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LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

AC JOSEPHSON EFFECT IN GRAPHENE FOR QUANTUM METROLOGY

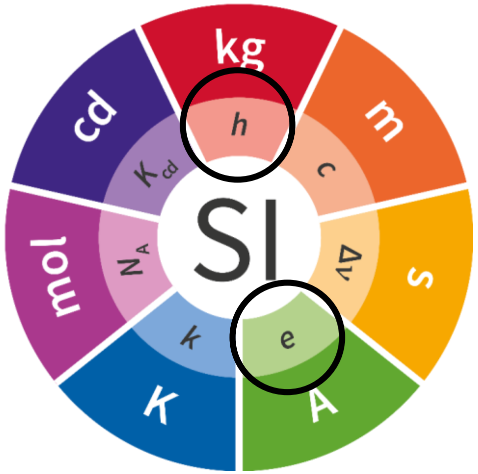
Nicolas Aparicio da Silva

TIDES 2026 – July 17

International System of units (SI)

- Revision of the SI in 2018
- Electrical units defined by condensed matter quantum effects

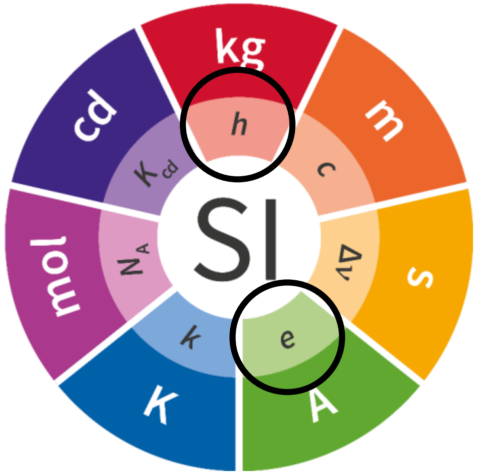
International System of units (SI)



- Revision of the SI in 2018
- Electrical units defined by condensed matter quantum effects

$h = 6.626\ 070\ 15 \times 10^{-34}$ J.s
$e = 1.602\ 176\ 534 \text{ x } 10^{-19}$ C

Quantum electrical metrology



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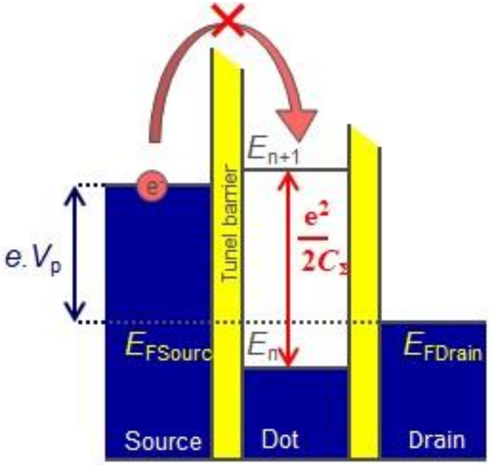
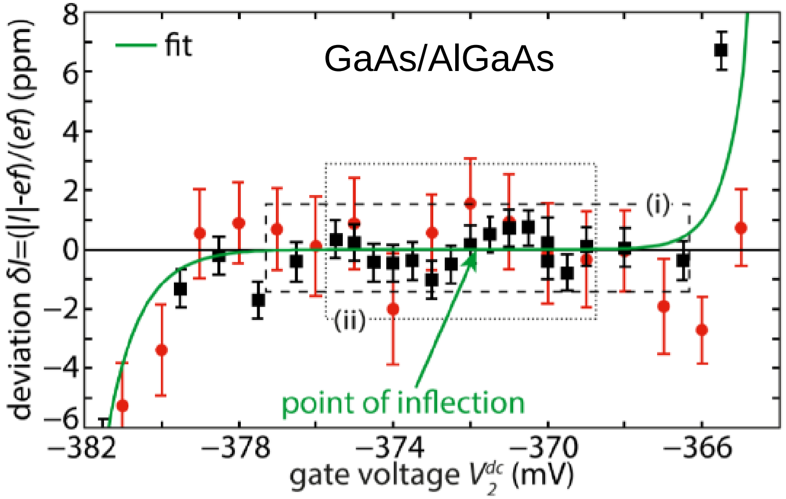
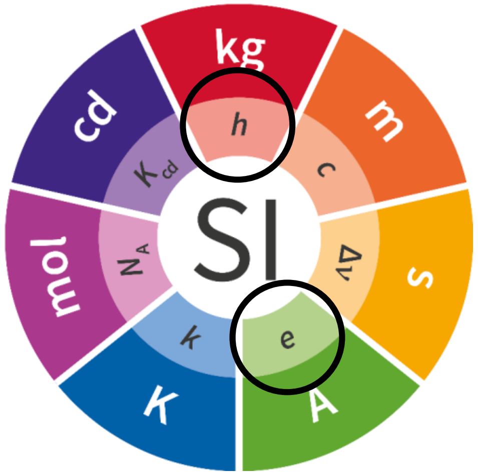


$$I_n = n e f_{RF}$$



Stein et al. *Appl. Phys. Lett.* 107, 103501 (2015)

Quantum electrical metrology



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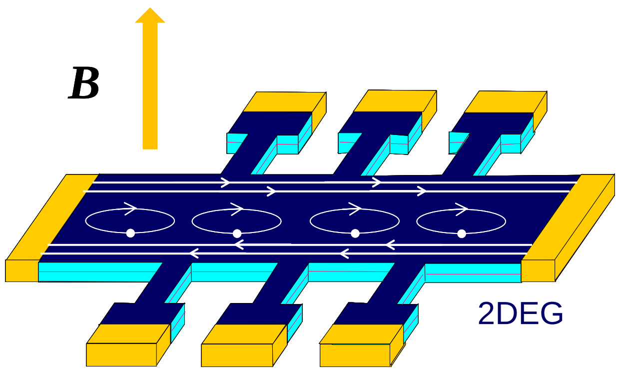
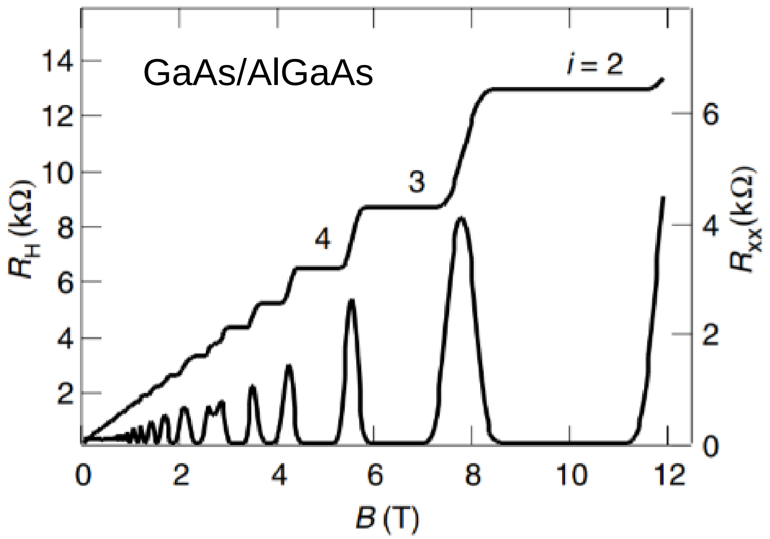
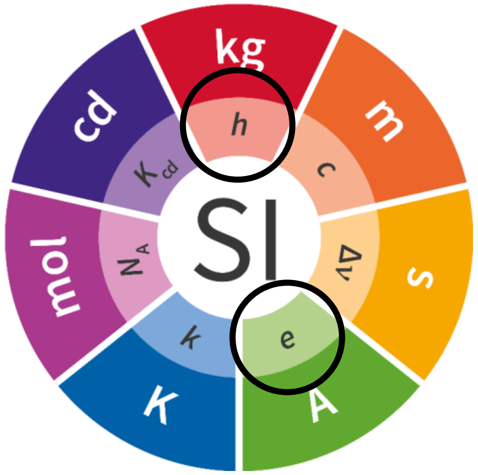


$$R_{\mathrm{H}} = \frac{h}{ie^2}$$



Jeckelmann and Jeanneret, *Rep. Prog. Phys.* 64(12), 1603 2001

Quantum electrical metrology



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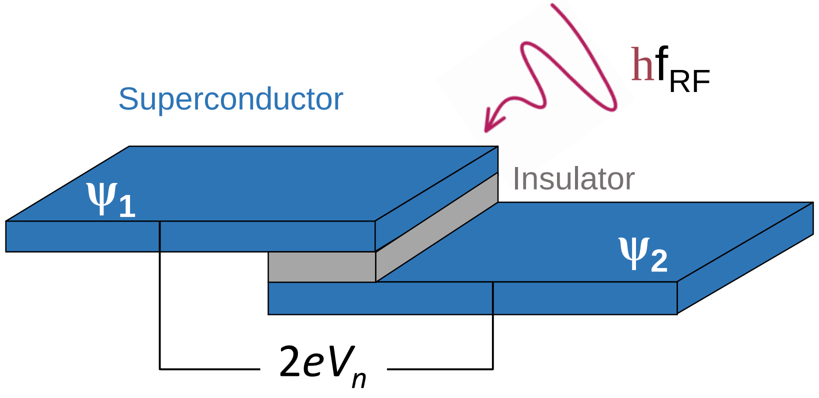
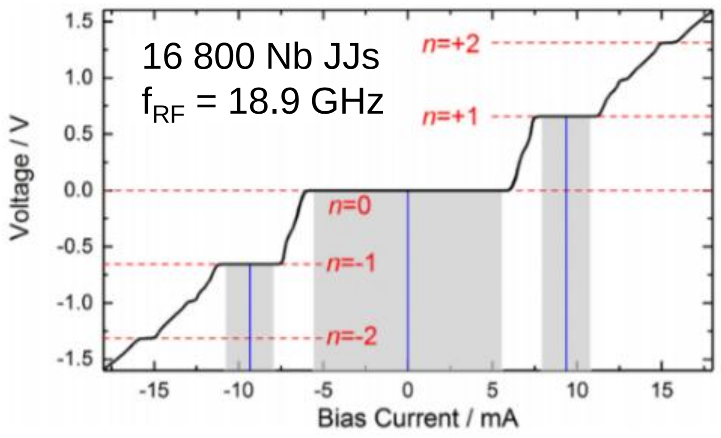


$$V_n = n\frac{h}{2e}f_{RF}$$



Rüfenacht et al. *Metrologia* 55(5), S152 (2018)

Quantum electrical metrology

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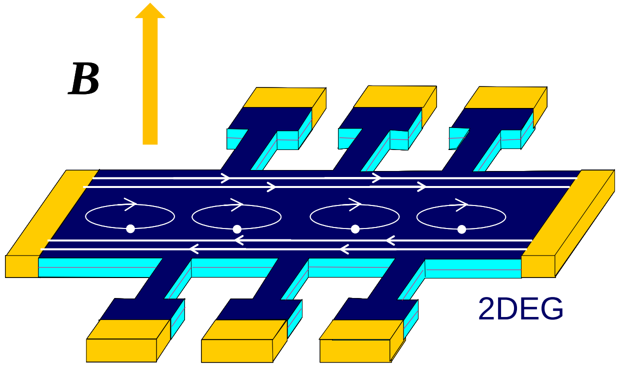

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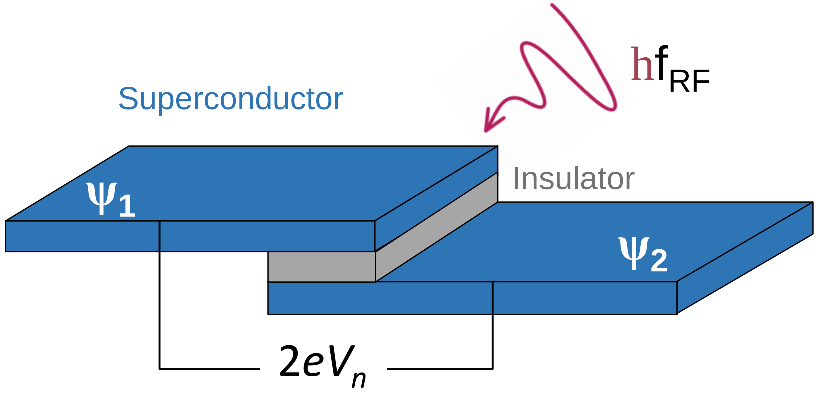

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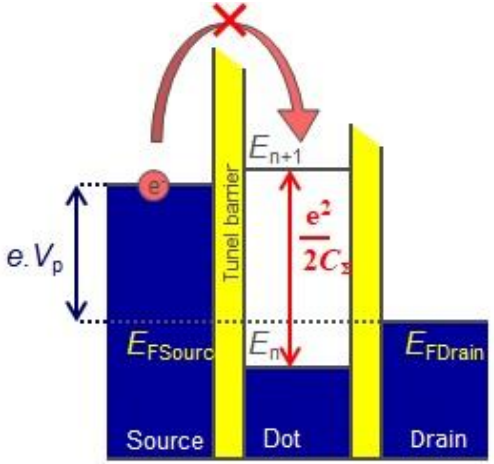
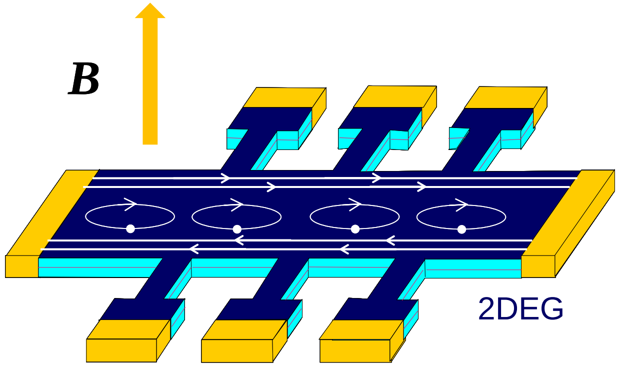


$$I_n = nef_{RF}$$

Quantum electrical metrology

Quantum Hall effect (Ω)



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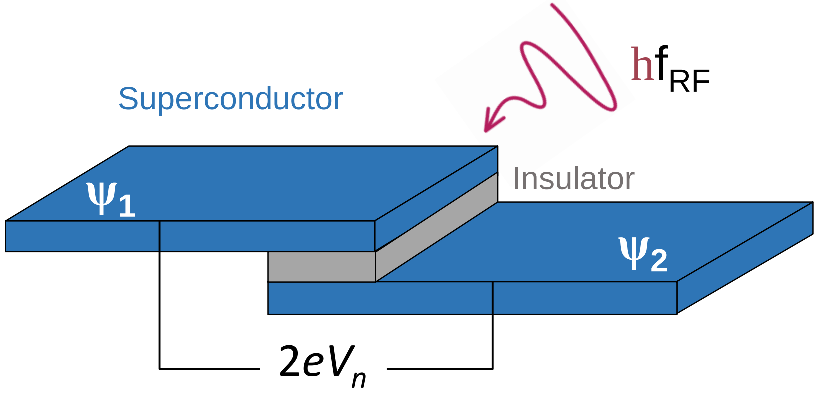

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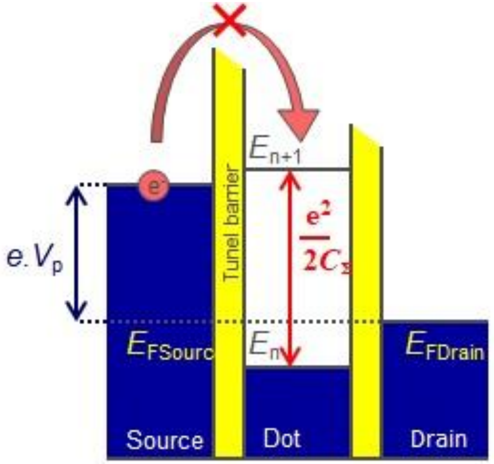

$$I_n = nef_{RF}$$

GaAs/AlGaAs (10 T) Graphene on SiC (4 T)	Nb-based SNS junctions (no magnetic field)	GaAs/AlGaAs (14 T)

Quantum electrical metrology

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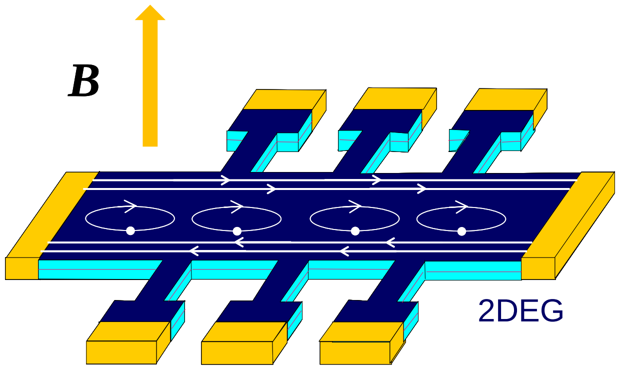

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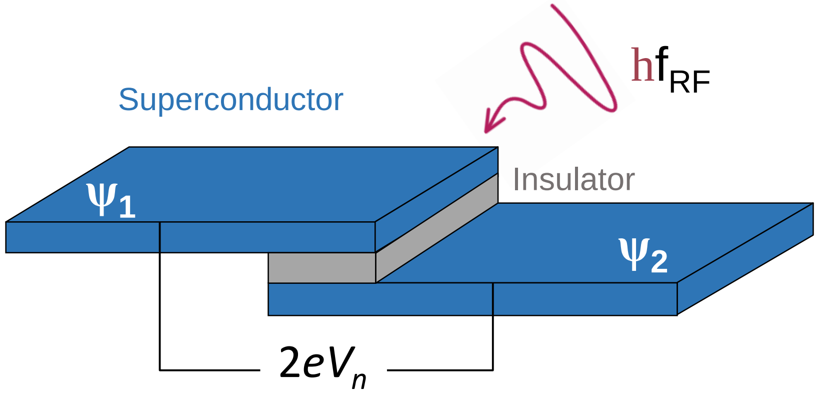

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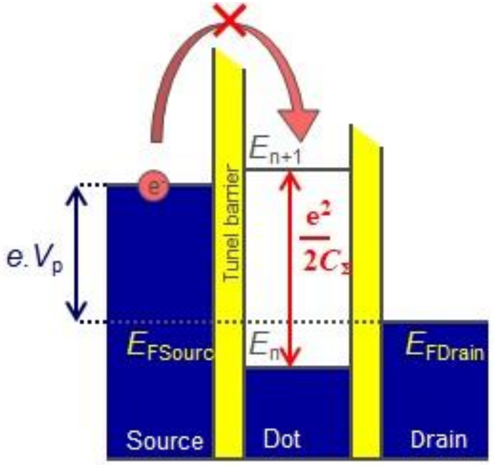

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GaAs/AlGaAs (10 T) Graphene on SiC (4 T)	Nb-based SNS junctions (no magnetic field)	GaAs/AlGaAs (14 T)

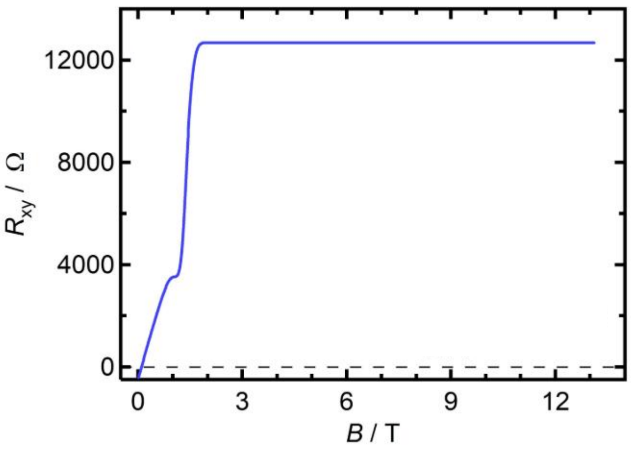
Towards integrated on-chip electrical standards

Graphene as a promising platform for quantum electrical metrology

- **Quantum Hall effect (Ω)**

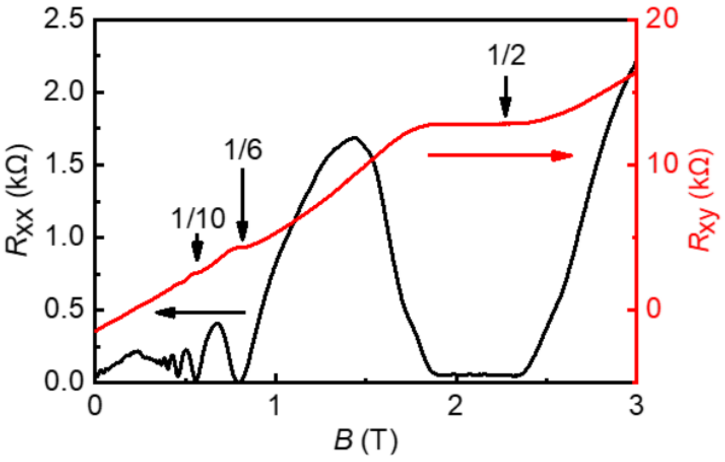
Towards a resistance standard below 1 T compatible with superconductivity

