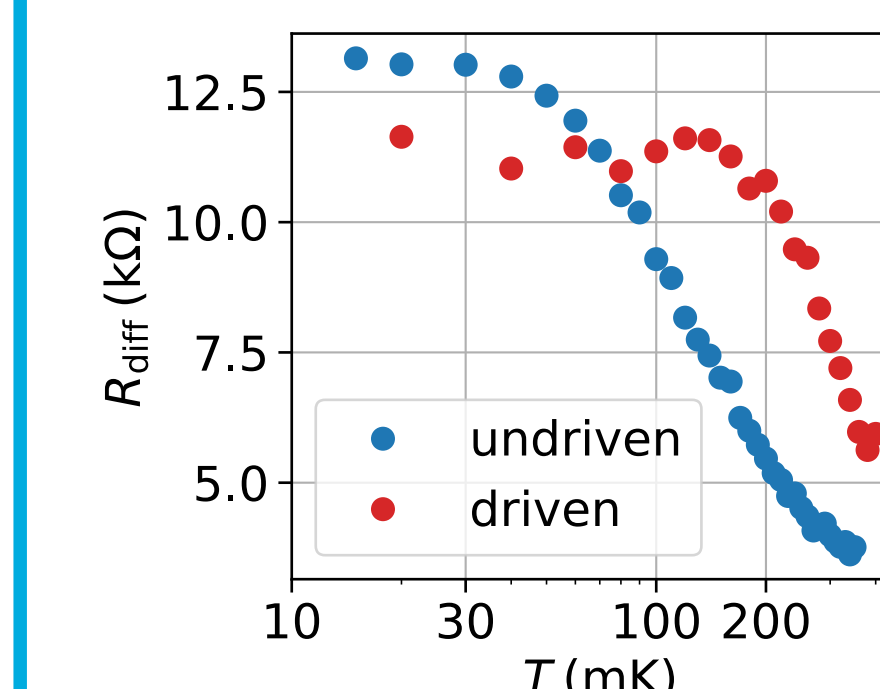
For more details see Ref. [9]:

F. Kaap et al., Demonstration of dual Shapiro steps in small Josephson junctions, *Nature Communications* 15, 8726 (2024)

References

- [1] K. K. Likharev, A. B. Zorin, J. Low Temp. Phys. 59 (1985)
- [2] S. Shapiro, Phys. Rev. Lett. 11 (1963)
- [3] K. v. Klitzing et al., Phys. Rev. Lett. 45 (1980)
- [4] D. Averin, A. B. Zorin, K. Likharev, Sov. Phys. JETP 61 (1985)
- [5] R. S. Shaikhaidarov et al., Nature 608 (2022)
- [6] N. Crescini et al., Nat. Phys. 19 (2023)
- [7] R. S. Shaikhaidarov et al., Nat. Comm. 15 (2024)
- [8] F. Kaap et al., Phys. Rev. Lett. 132 (2024)
- [9] F. Kaap et al., Nat. Comm. 15 (2024)
- [10] S. V. Lotkhov, Nanotechnology 24 (2013)
- [11] L. Grünhaupt & M. Spiecker et al., Nature Mat. 18 (2019)

Next steps and outlook



The amplitude of quantized current steps is drastically reduced compared to the undriven Coulomb blockade. By measuring the differential resistance for the Coulomb blockade as a function of chip temperature, we find that in the undriven case (blue) the electron temperature is significantly lower (30 mK) than in the driven case (red, 200 mK).

- Demonstrated steps at quantized currents $I = 2ef$ between ~ 0.3 and $\sim 2.0 \text{ nA}$
- Current experimental implementation likely limited by heating due to the drive
- To increase the precision of steps, optimize device design for minimal heating
- Future work targets an increased current range with larger, and steeper steps for potential metrological application