InSb Nanoflags SQUIDs

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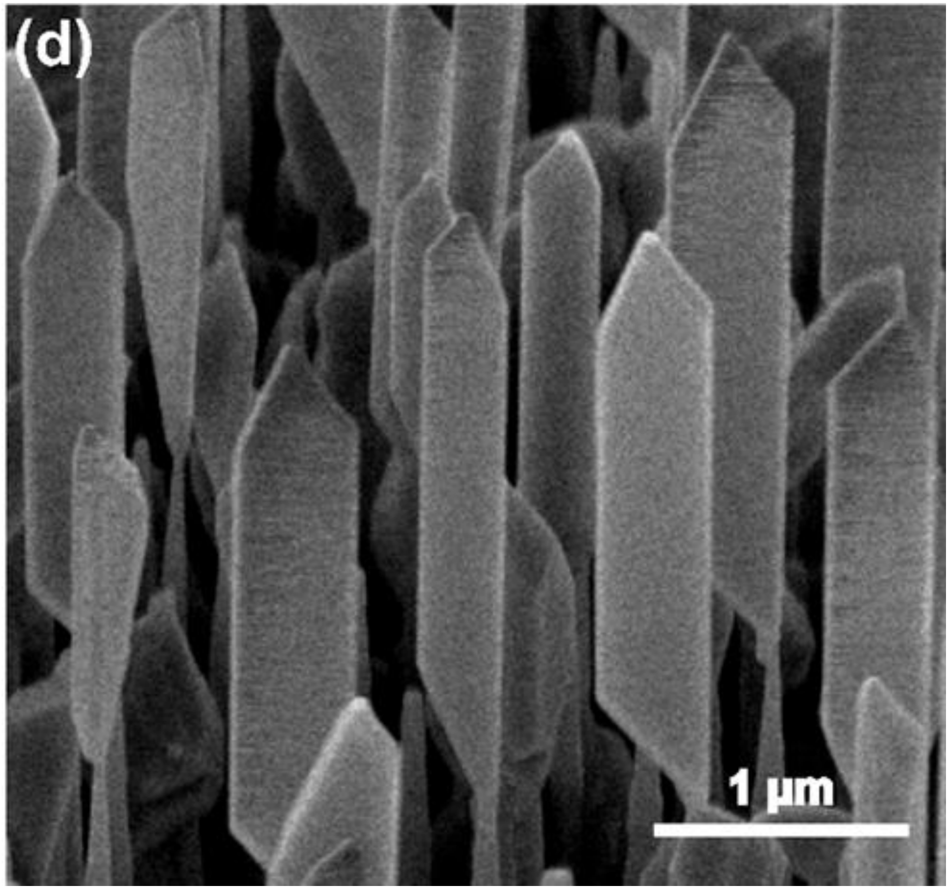
Outline

- Two Josephson Junctions in parallel
  - Conductance of a Josephson Junction
  - Conductance of SQUIDs
- Interference
  - Symmetric SQUID
  - Asymmetric SQUID
- Top Gates, “controlling” the single Junction

InSb Nanoflags

- Single crystal, ZB structure
- length ~ 2.8 μm
- width ~ 500 nm
- thickness ~ 100 nm
- $m^* = 0.02m_e$
- $E_g = 0.23$ eV
- $|g^*| = 50$