Graphene on SiC



Couëdo et al. *Appl. Phys. Lett.* 128, 034005 (2026)

Encapsulated Graphene



Zhou et al. *Nanomaterials* 12, 3777 (2022)

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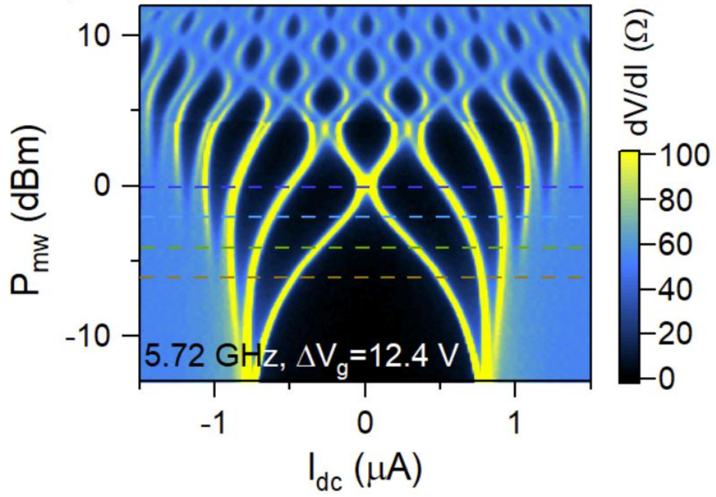

Heersche et al. *Nature* 446, 56-59 (2007)
Huang et al. *Appl. Phys. Lett.* 122, 262601 (2023)

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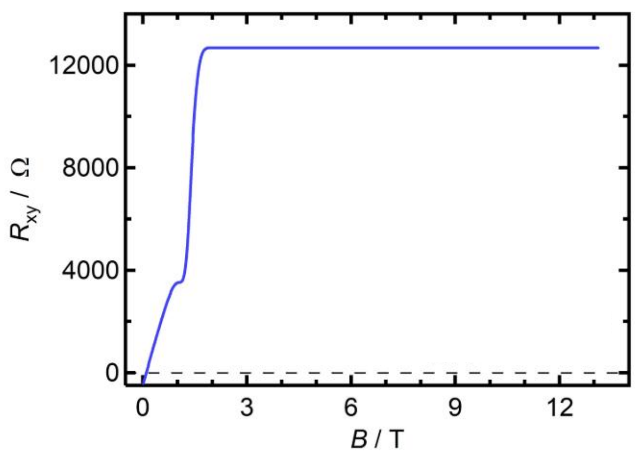

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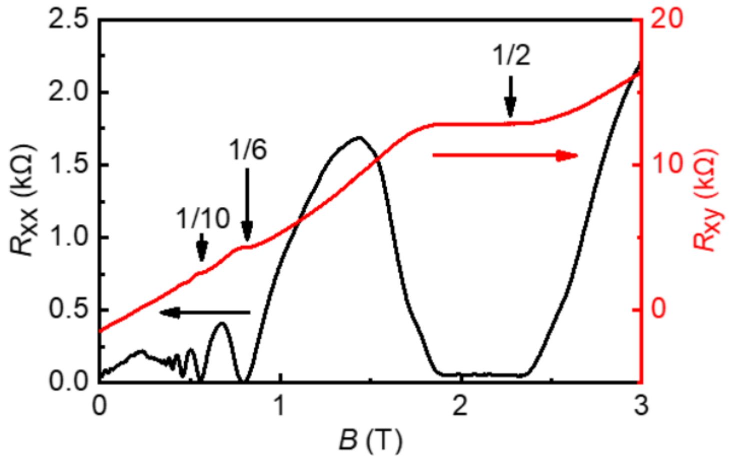
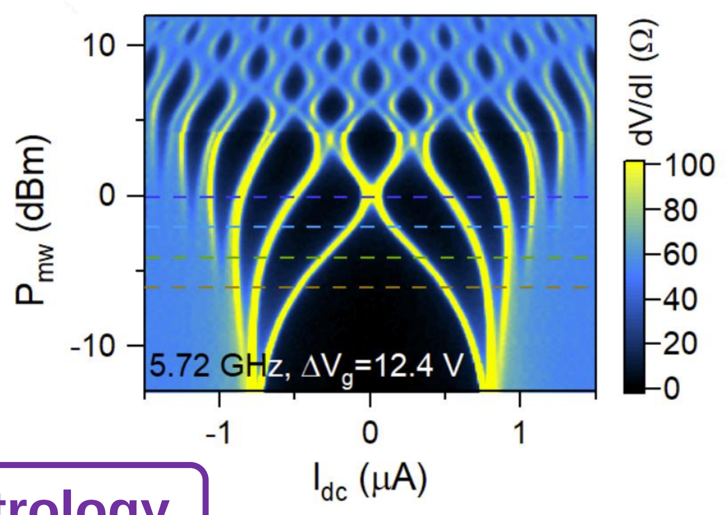


Zhou et al. *Nanomaterials* 12, 3777 (2022)

- **AC Josephson effect (V)**

  - Junction characterisation

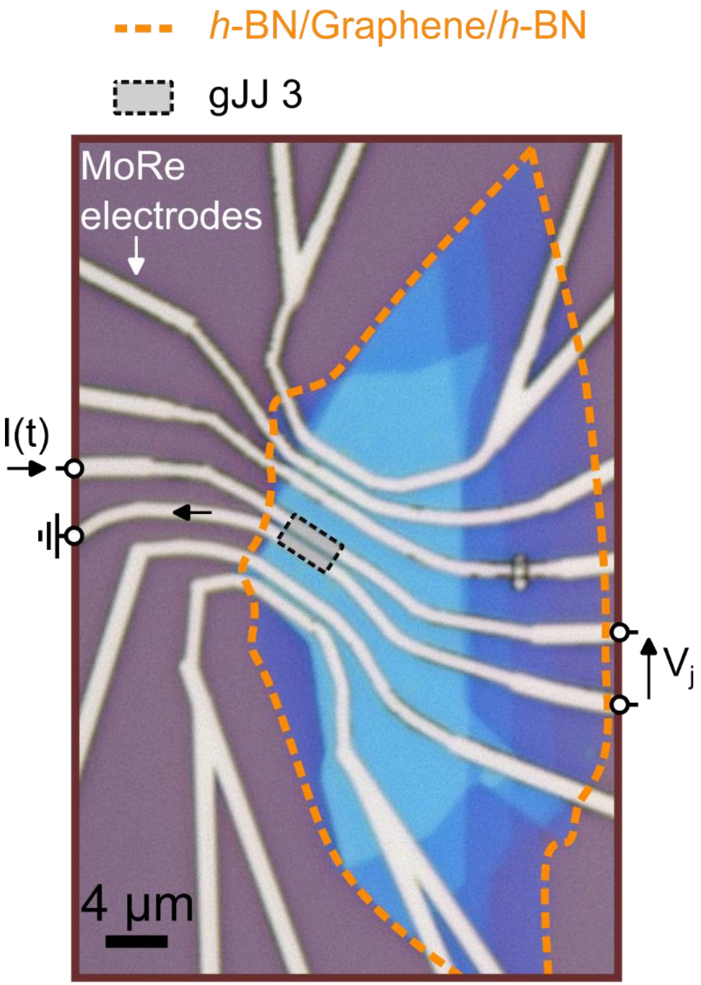
  - Voltage metrology



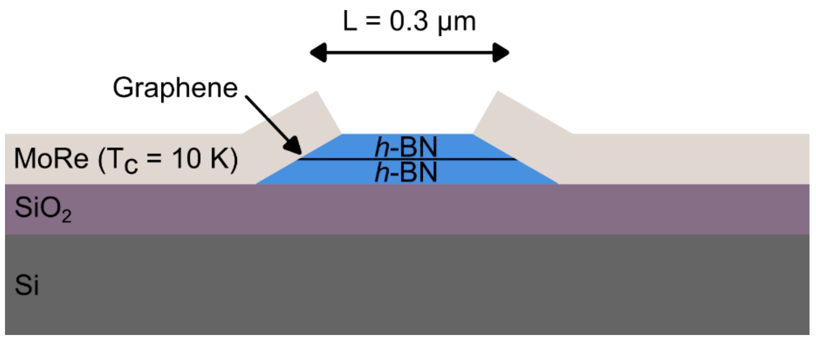
Heersche et al. *Nature* 446, 56-59 (2007)
Huang et al. *Appl. Phys. Lett.* 122, 262601 (2023)

Exploring graphene for voltage metrology

A graphene Josephson junction (gJJ)



Fabricated at LMU (Efetov's group)



Length = 0.3 µm
Width = 4.2 µm
n-doped at $V_{gate} = 0$

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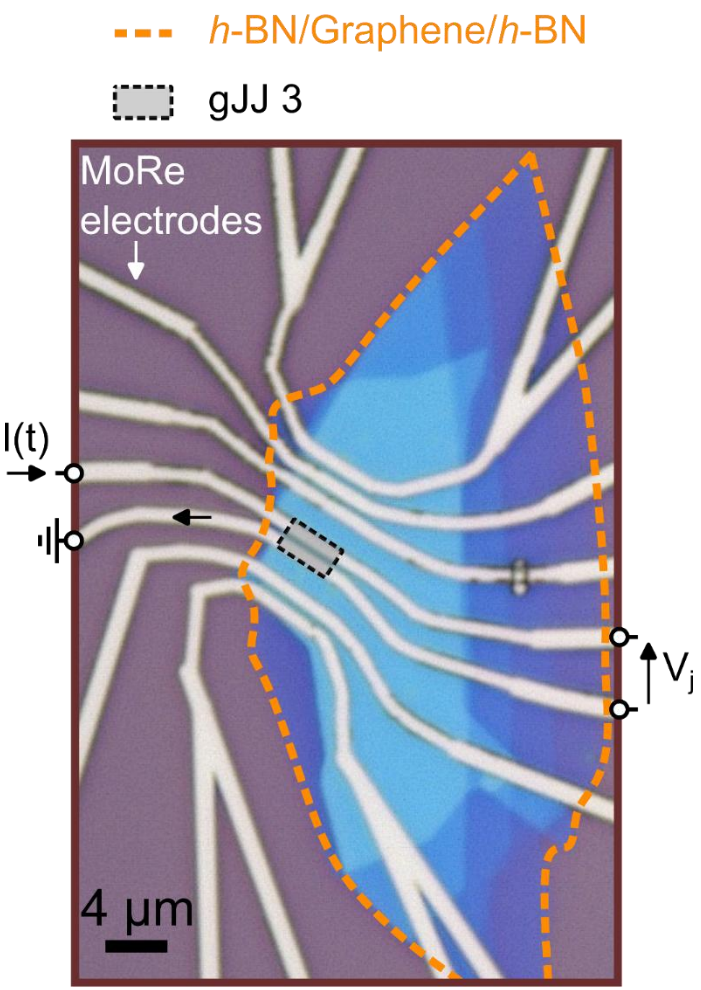

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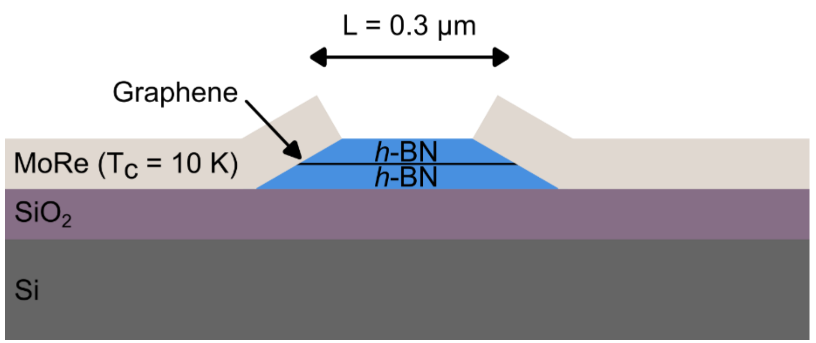

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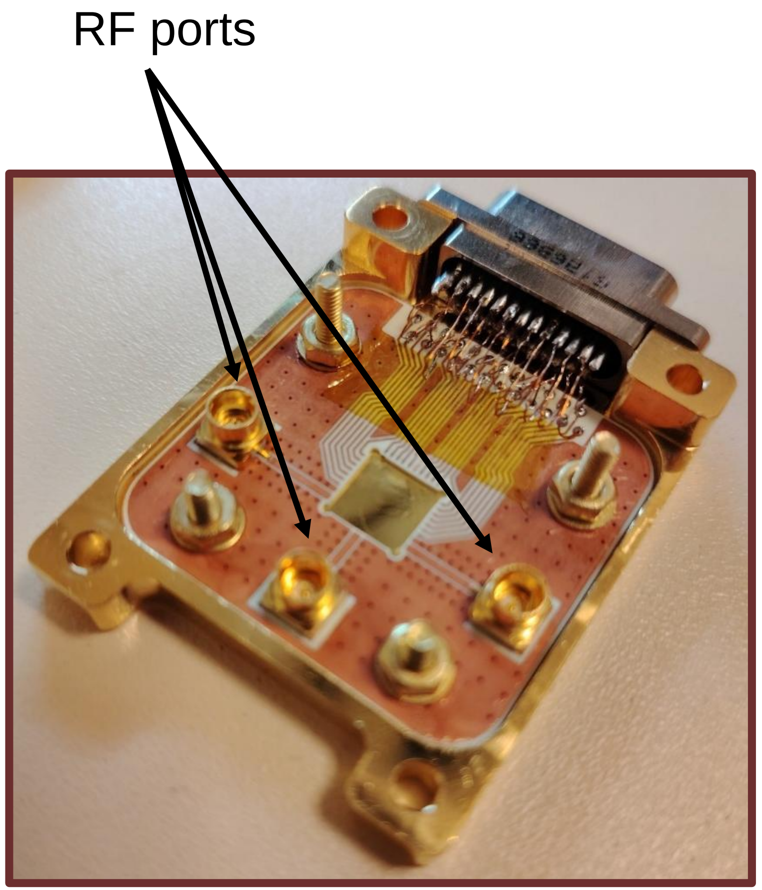

Sample holder

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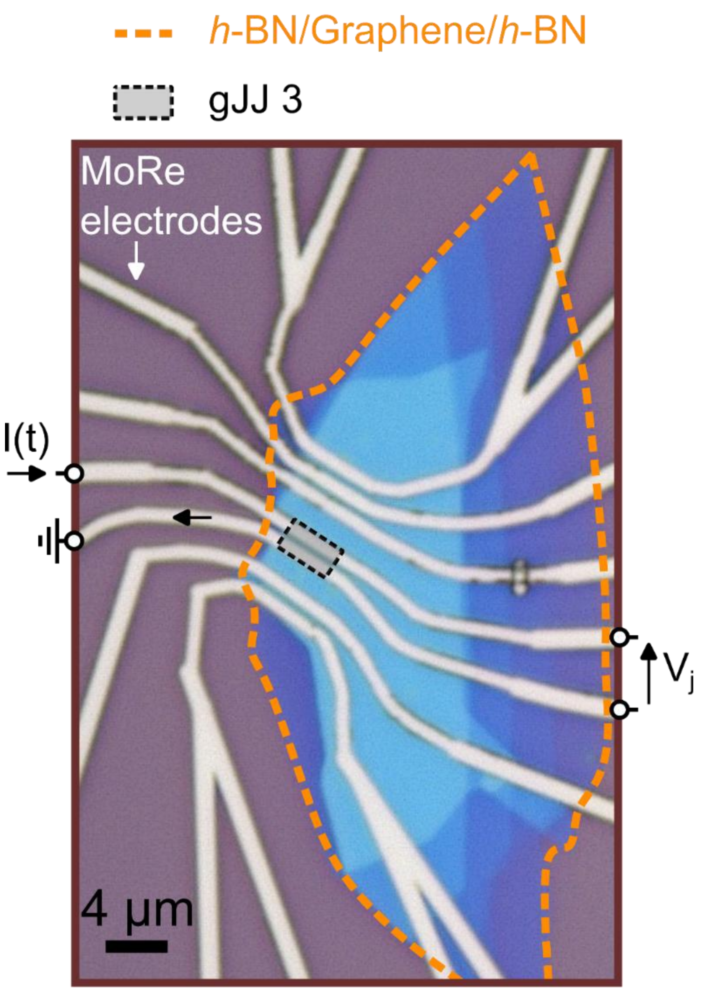
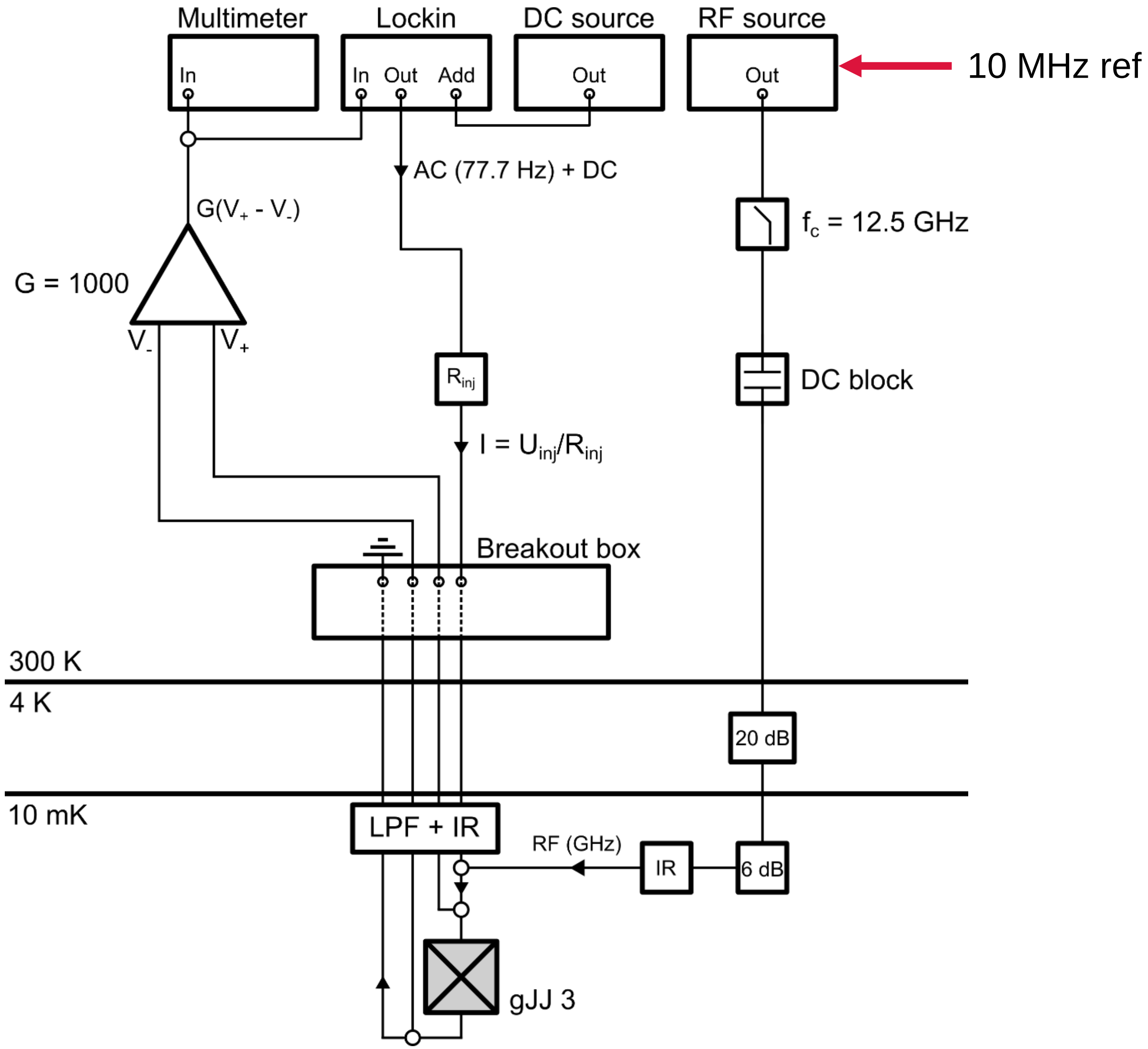
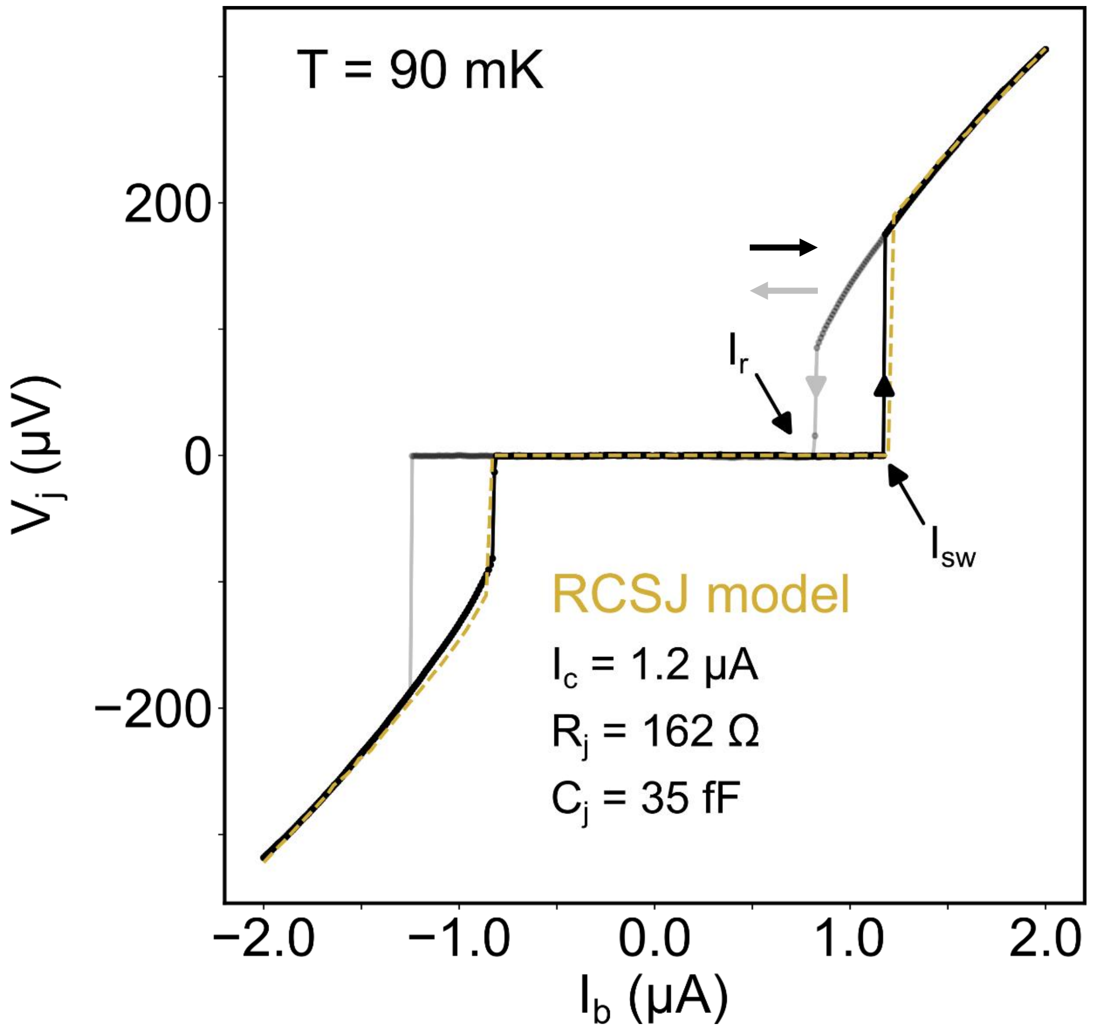
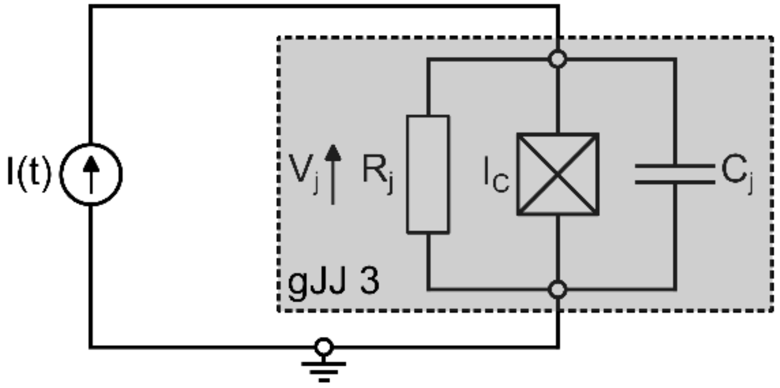




Dedicated DC & RF characterisation setup down to 10 mK

Supercurrent in graphene





RCSJ equivalent electrical circuit

I_{sw} = 1.2 μA

I_r = -0.84 μA

Junction's quality factor Q = 1.83

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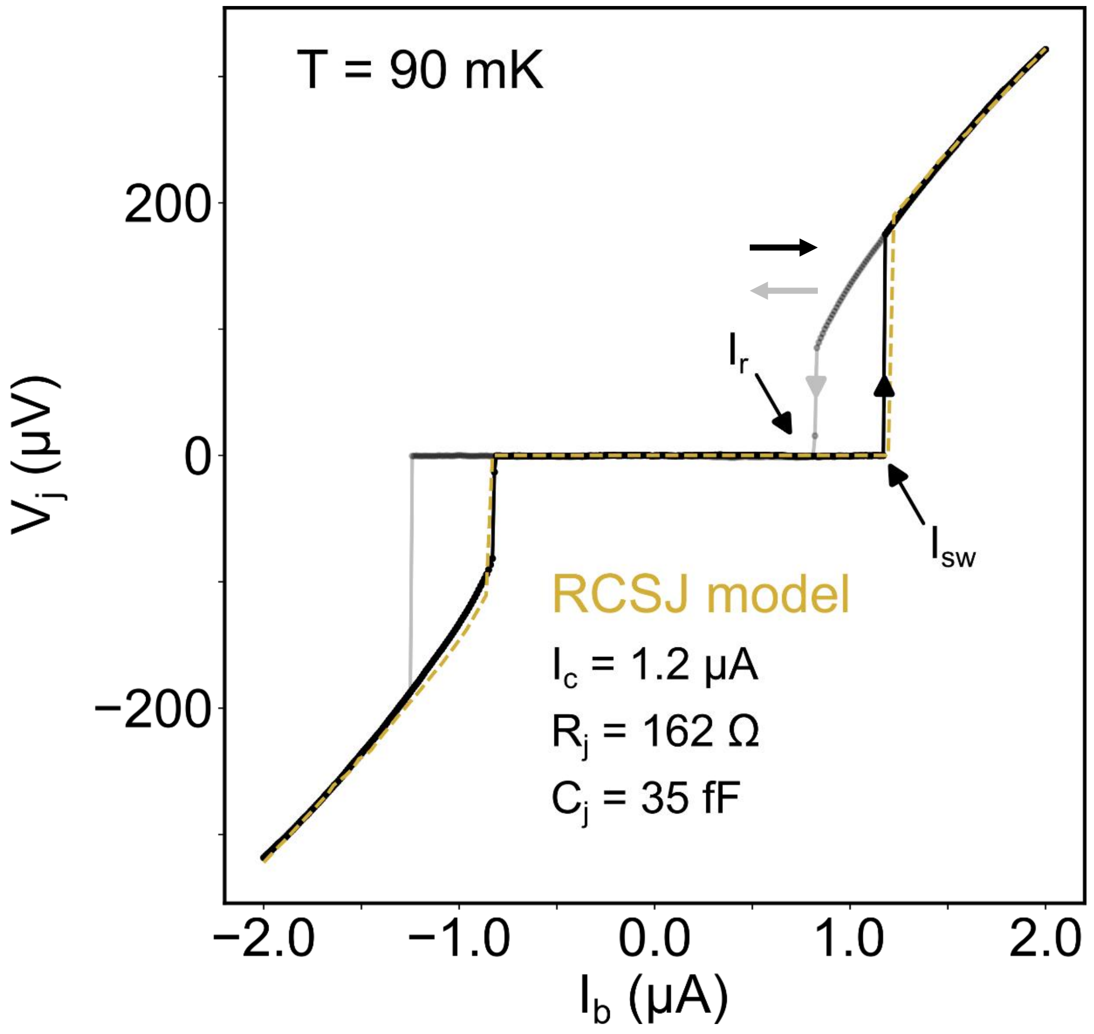

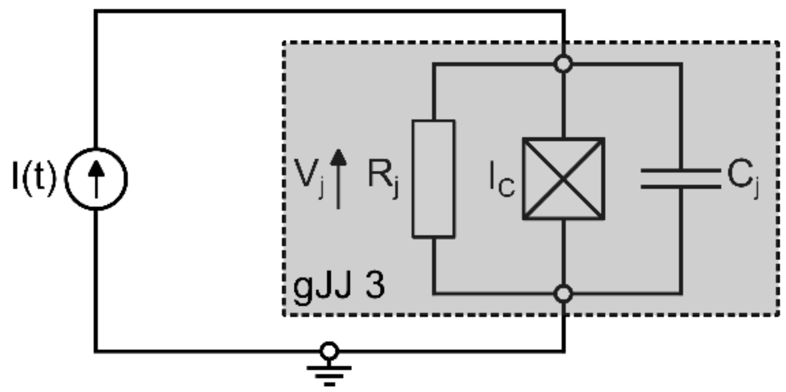

RCSJ equivalent electrical circuit

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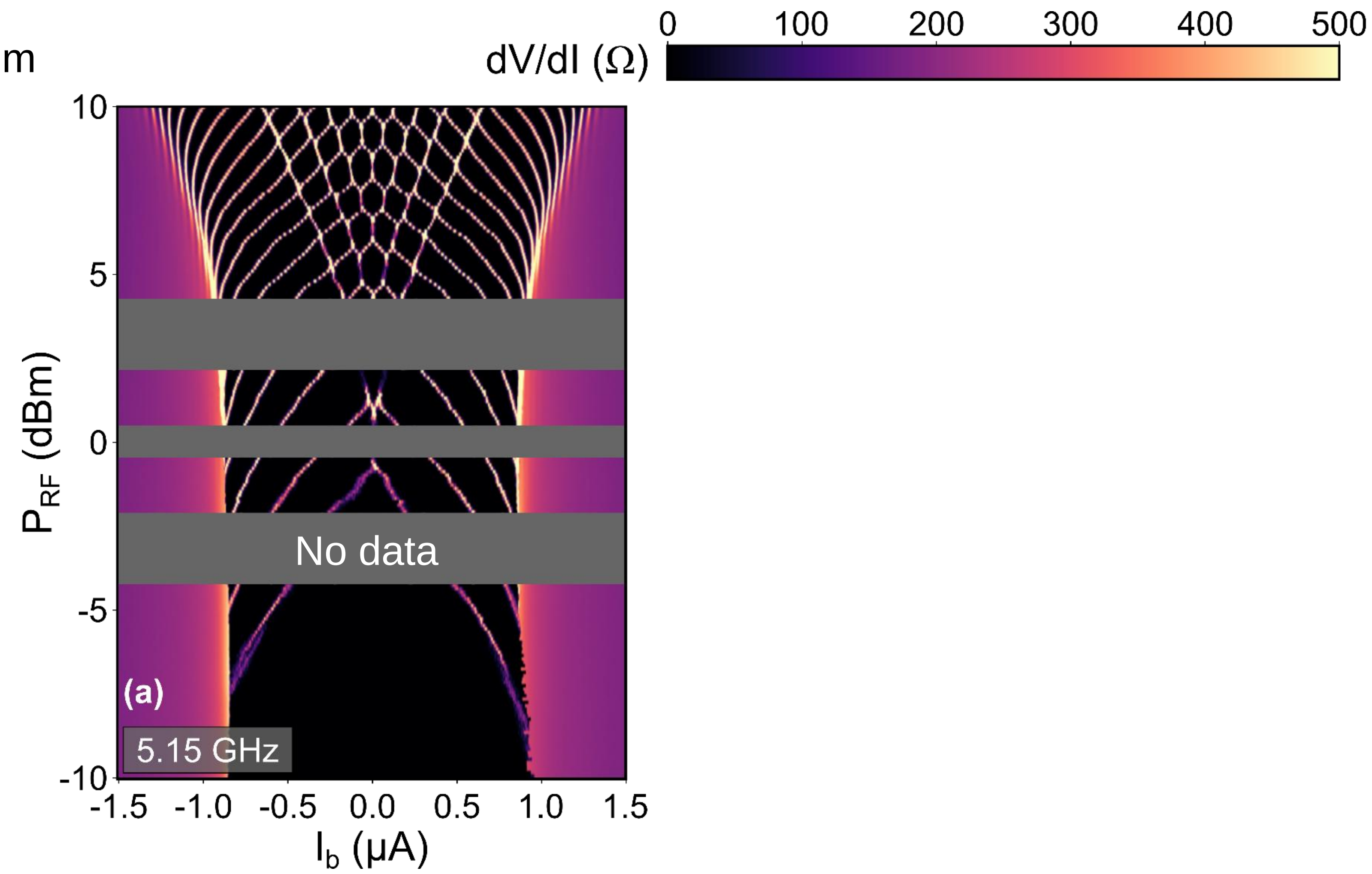
Supercurrent in slightly underdamped graphene junction

AC Josephson effect at T = 90 mK

20 dBm



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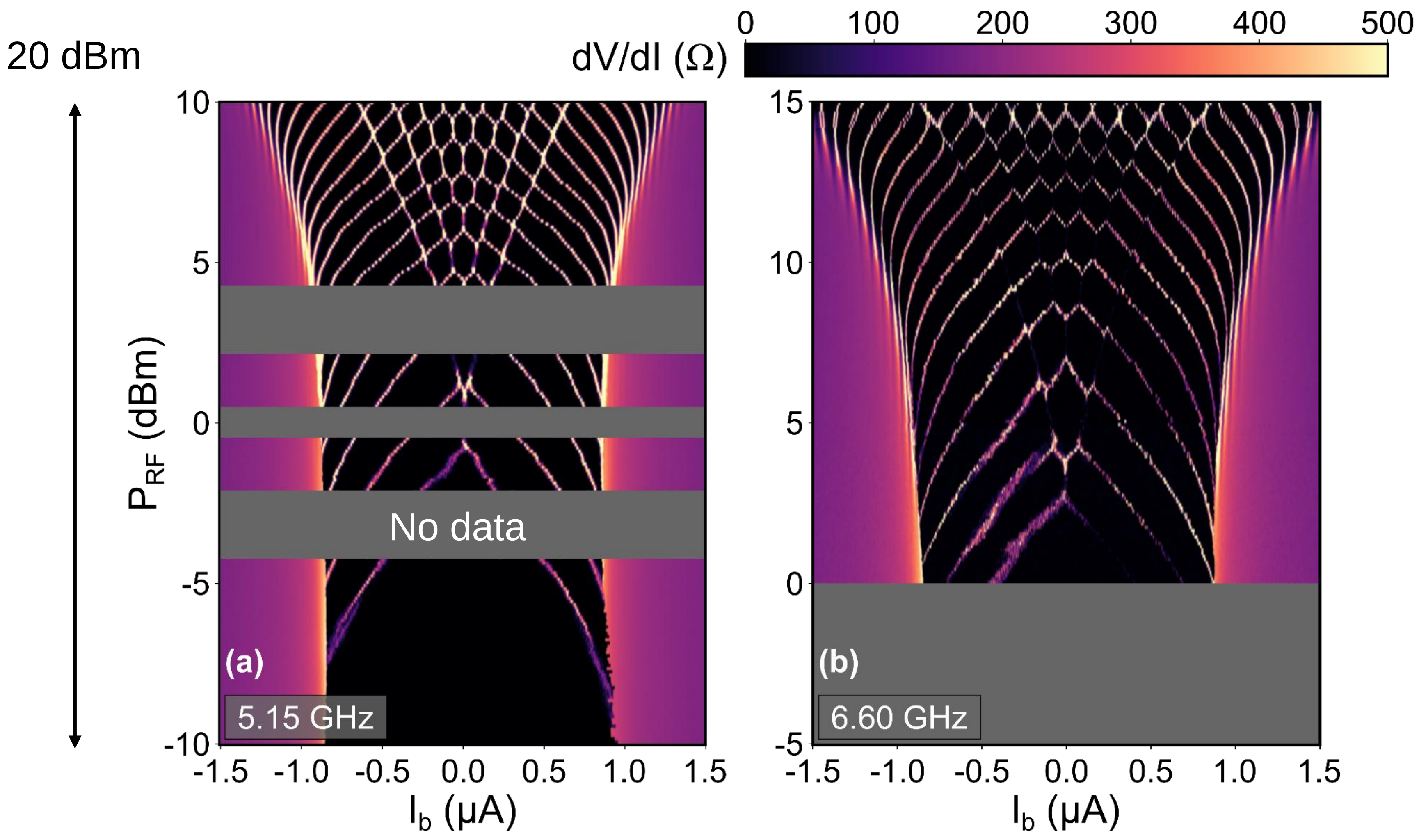

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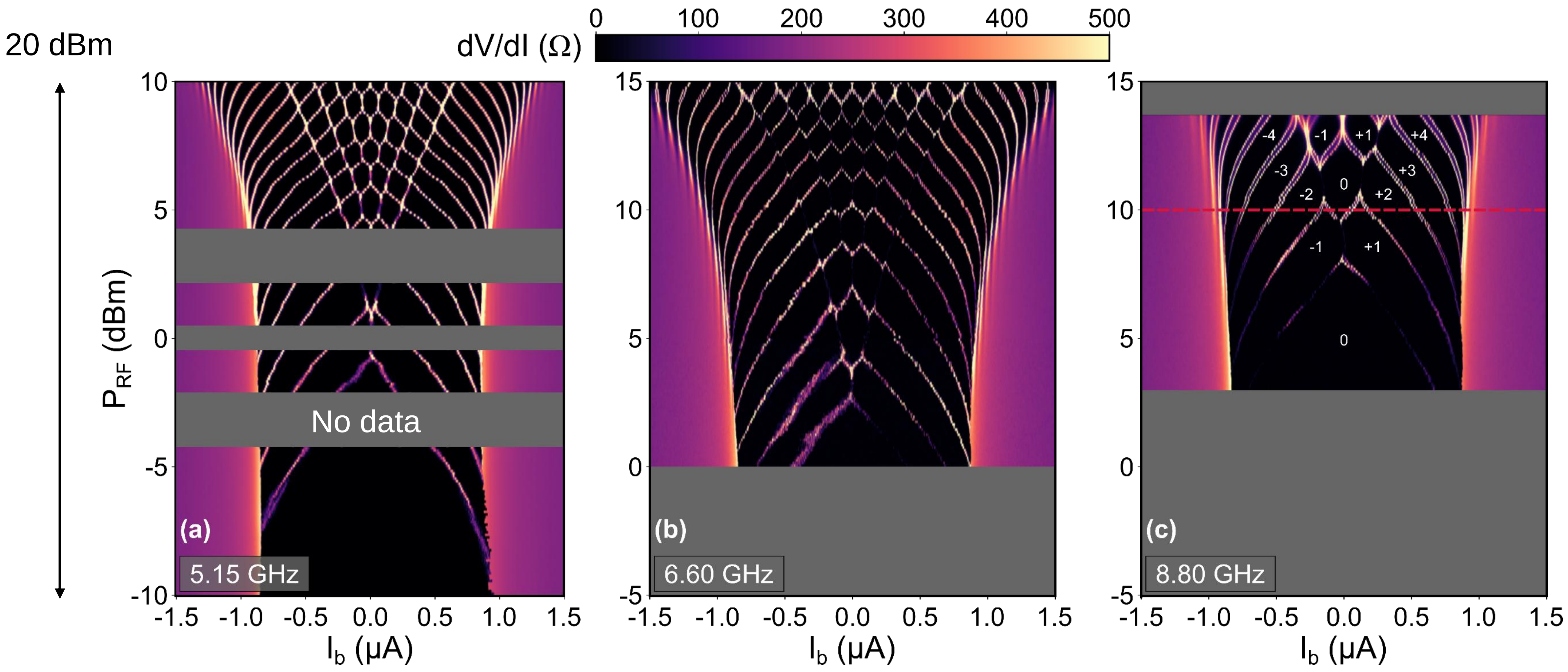