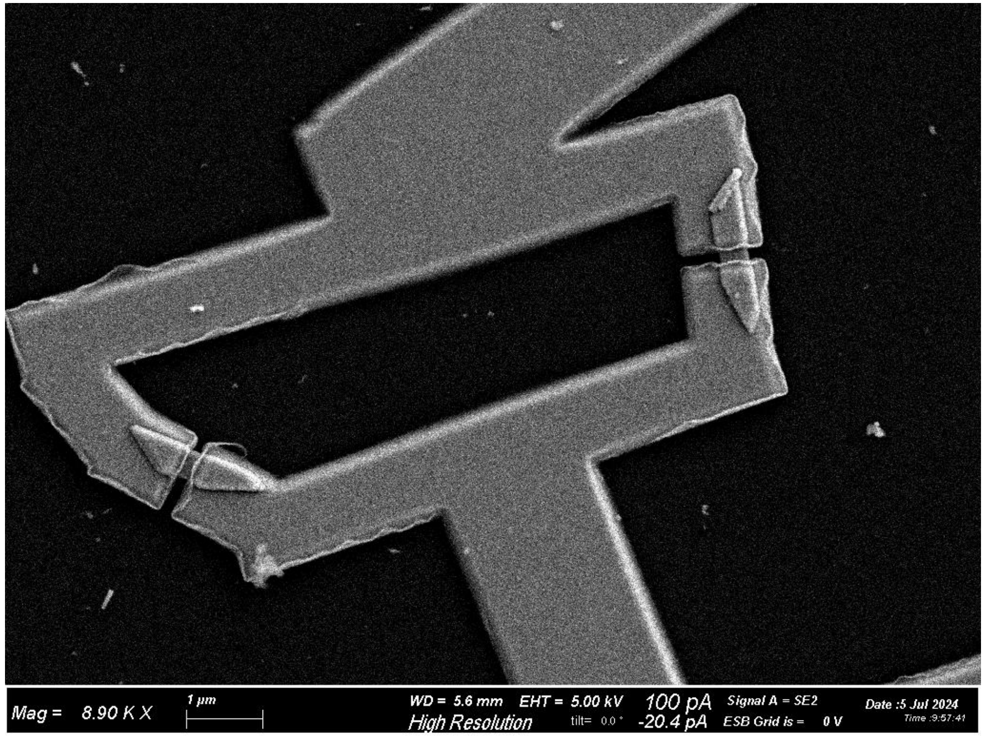


[ACS Appl.NanoMater.2021,4,5825−5833]