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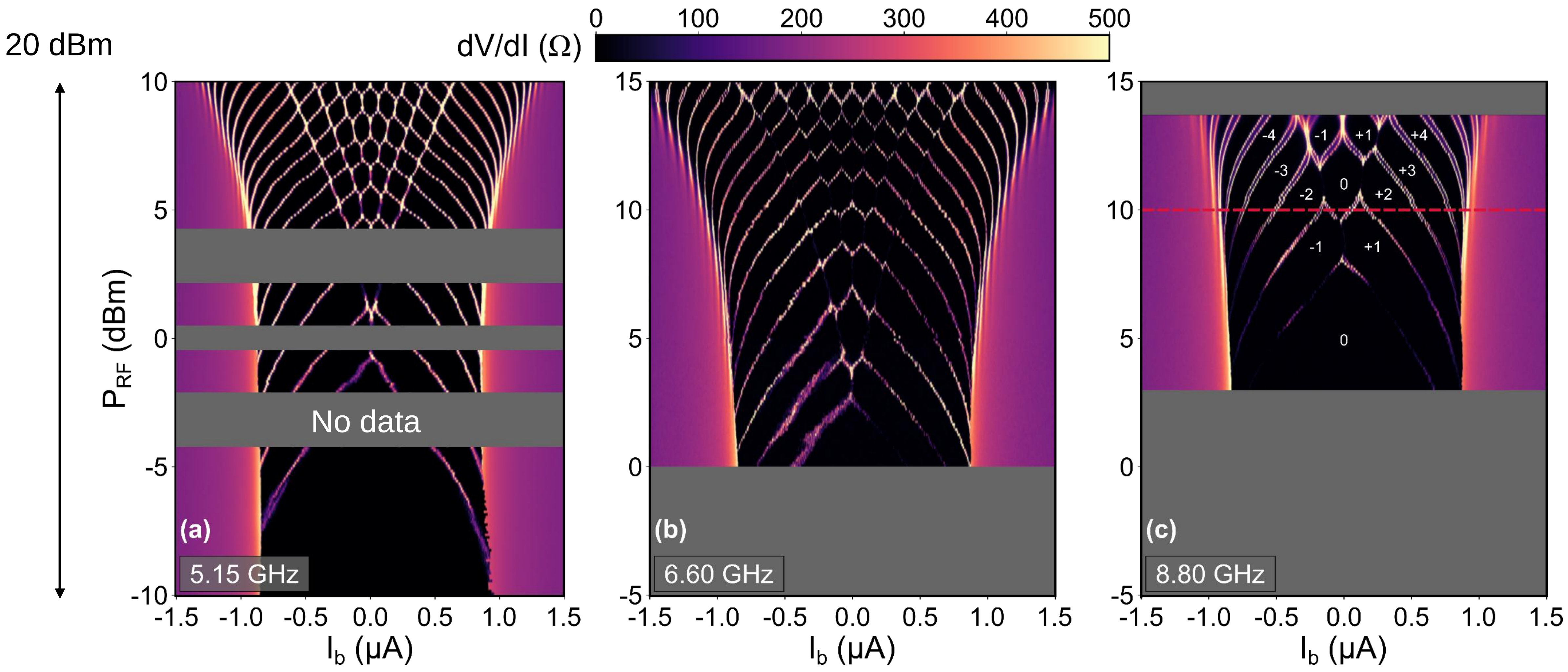
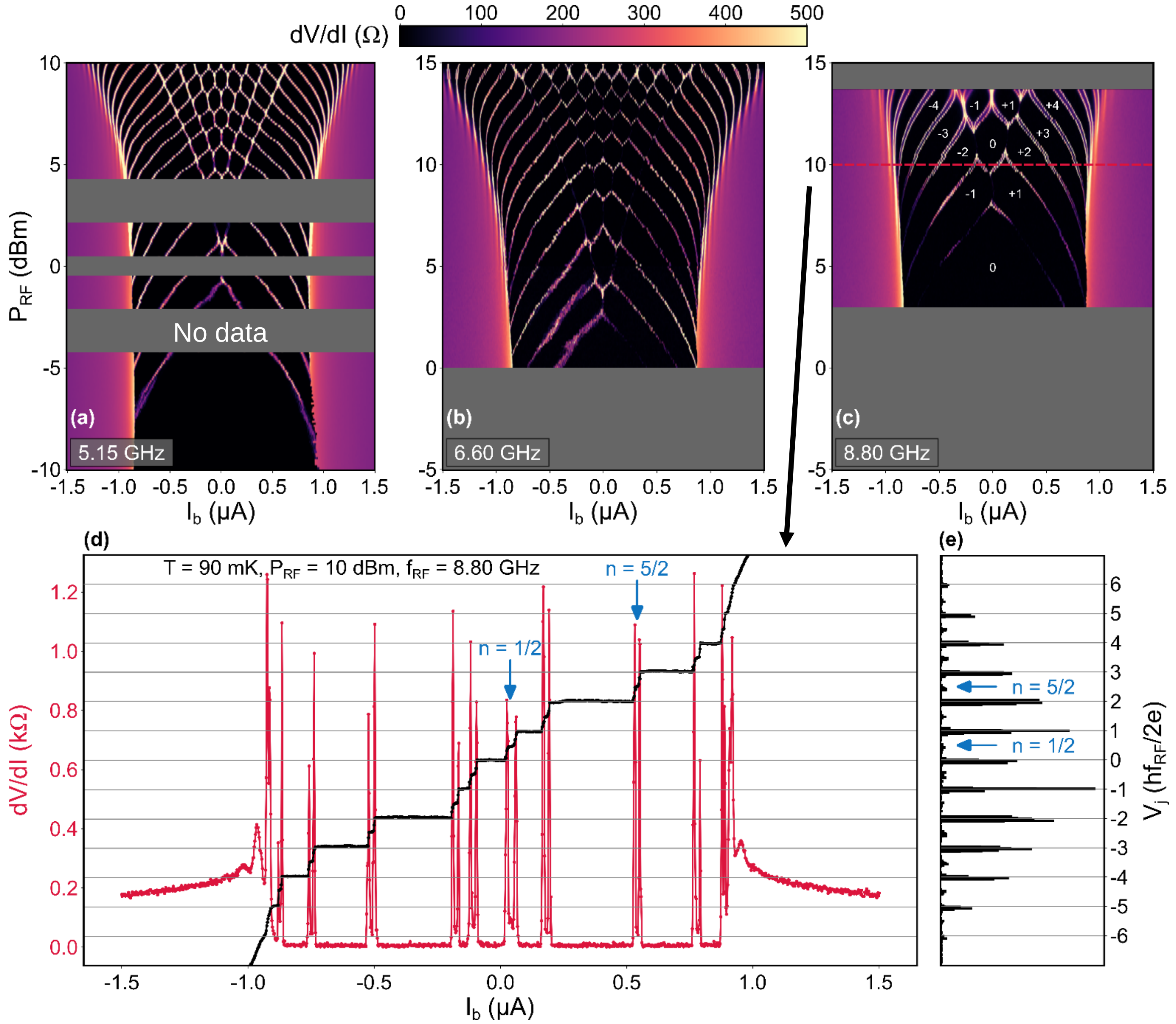


Appearance of other plateaus at larger f_{RF}

Half-integer Shapiro steps in graphene



- Half-integers observed in Ti/Al gJJ

Huang et al. *Appl. Phys. Lett.* 122, 262601 (2023)

- Non purely sinusoidal current-phase relation (CPR)

i.e. $\mathrm{I}(\varphi) = \sum_{n=0}^{\infty} I_{C,n} \sin(n\varphi)$

Messelot, Aparicio et al. *Phys. Rev. Lett.* 133, 106001 (2024)
Nanda et al. *Nano Lett.* 17, 6, 3396-3401 (2017)

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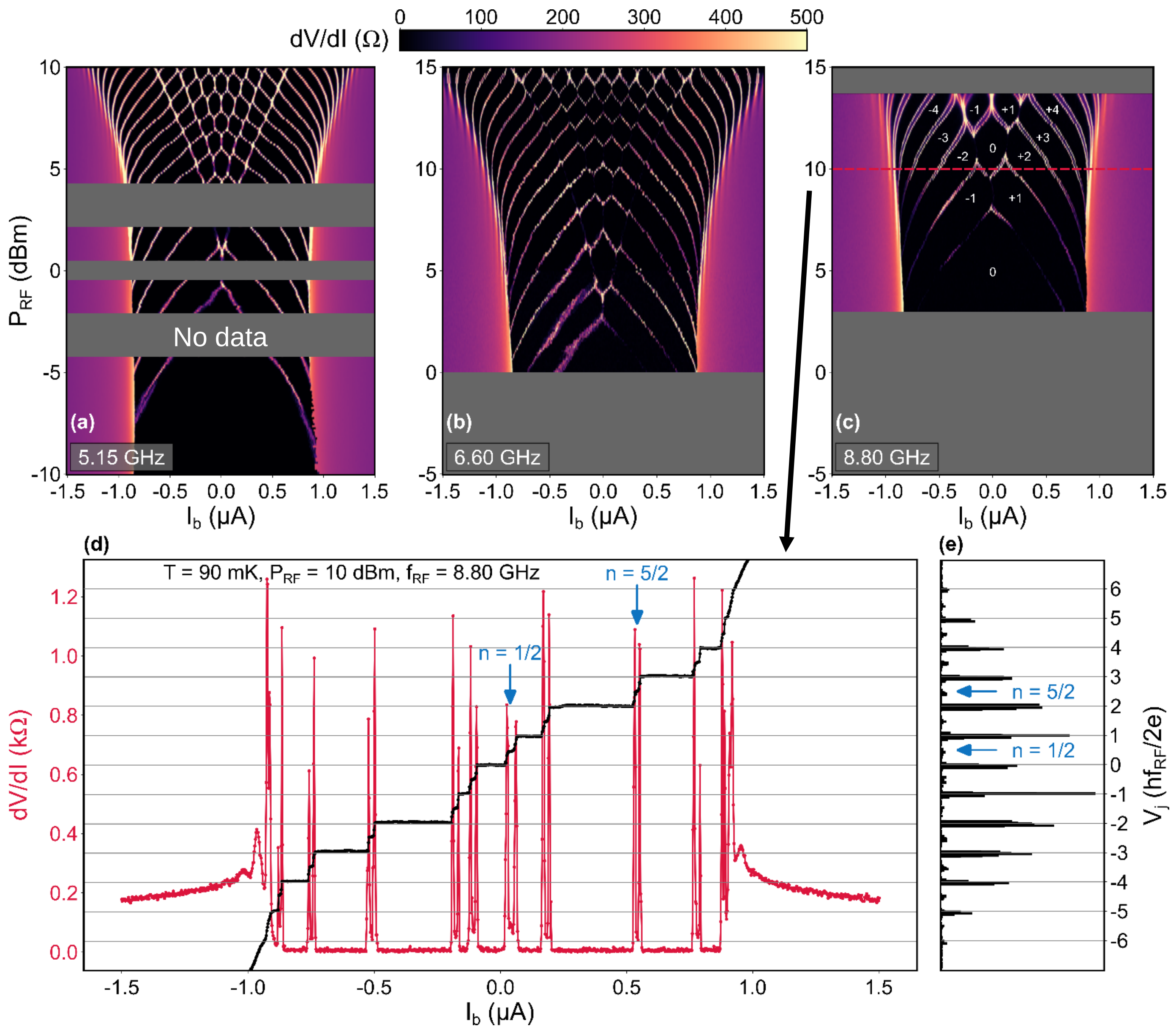

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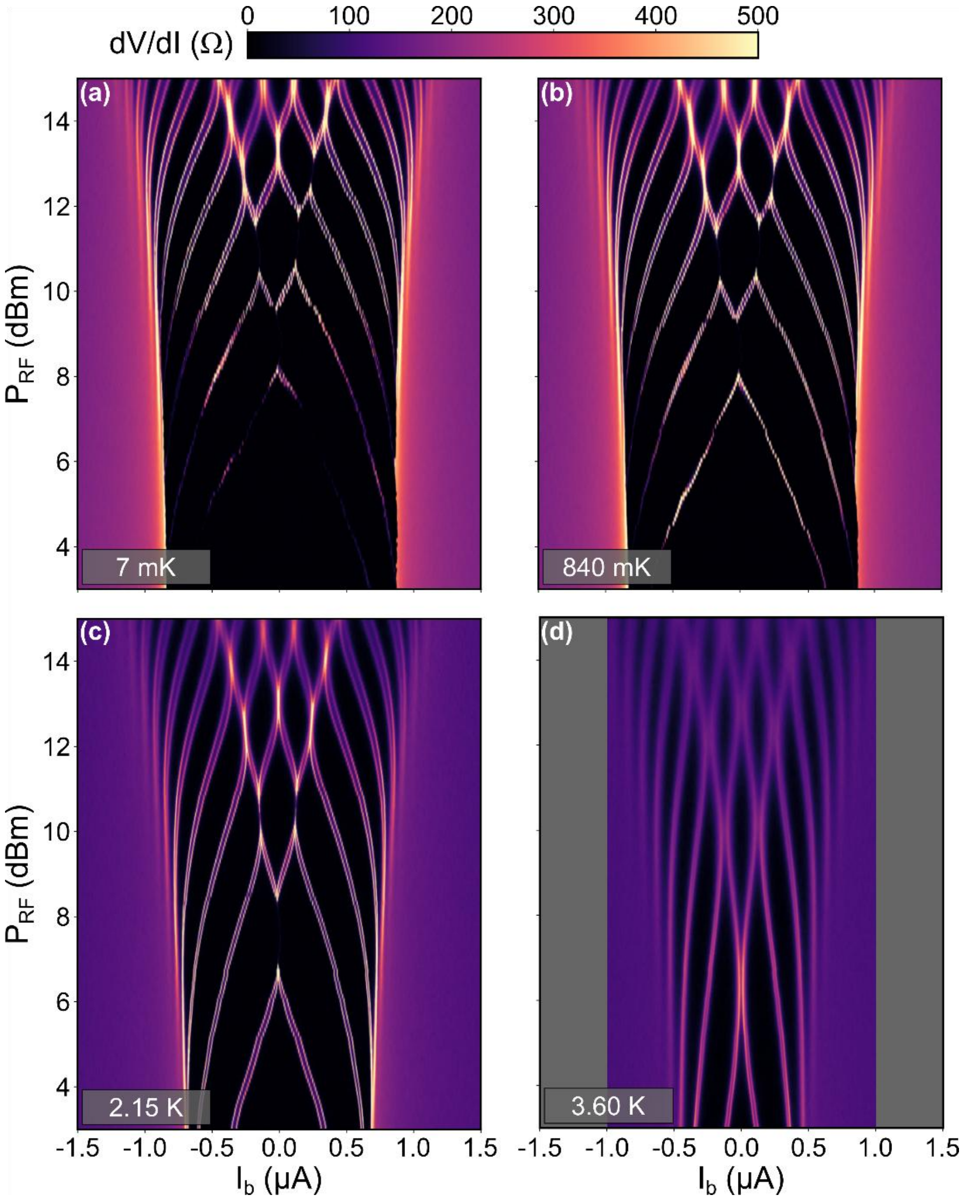
Non pure-sine CPR

AC Josephson effect at f_{RF} = 8.8 GHz

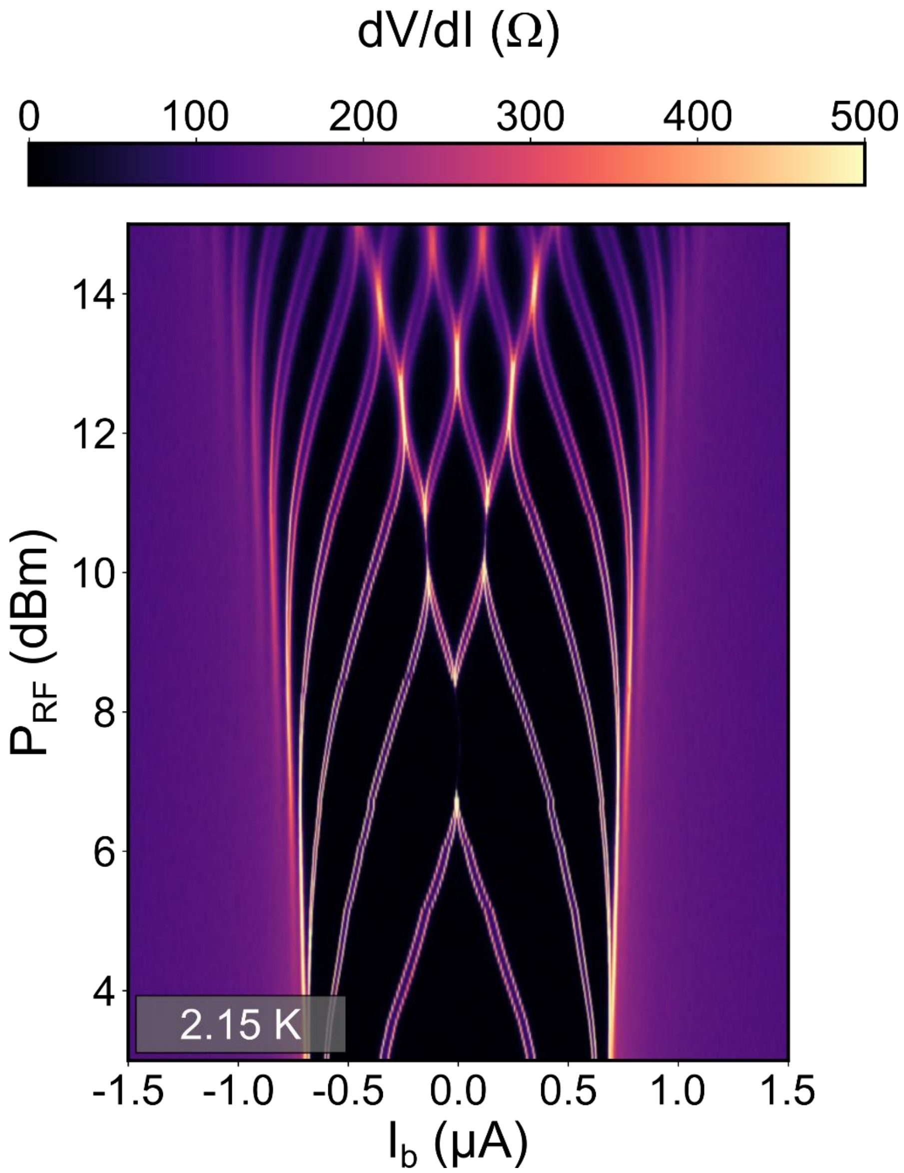


- Shapiro steps in MoRe gJJ up to 3.6 K

Larson et al. Nano Lett. 20, 10, 6998 – 7003 (2020)
Kalantre et al. *Phys. Rev. Research* 2, 023093 (2020)

- Half-integer steps seem better defined at T = 2.15 K
  RCSJ simulation (ongoing analysis)

AC Josephson effect at f_{RF} = 8.8 GHz – RCSJ simulation



$$\mathrm{I}(\varphi) = \sum_{n=0}^{\infty} I_{C,n} \sin(n\varphi)$$

I_c = 0.68 μA
C_j = 22 fF
R_j = 155 Ω

(a): $I_{c,1} = I_c$ (pure sine CPR)

(b): $I_{c,1} = 0.2 I_c$ & $I_{c,2} = 0.8\ I_c$

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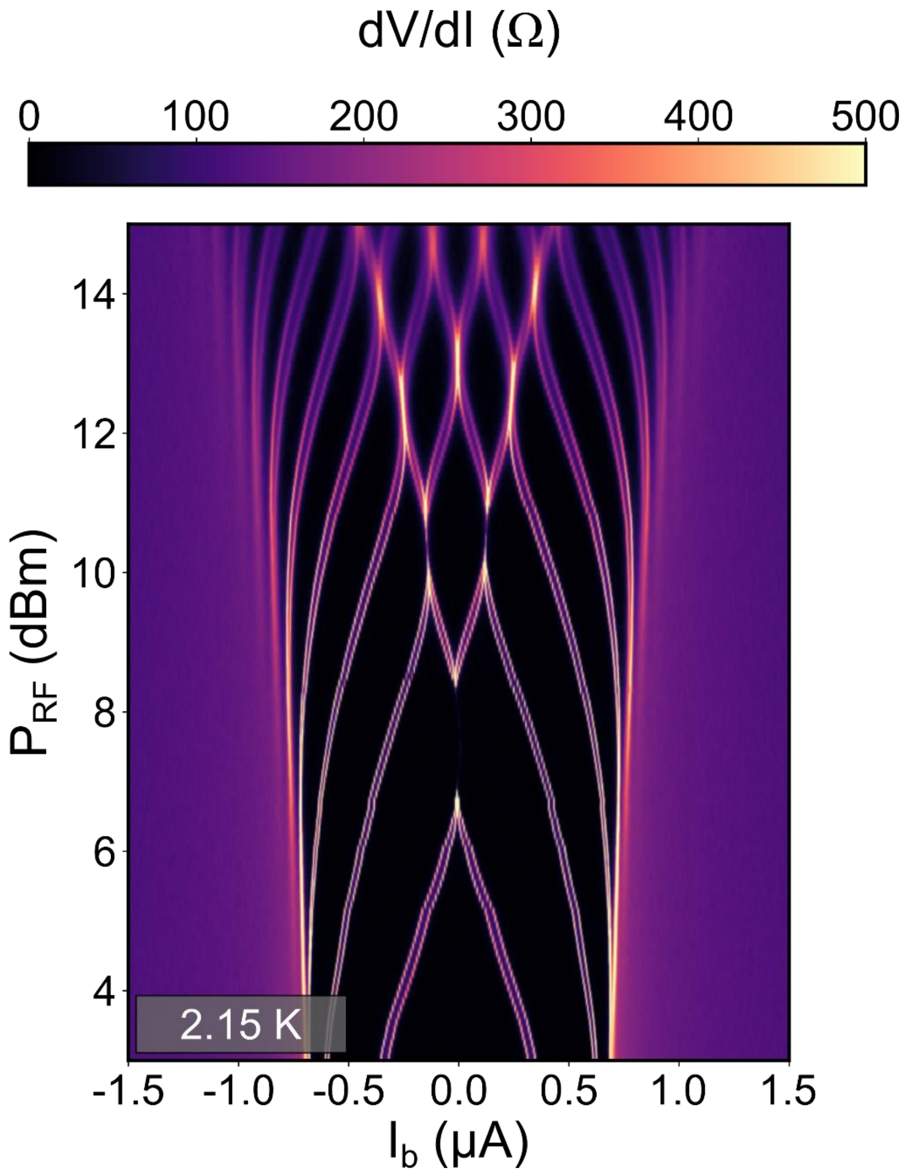