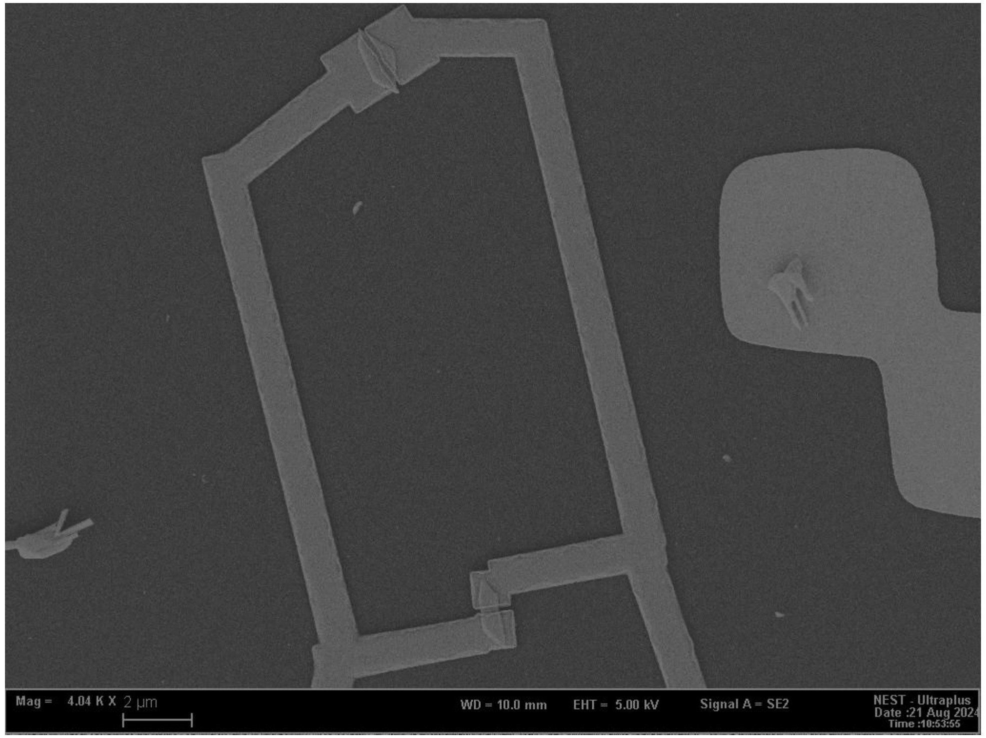
Two Josephson Junctions in parallel

Devices: Symmetric and Asymmetric SQUIDs

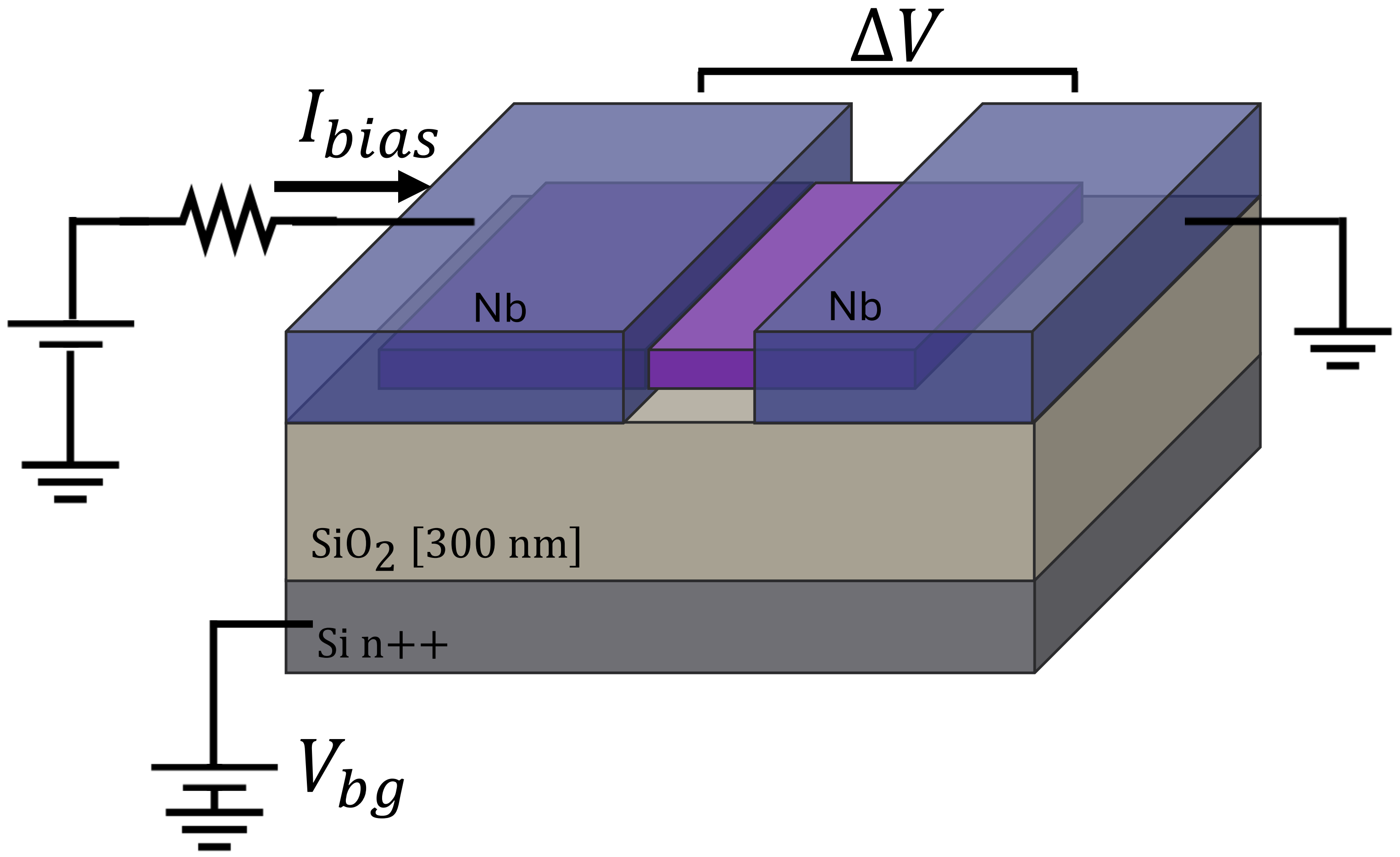
Symmetric SQUID



Asymmetric SQUID



Measurement Mode: Current Bias