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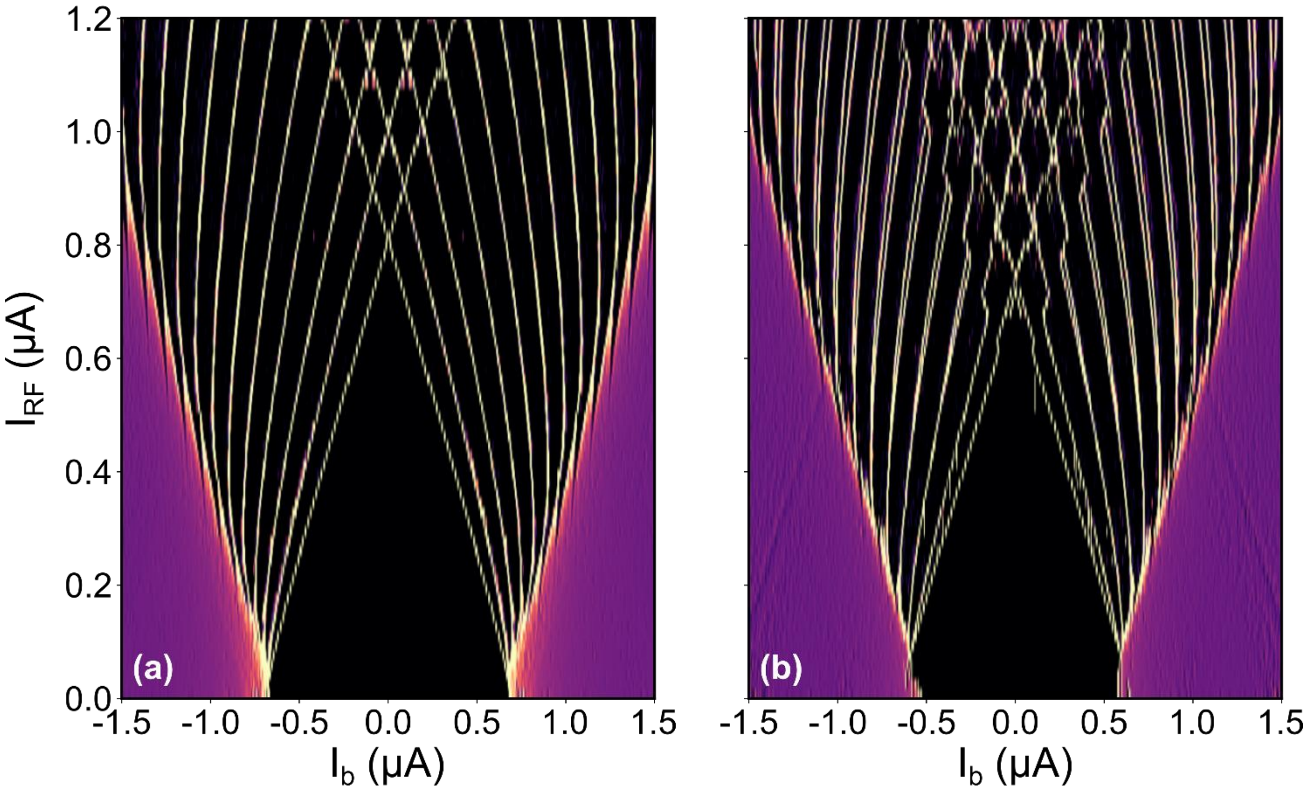

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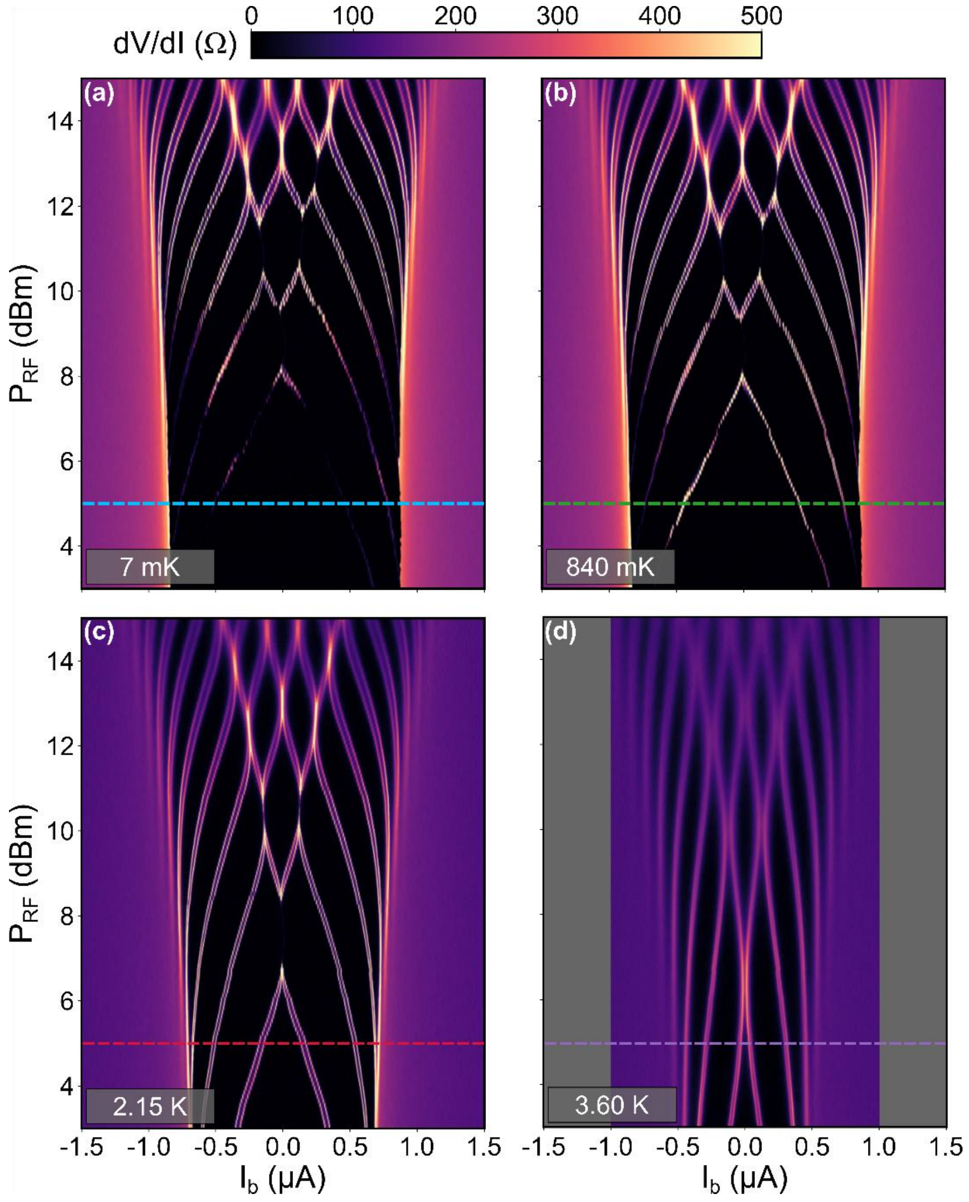
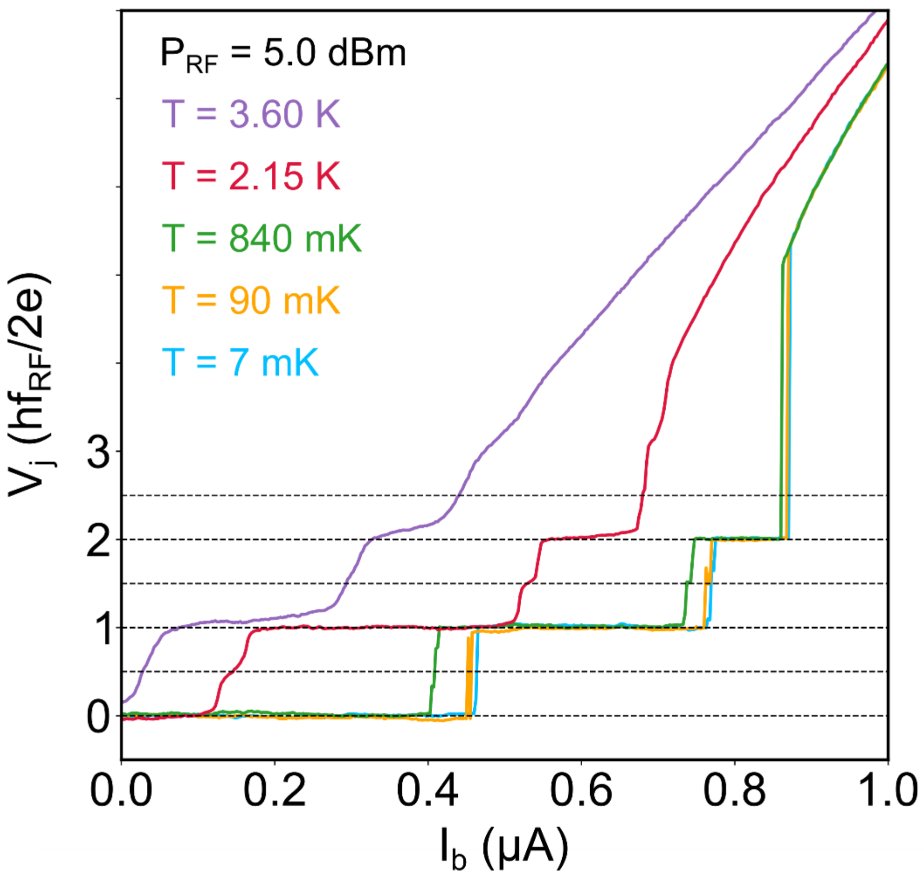
AC Josephson effect at f_{RF} = 8.8 GHz – Thermal effect





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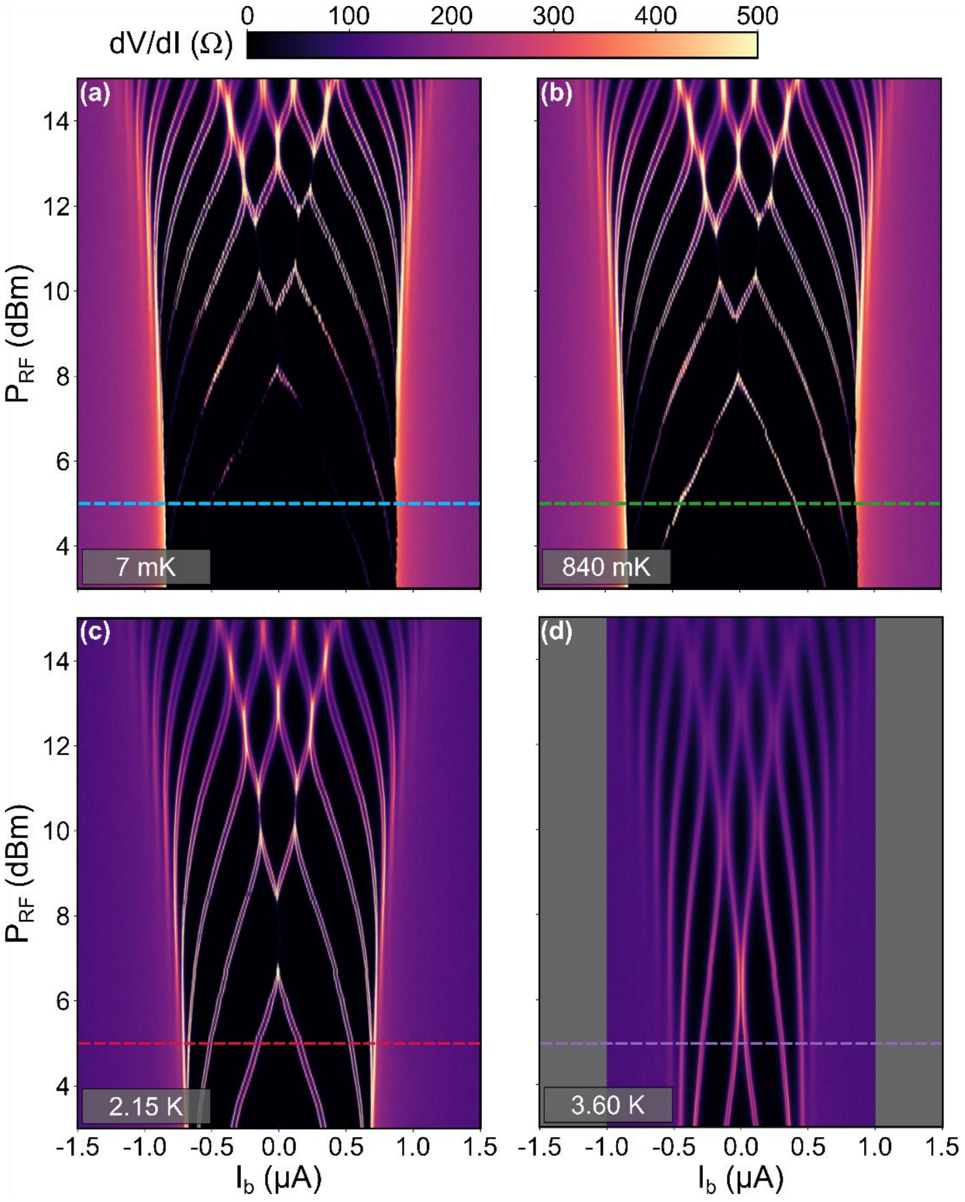
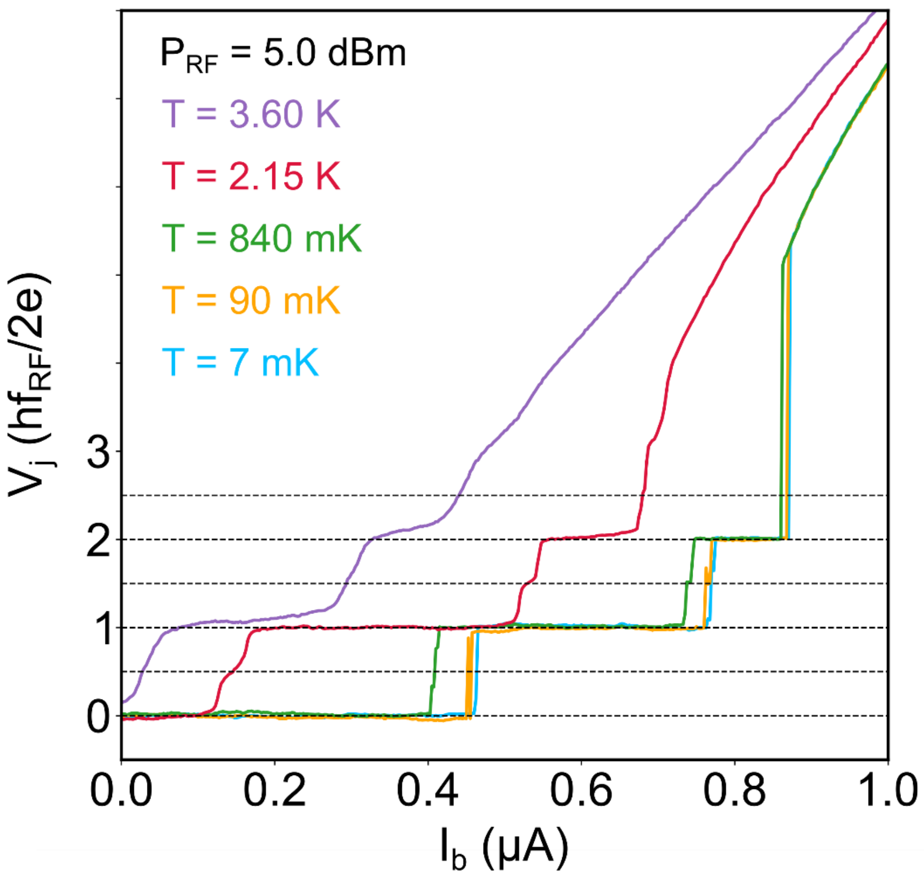
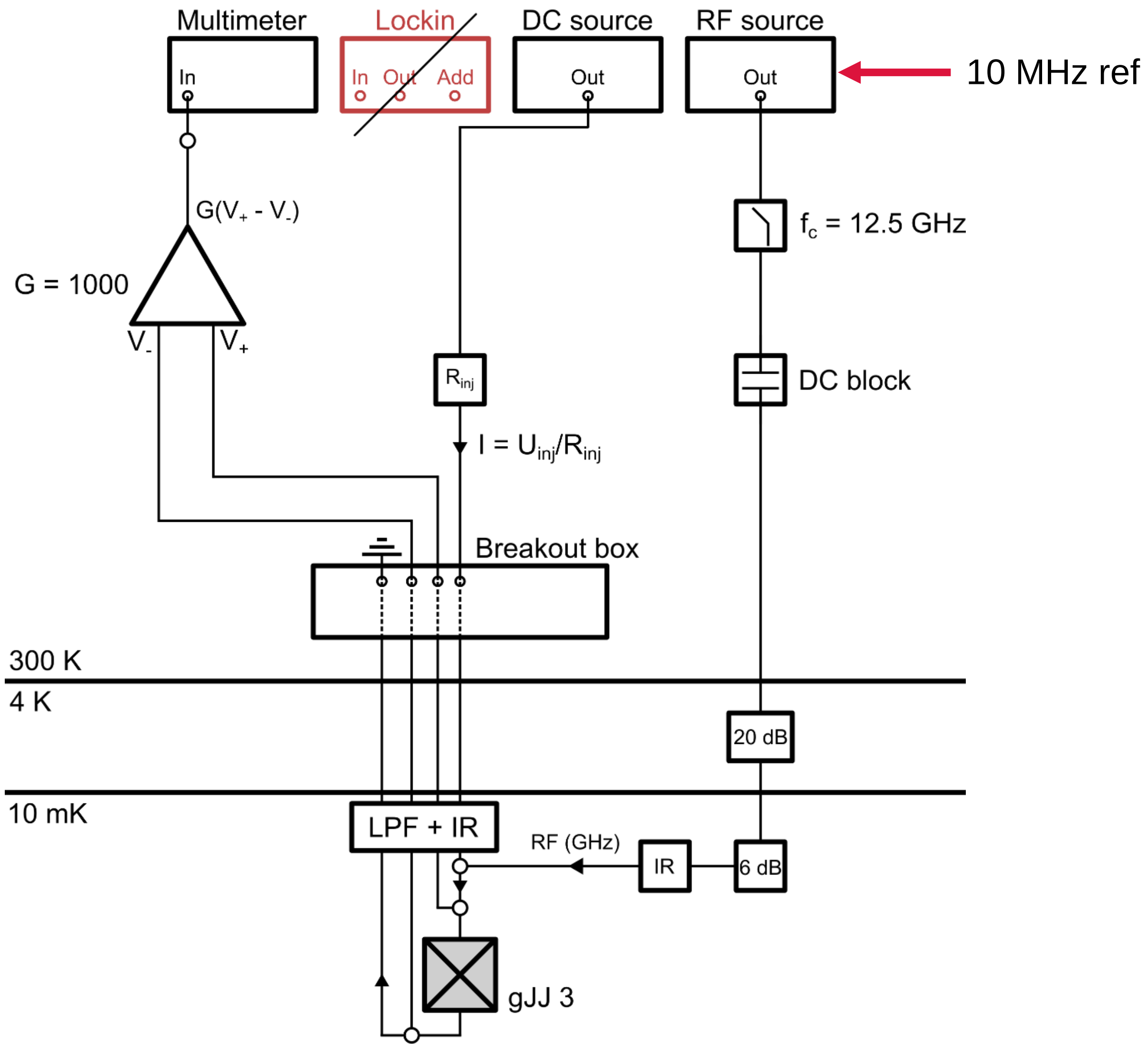




Temperature-resilience of the n = 1 Shapiro plateau ?

Voltage metrology in graphene



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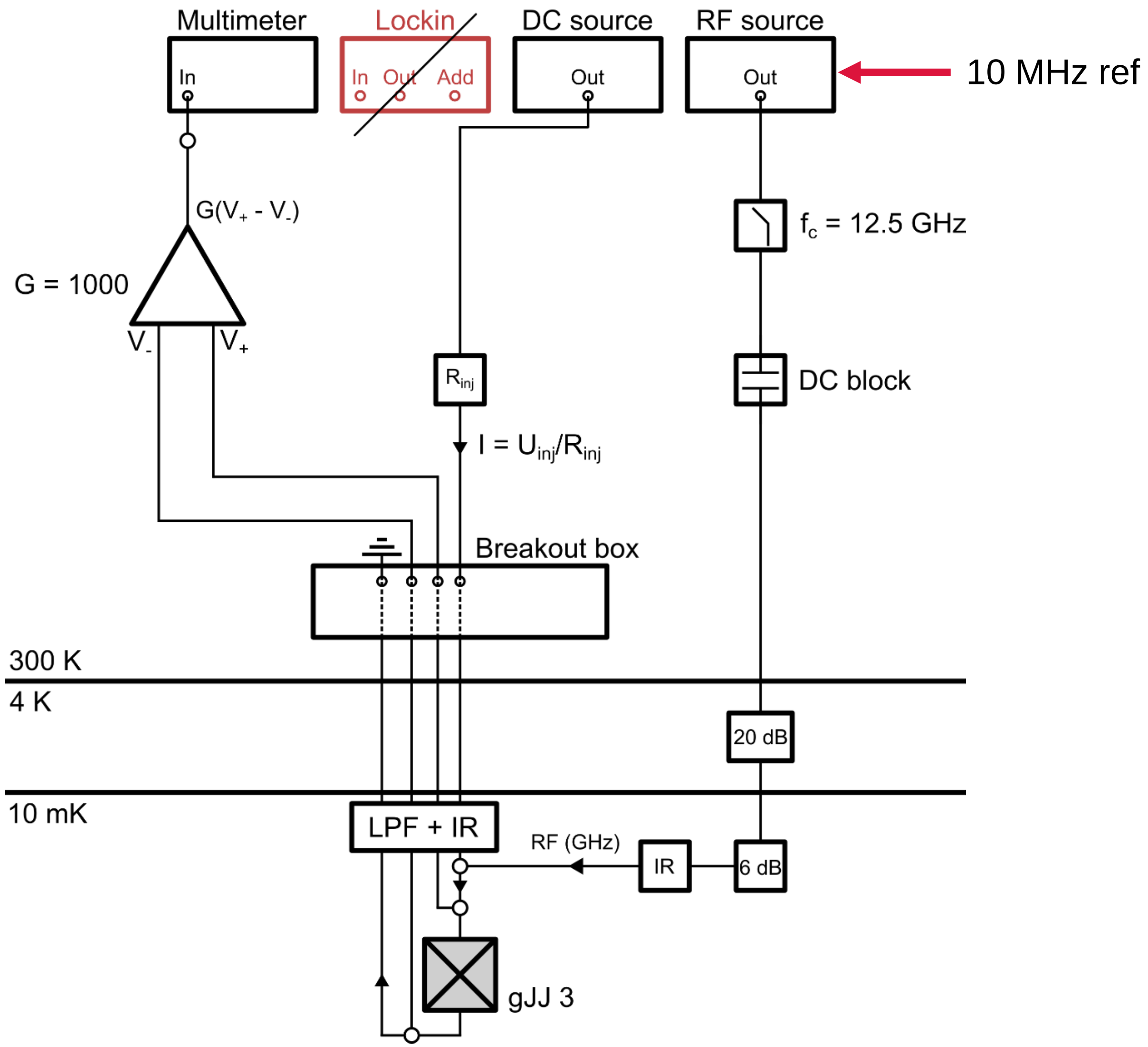

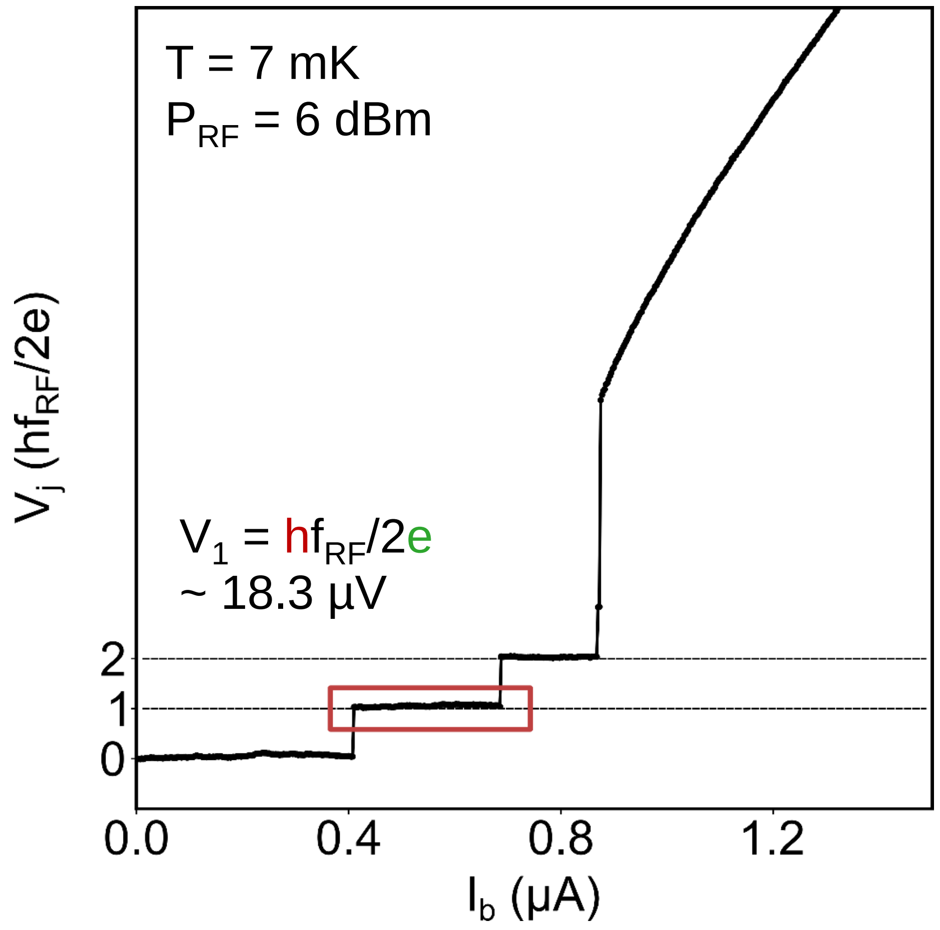

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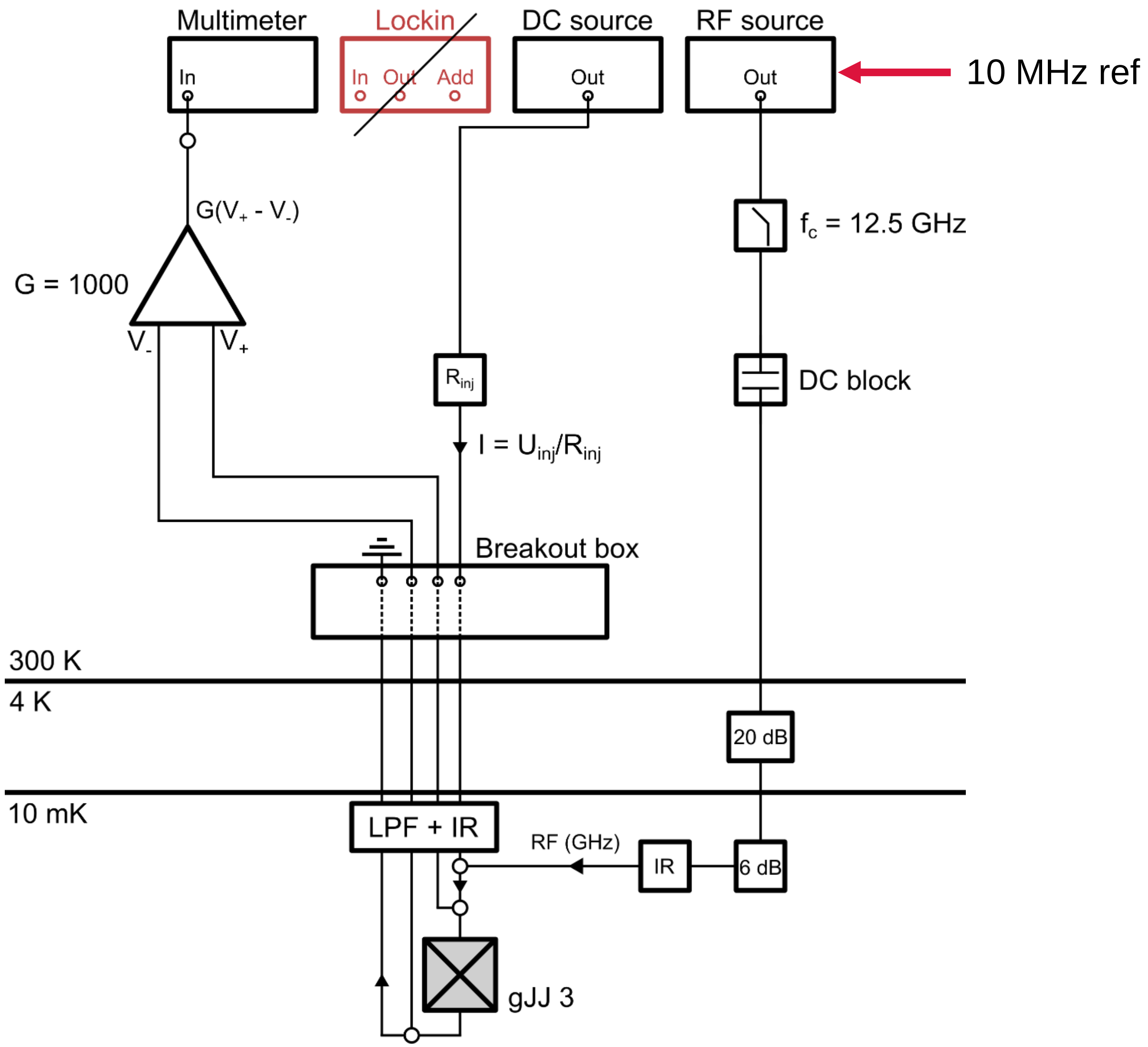
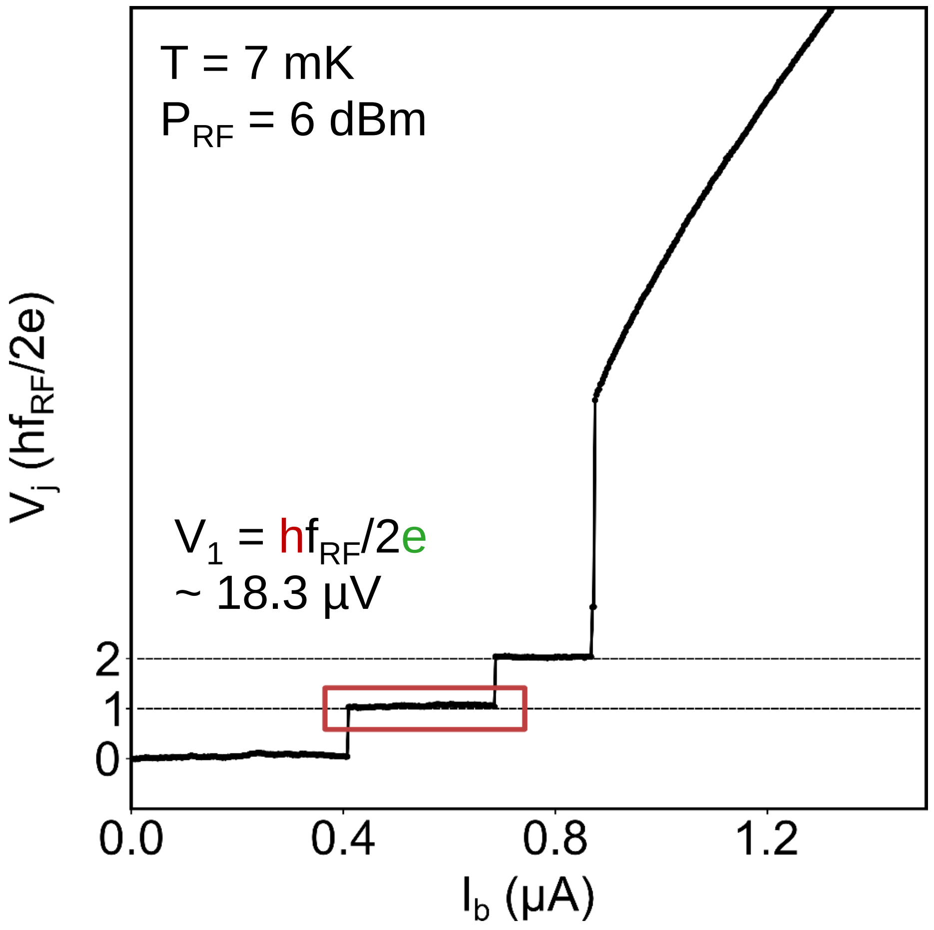
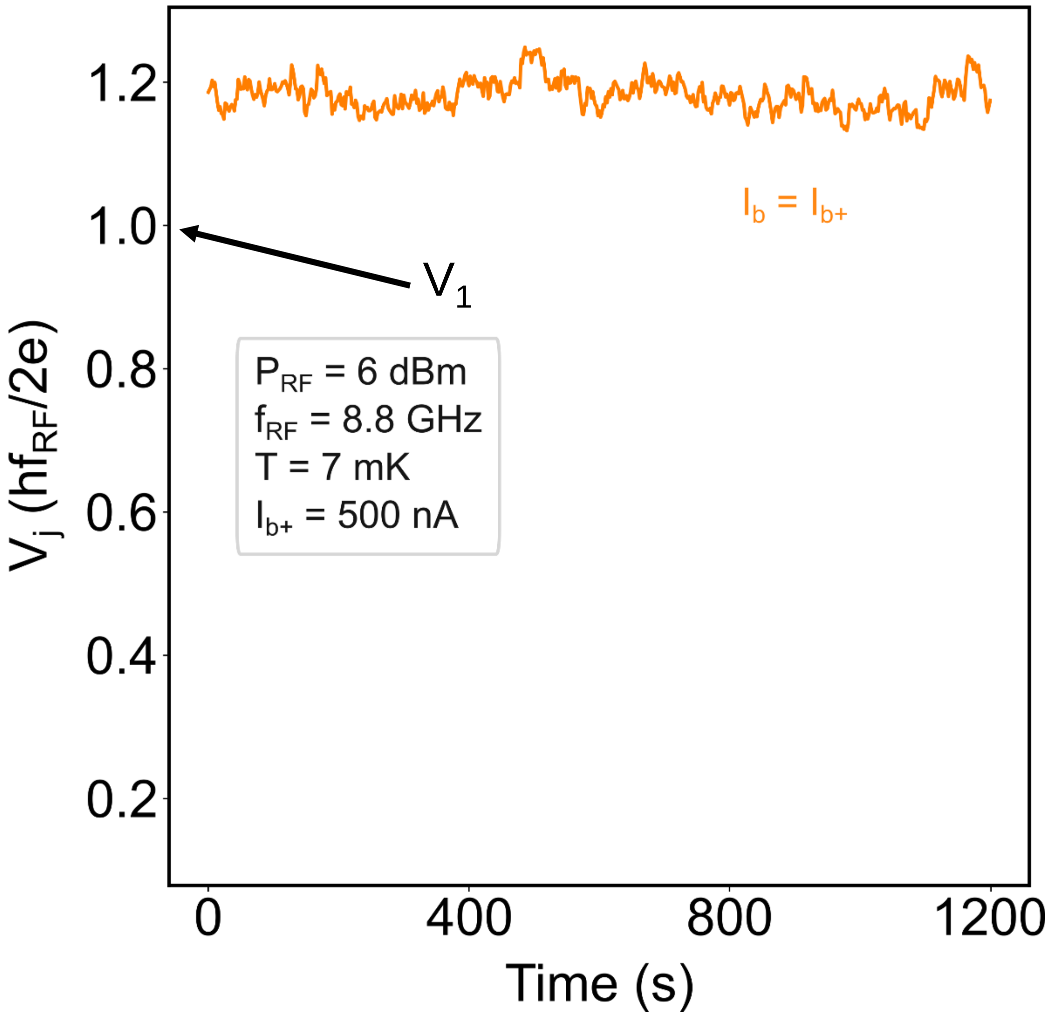
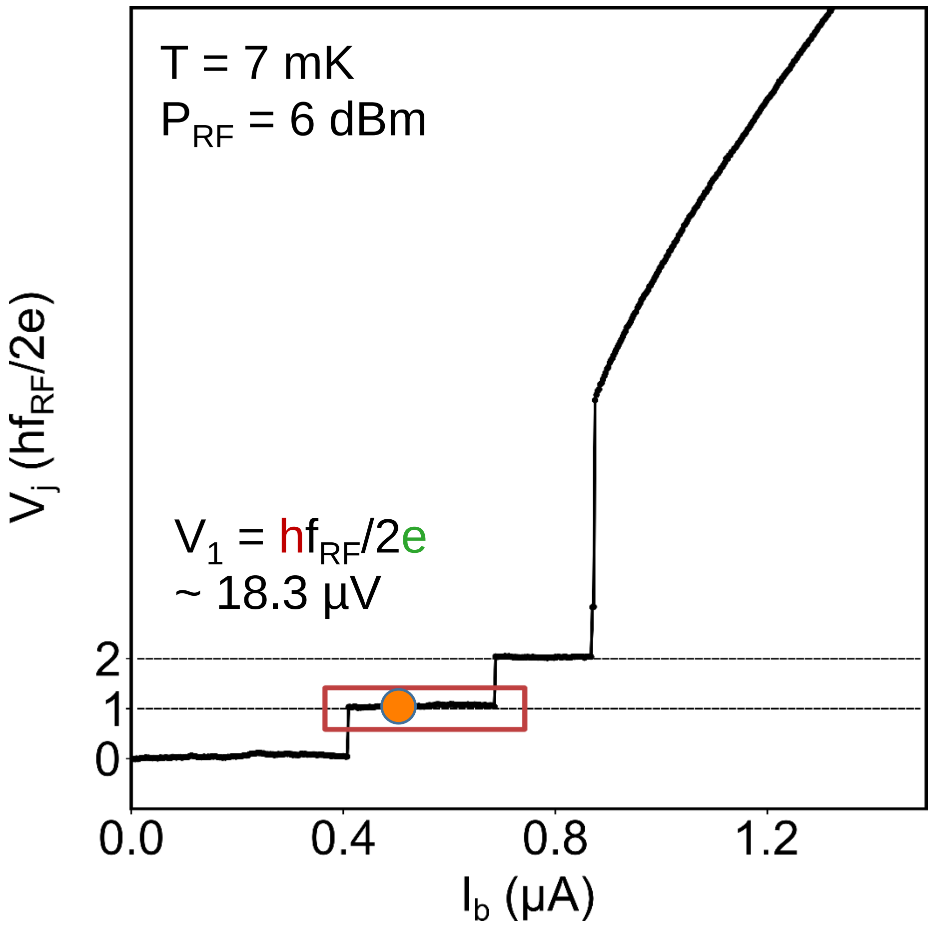




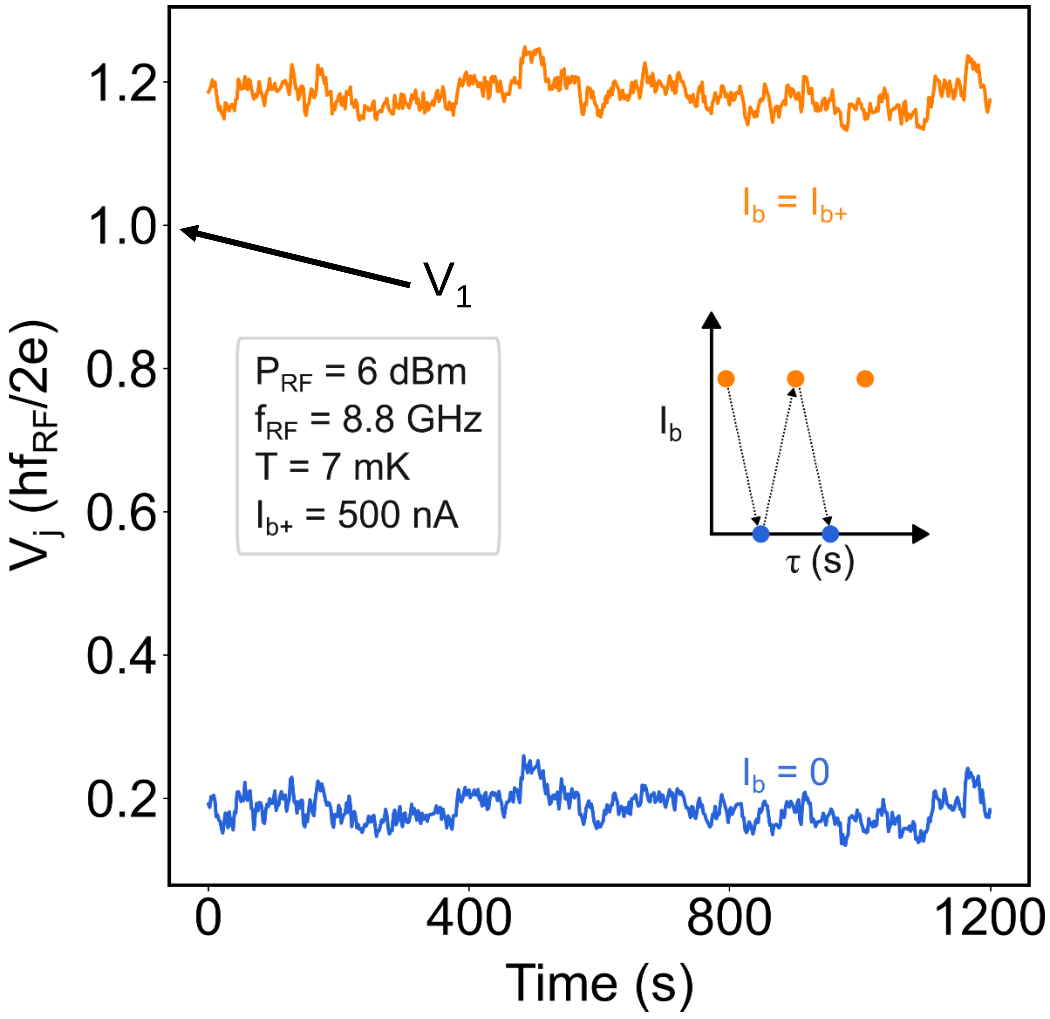
How accurate and stable is V_1 in the graphene junction ?