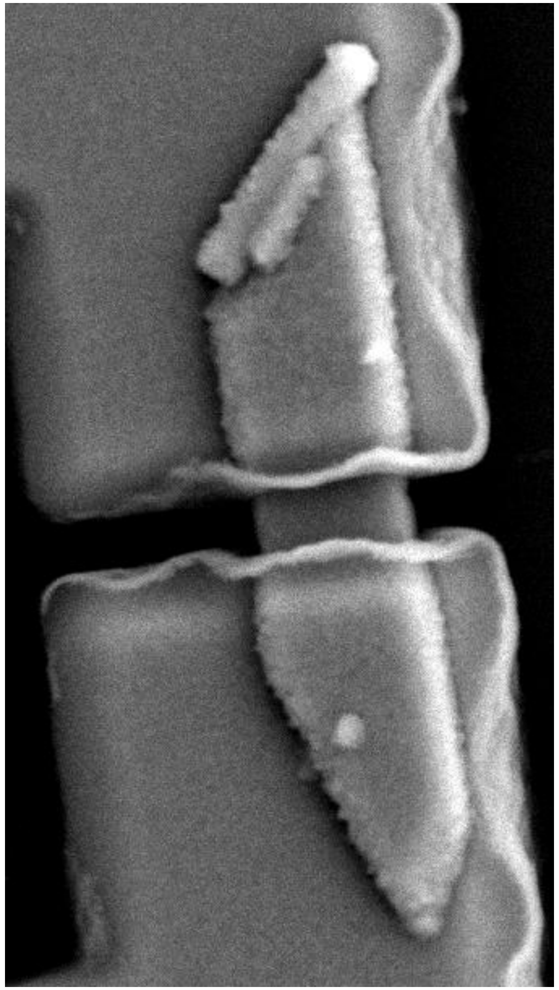


- Quasi four probes configuration
- Contact resistance R_c must be included in the conductance model

Single Josephson Junction

$L = 200\ \mathrm{nm}$
$W = 380\ \mathrm{nm}$
$c_{ox} = 1.15 \cdot 10^{-8}\ \mathrm{F\,cm^{-2}}$

$$\frac{1}{G_{JJ}} = R_c + R_N + R_c$$

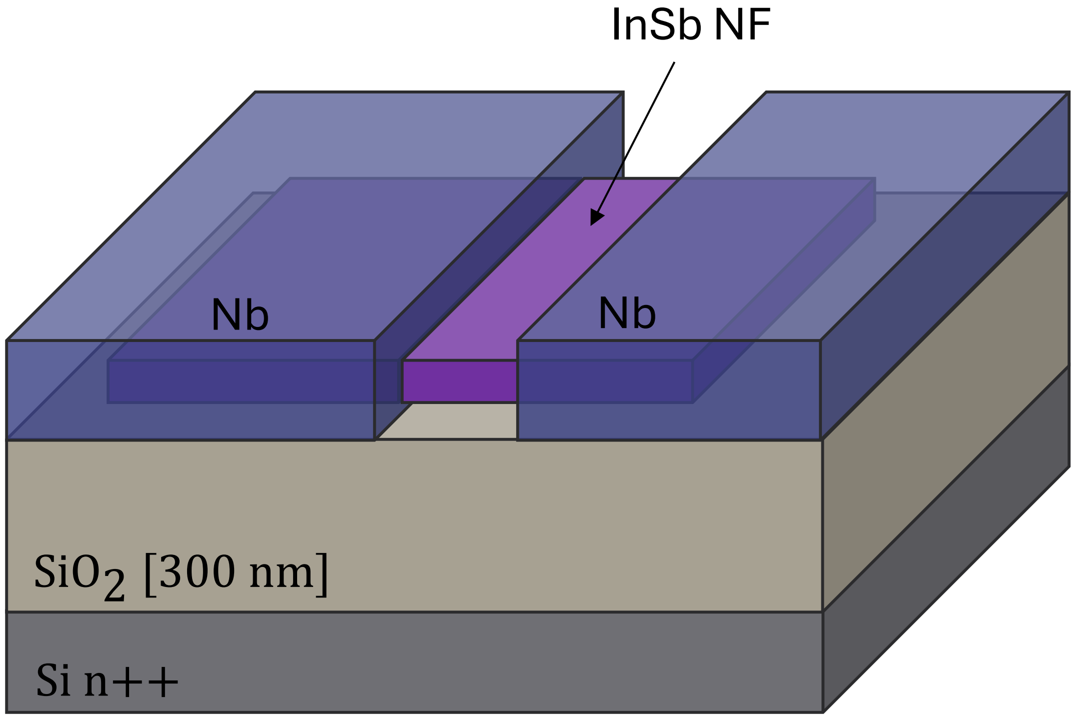


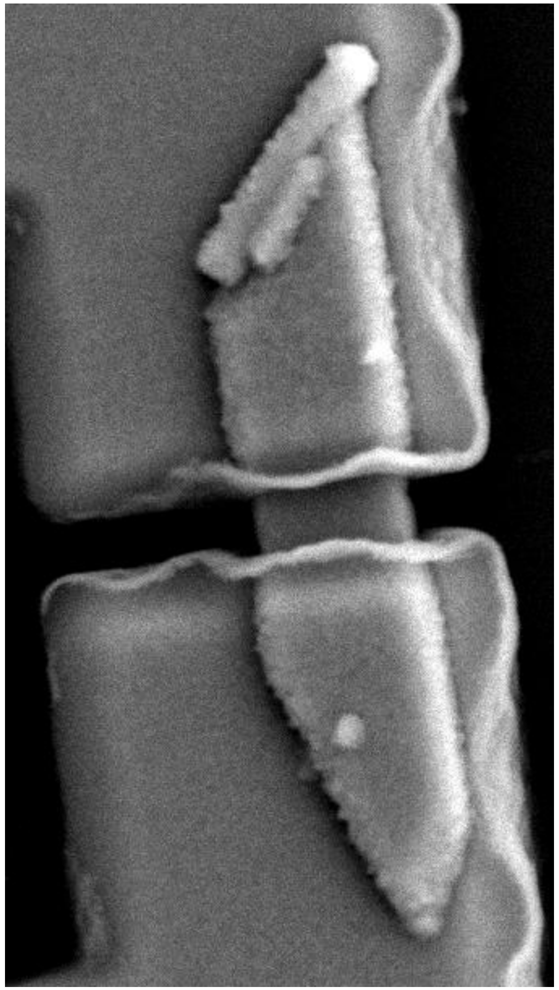
JJ of SQUID3 – C2S4

Single Josephson Junction

$$R_N = \left(c_{ox} \frac{W}{L} \mu (V_{bg} - V_{th}) \right)^{-1}$$

$L = 200$ nm
$W = 380$ nm
$c_{ox} = 1.15 \cdot 10^{-8}$ F cm^{-2}



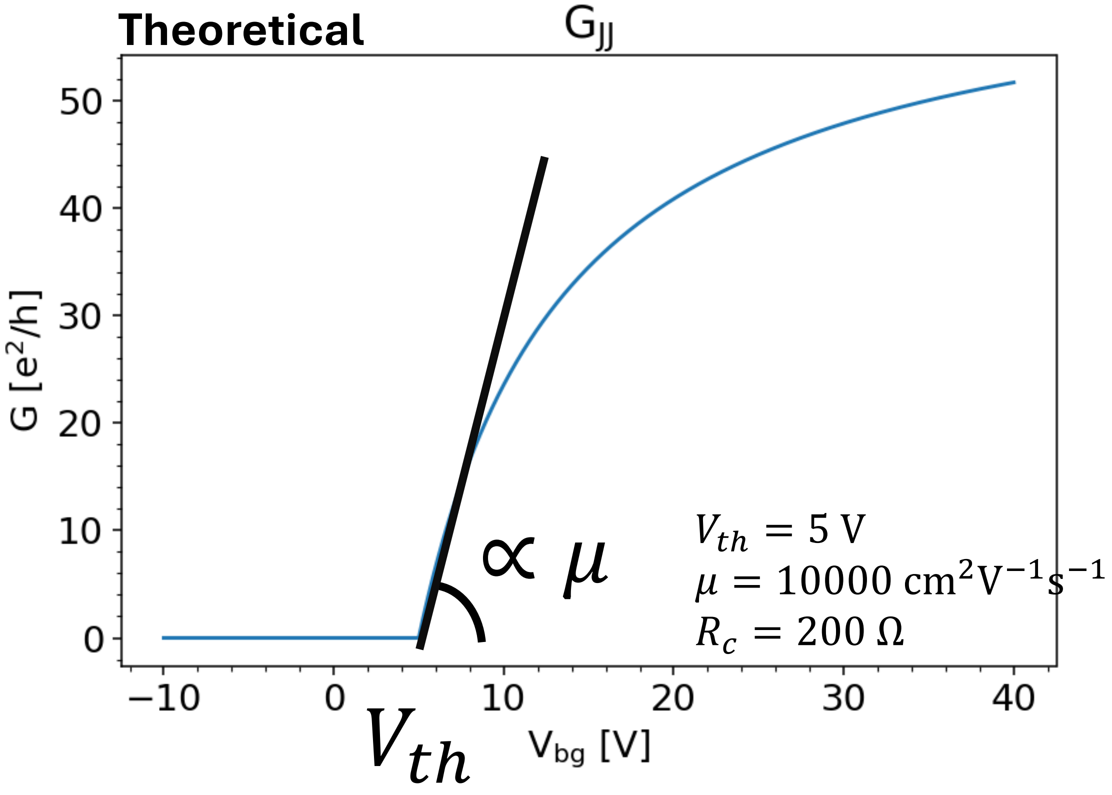