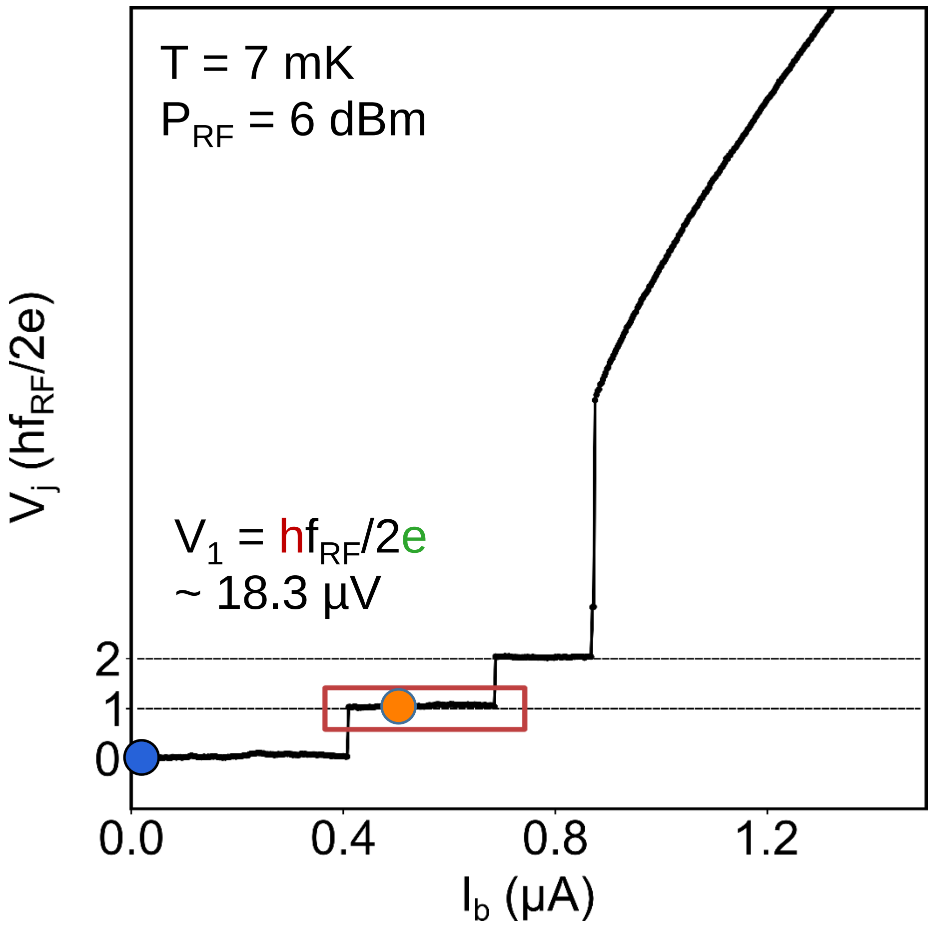
Relative deviation to V_1



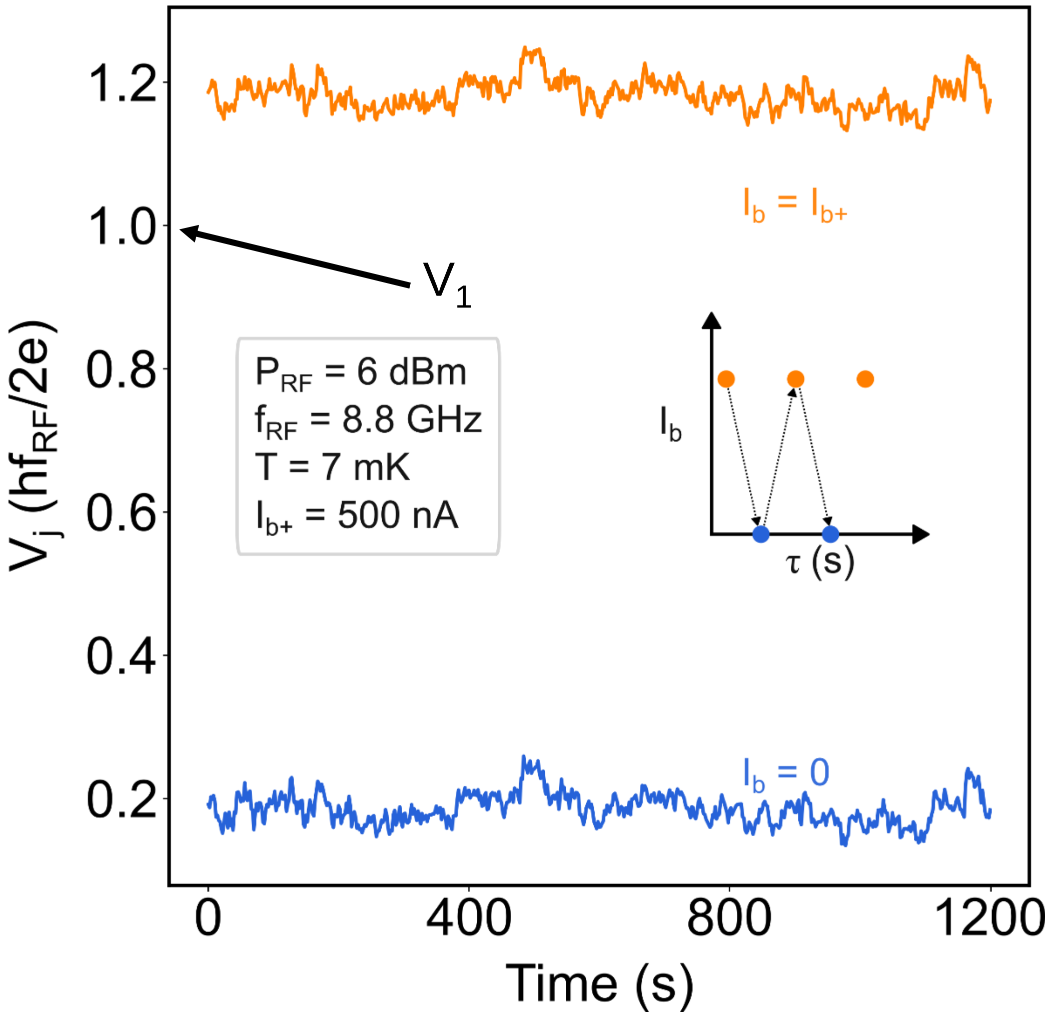


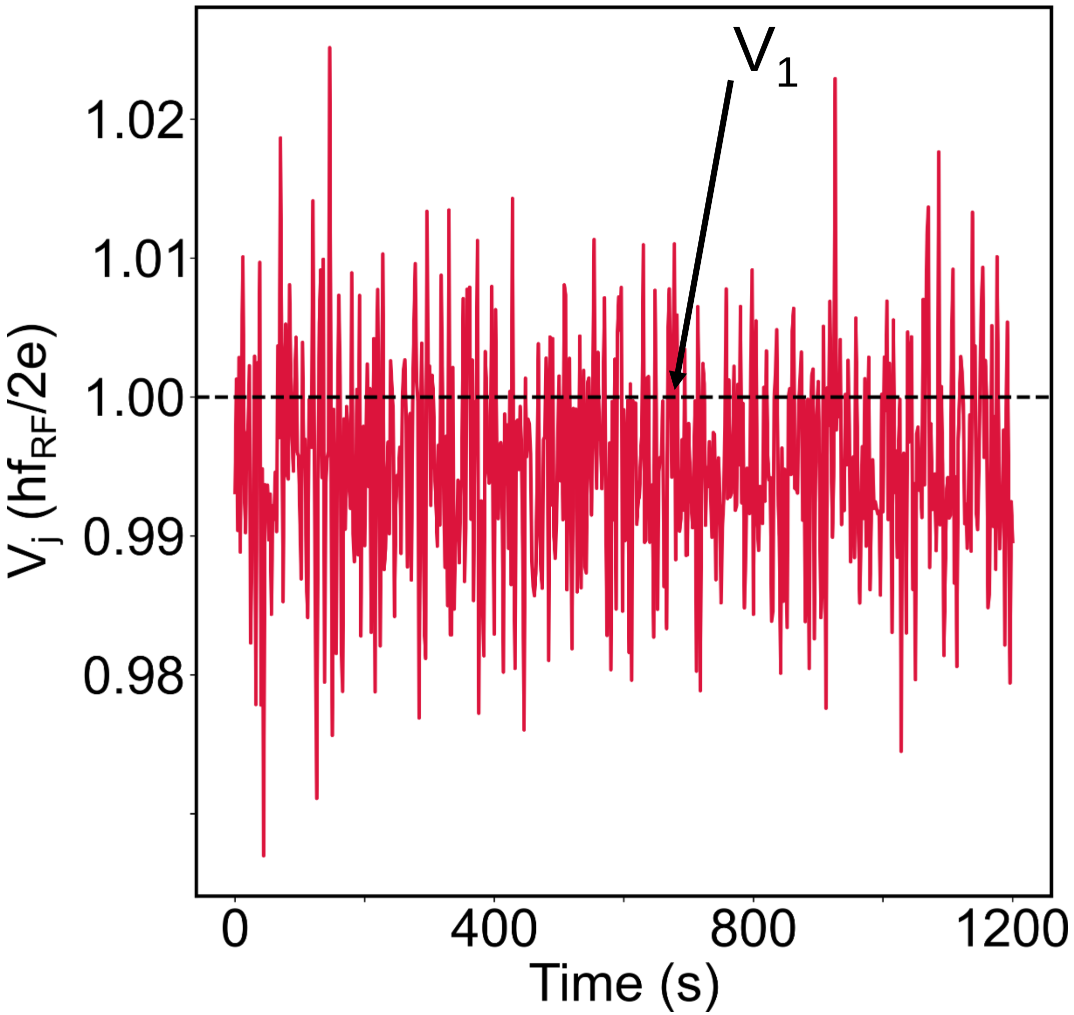
Relative deviation to V_1





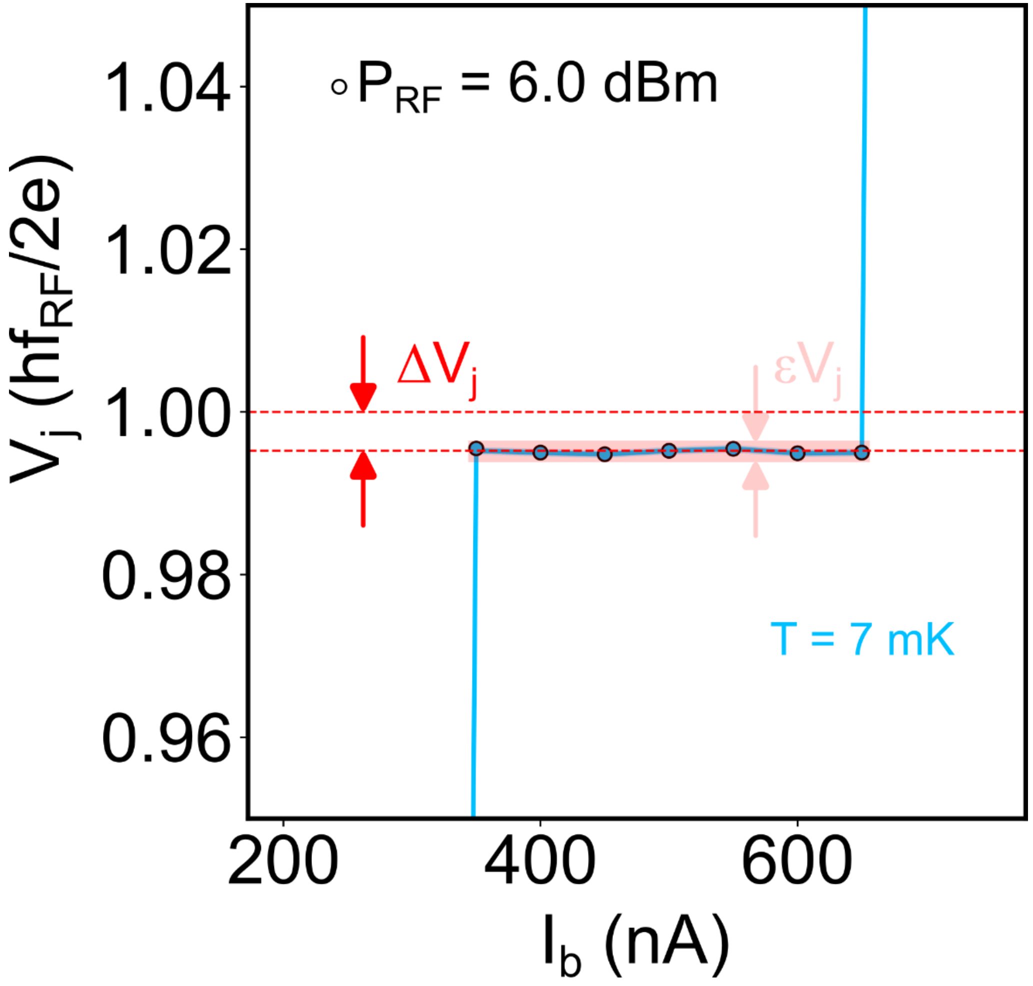
Relative deviation to V_1





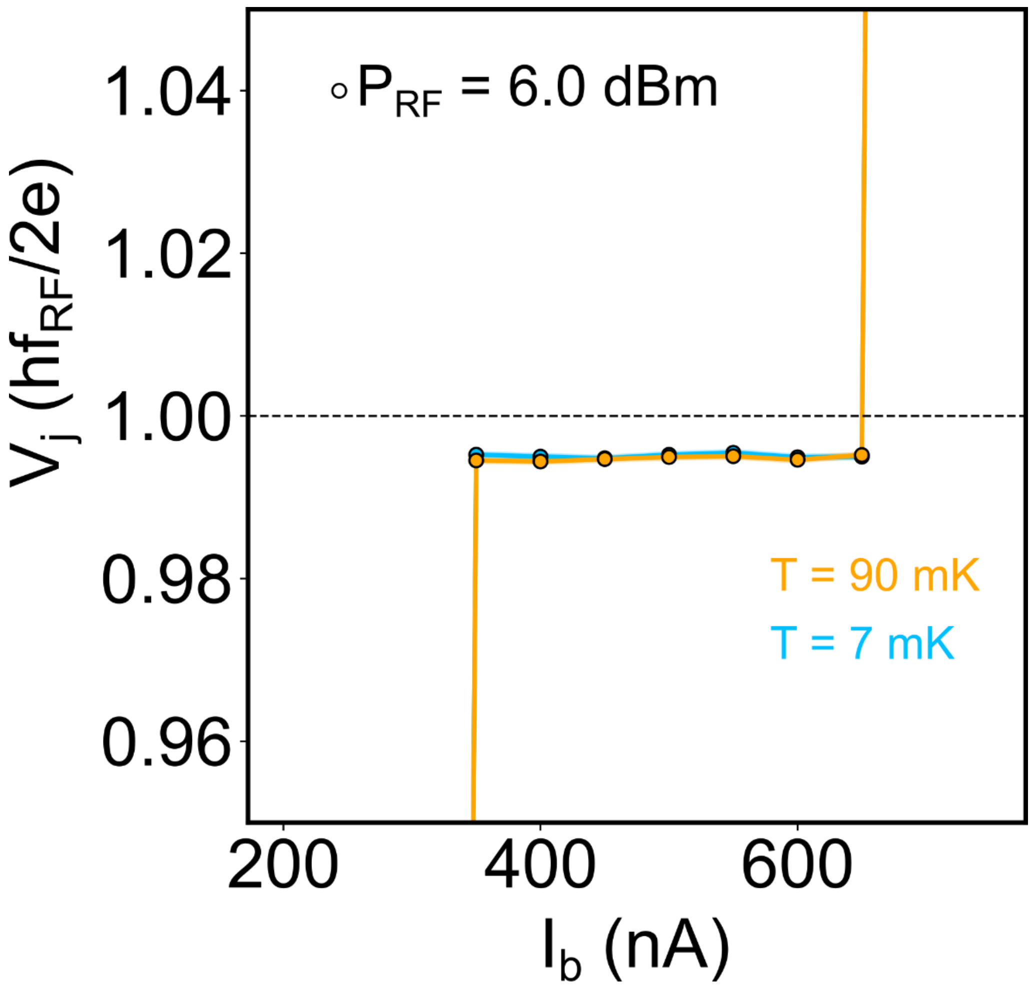
Reduction of parasitic DC offsets

Accuracy of the n = 1 Shapiro plateau



Temperature (mK)	Mean(V_j) $\left(\frac{hf_{RF}}{2e}\right)$	ΔV_j (%)	εV_j (%)
7	0.9950	-0.50	0.067
90			
840			
2150			

Accuracy of the n = 1 Shapiro plateau



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90	0.9948	-0.52	0.079
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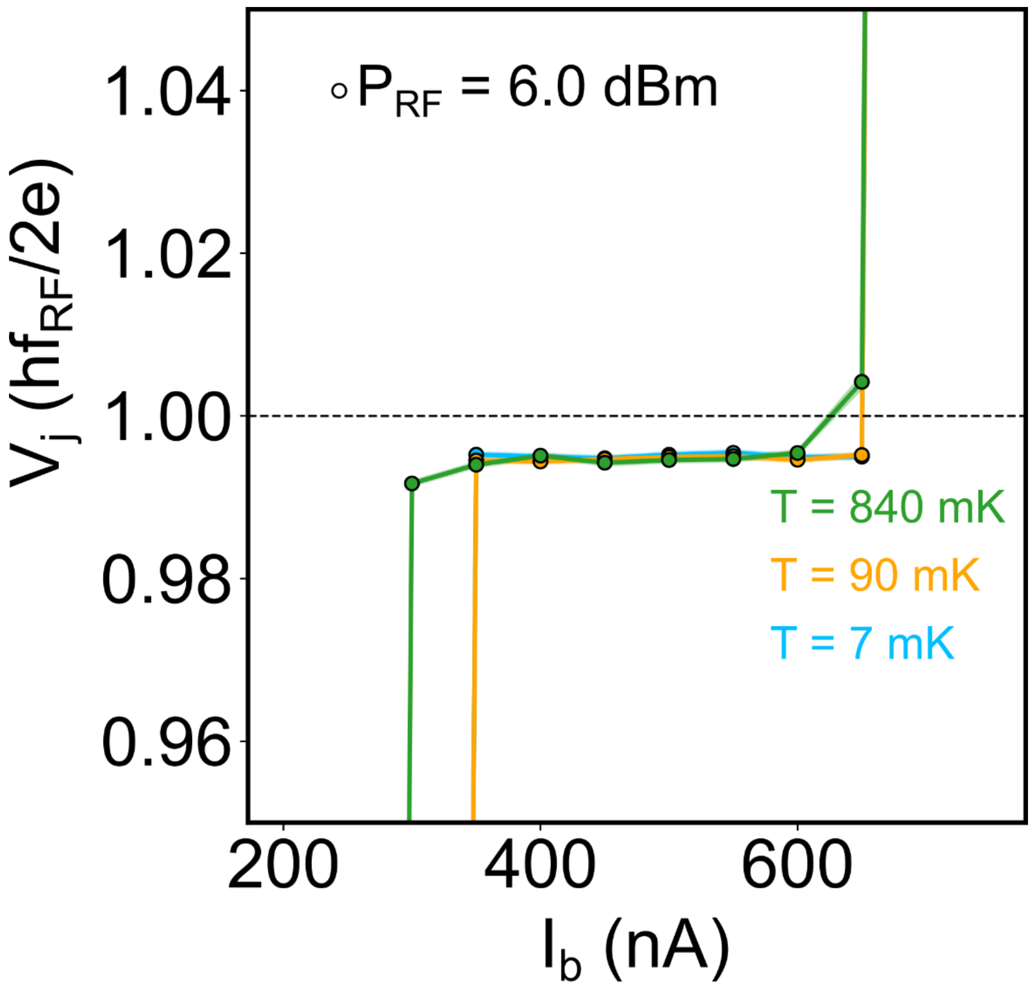