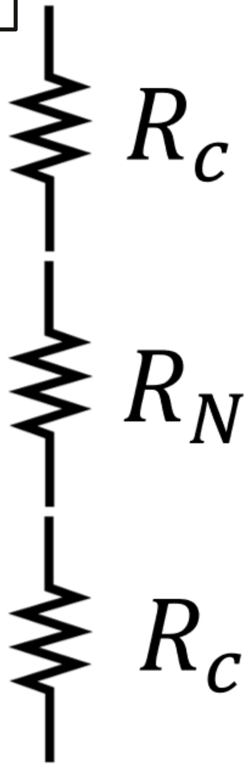
JJ of SQUID3 – C2S4

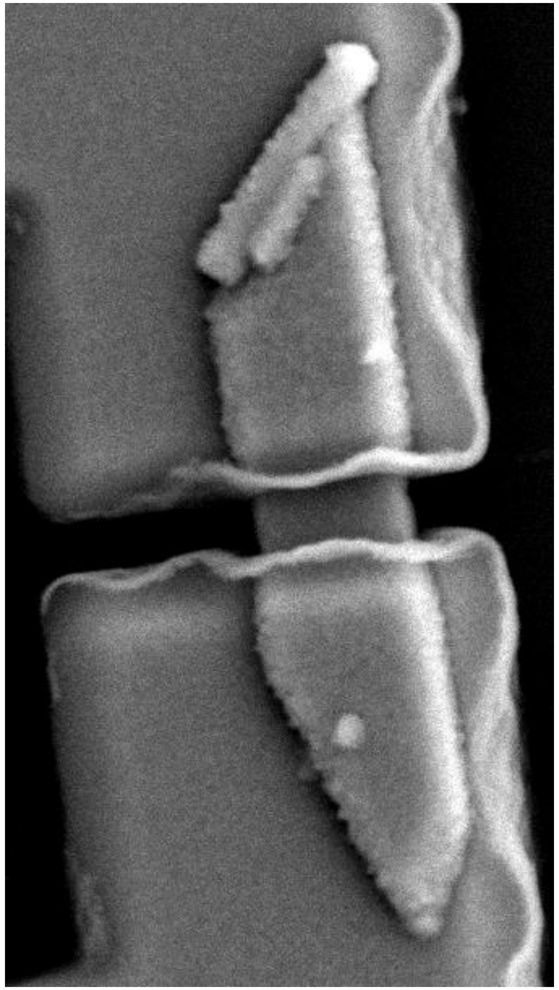
Single Josephson Junction

$$\frac{1}{G_{JJ}} = 2R_c + \left(c_{ox} \frac{W}{L} \mu (V_{bg} - V_{th}) \right)^{-1}$$

$L = 200\ \mathrm{nm}$
$W = 380\ \mathrm{nm}$
$c_{ox} = 1.15 \cdot 10^{-8}\ \mathrm{F\ cm^{-2}}$