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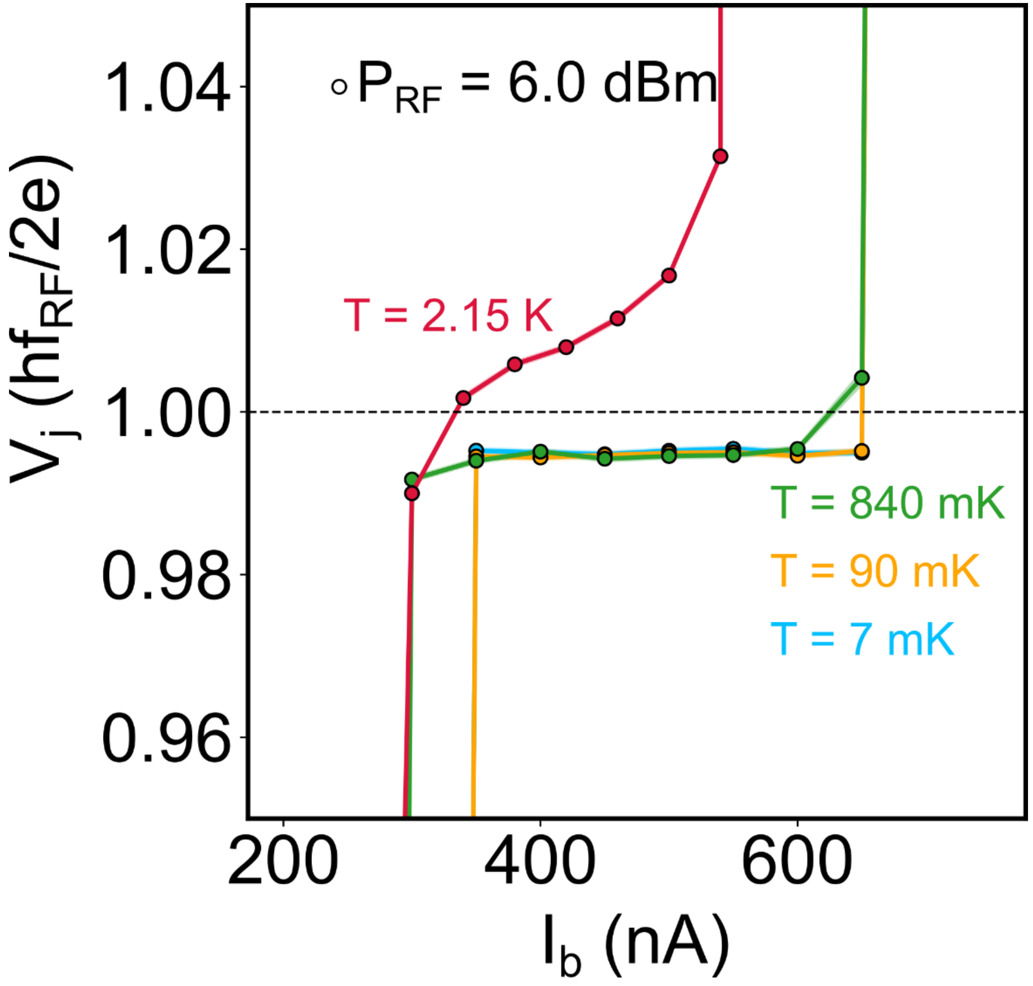

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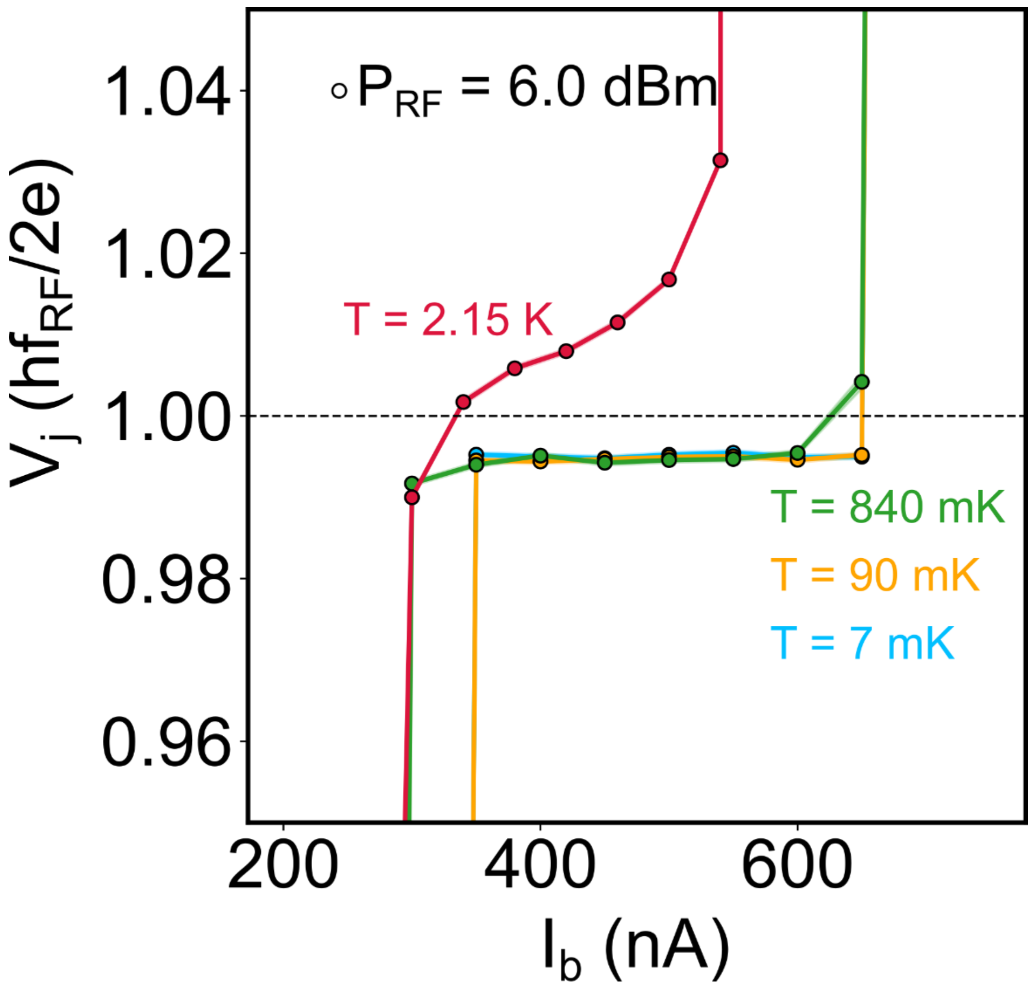

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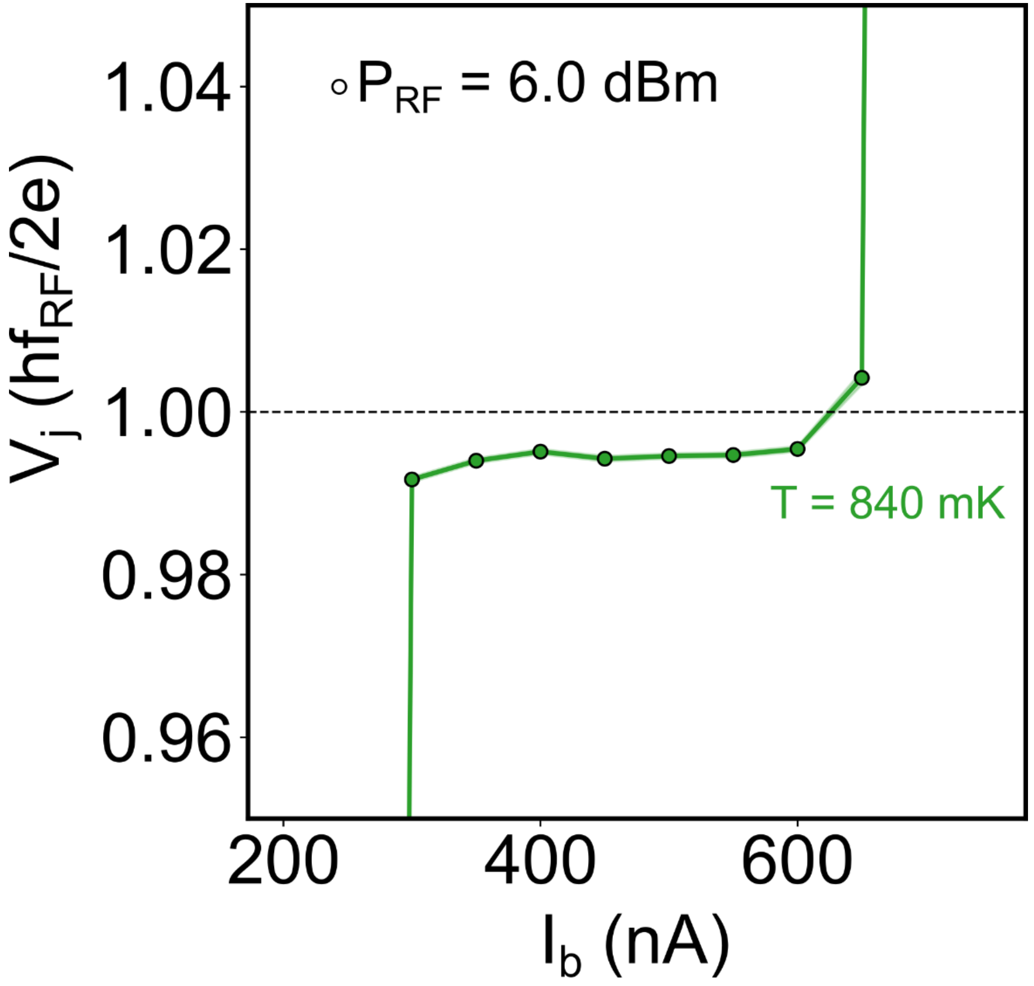
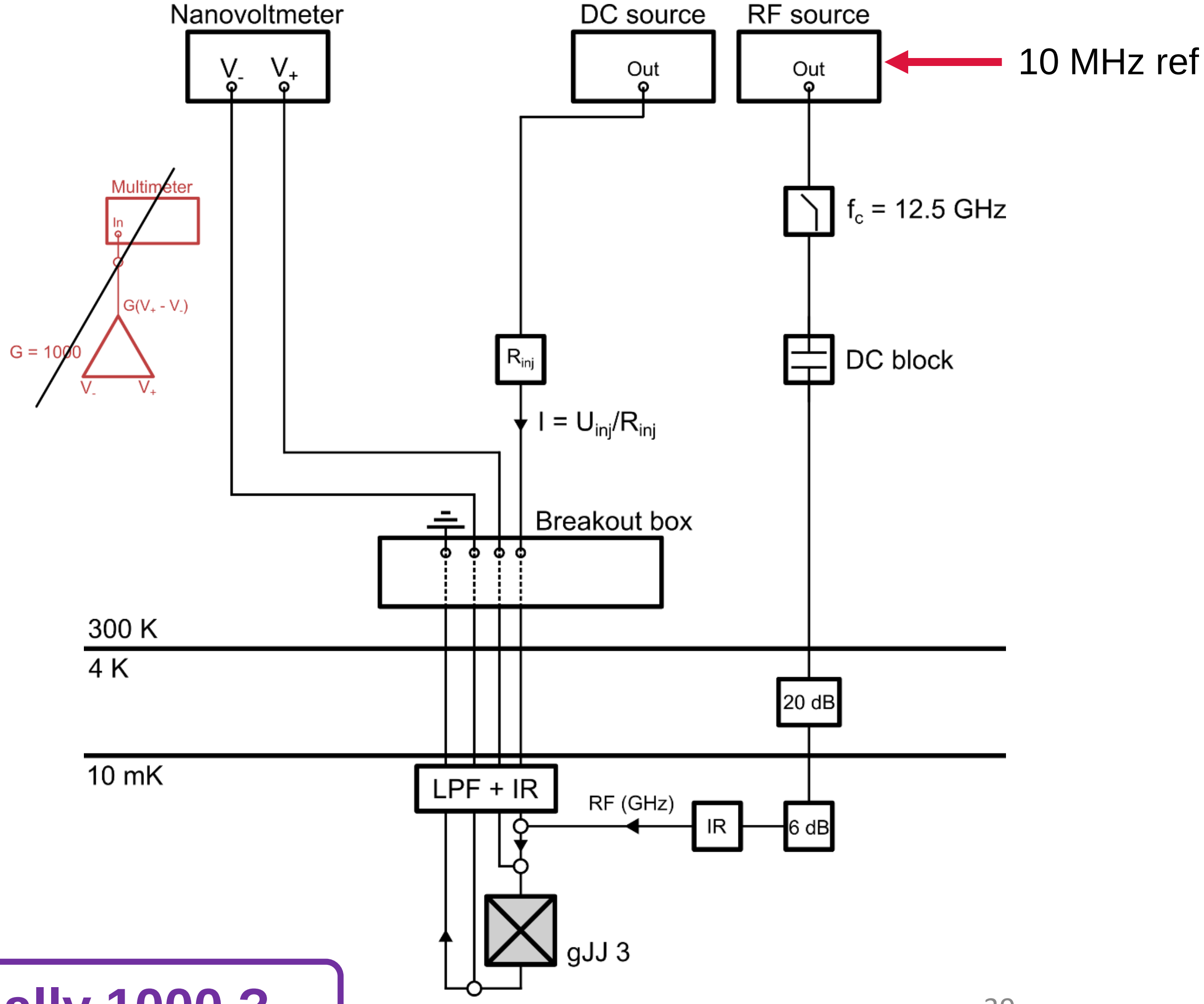
Limiting factors and voltage calibrated measurement

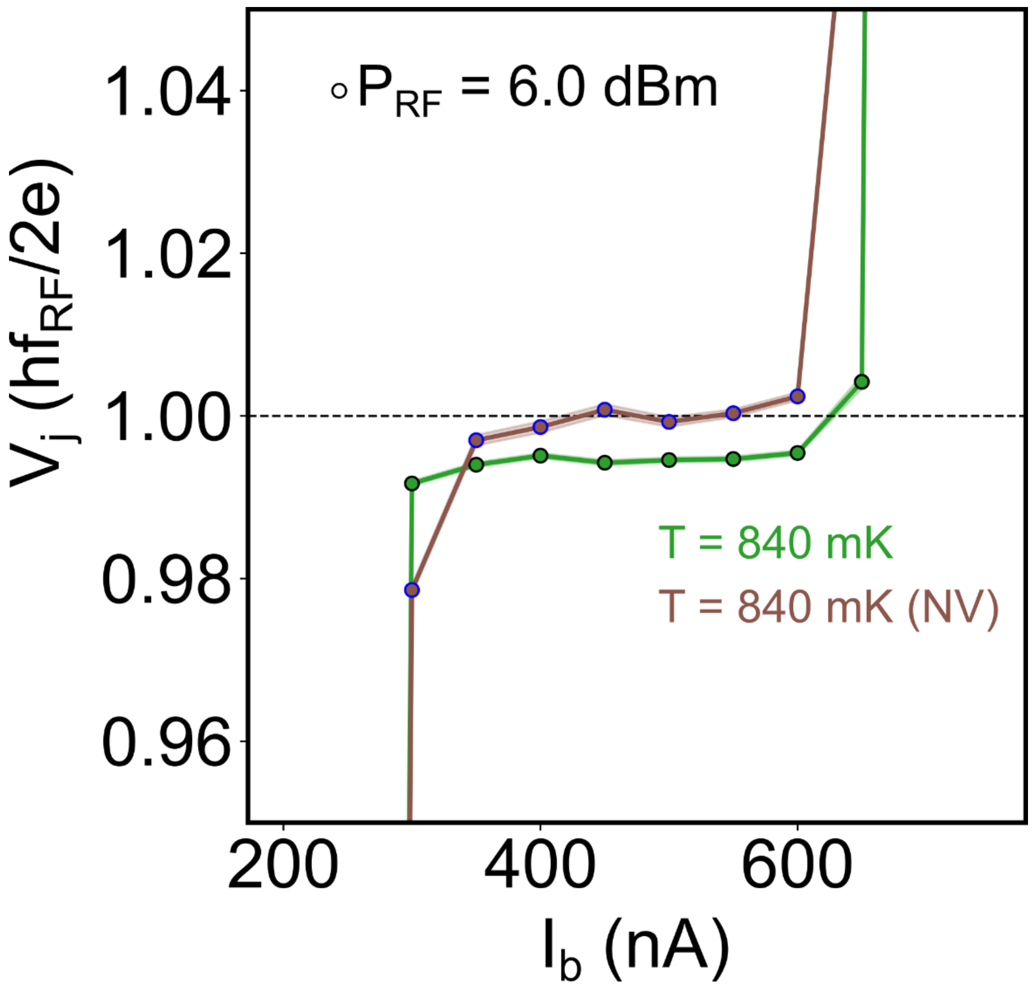
- Use of a calibrated nanovoltmeter (Agilent 34420A)





Is G = 1000 actually 1000 ?

Limiting factors and voltage calibrated measurement



- Relative deviation: -0.53 to -0.027 %

  i.e. $V_j = V_1 \pm 270$ ppm

From % to ppm: entry into the field of metrology

Conclusion

- AC Josephson effect in MoRe-graphene Josephson junction

  Accessible at « high » temperature up to 3.6 K

  Half-integer Shapiro steps

  RCSJ model

- Integrated platform for voltage metrology

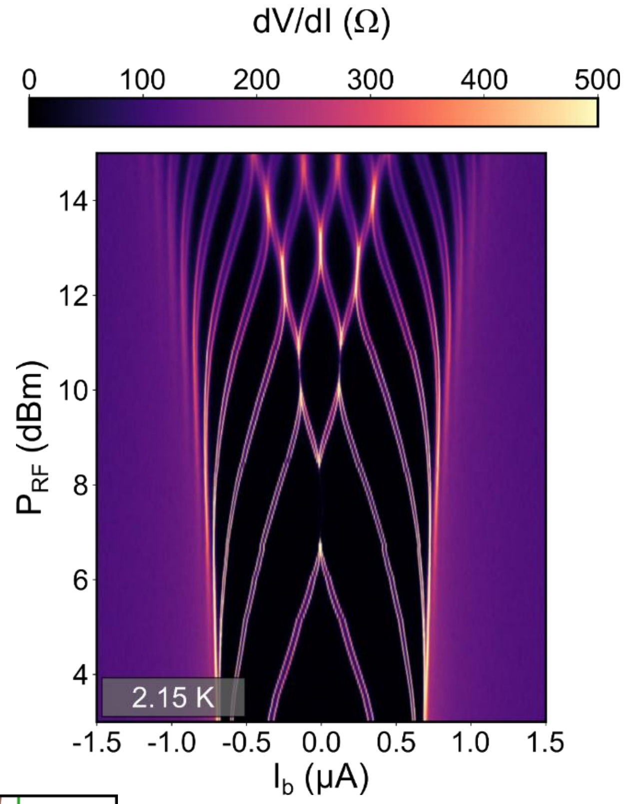
  $V_j = V_1 \pm 270$ ppm

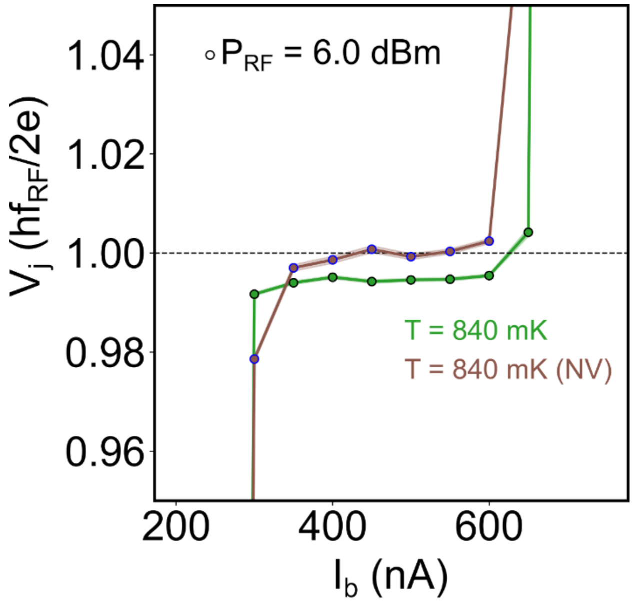
  Importance of the instrumentation

  JJ design/engineering

  RF coupling

  Magnetic field resilience ?





Mathieu Taupin
François Couëdo
Xavier Ballu-Garnier
Aya el Kanj
Gaël Bastien

Yuxiao Wu
Dmitri Efetov

European FLATS project

Thank you for your attention !

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