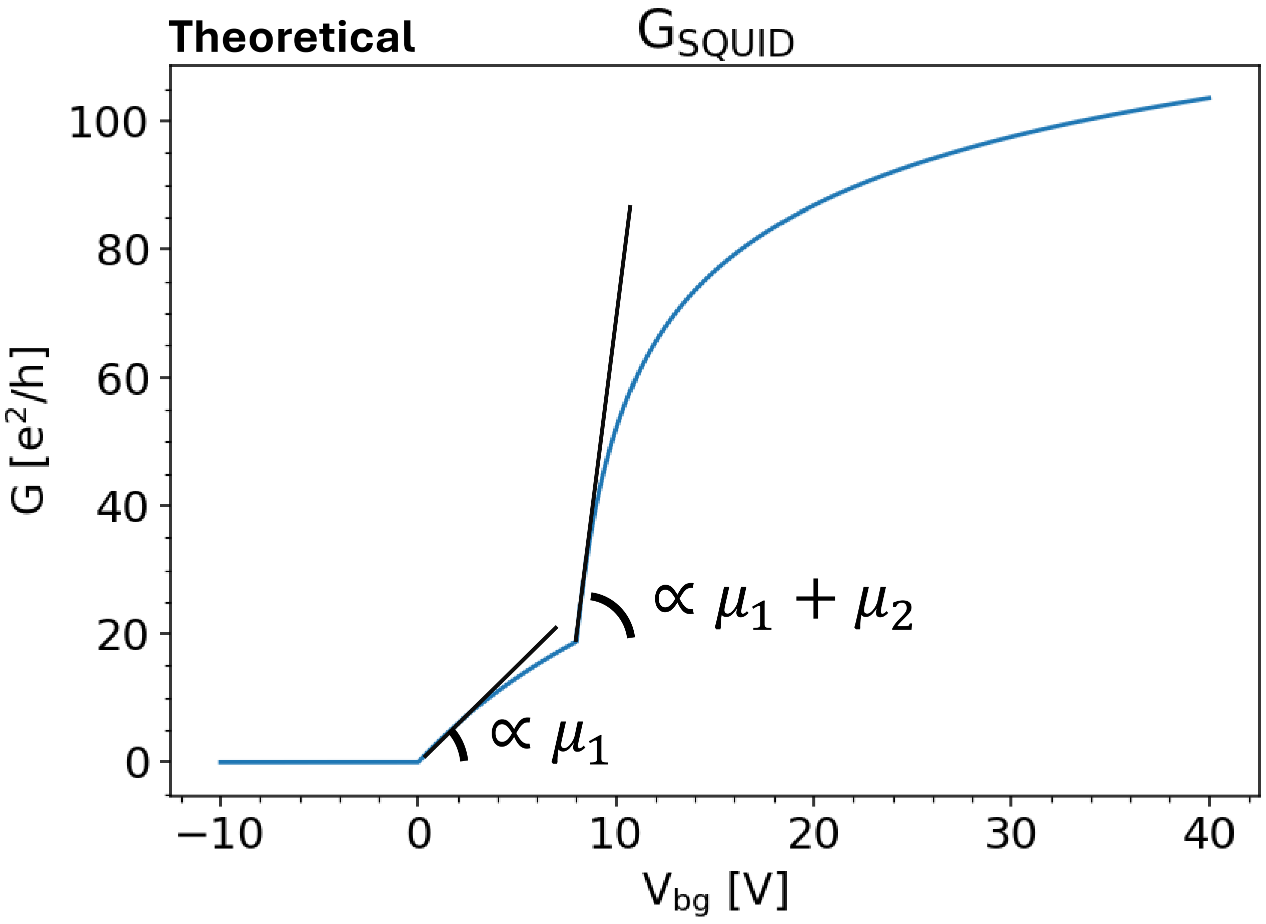






JJ of SQUID3 – C2S4

Theoretical conductance model for the SQUID



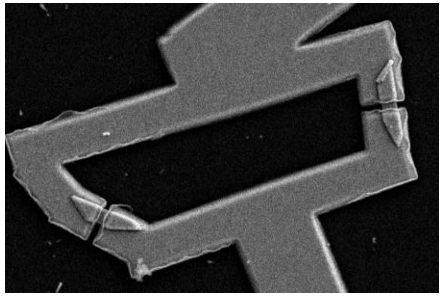
$$G_{SQUID} = G_{JJ,1} + G_{JJ,2}$$

$V_{th1} = 0$ V,
$\mu_1 = 4000\ \mathrm{cm^2V^{-1}s^{-1}}$

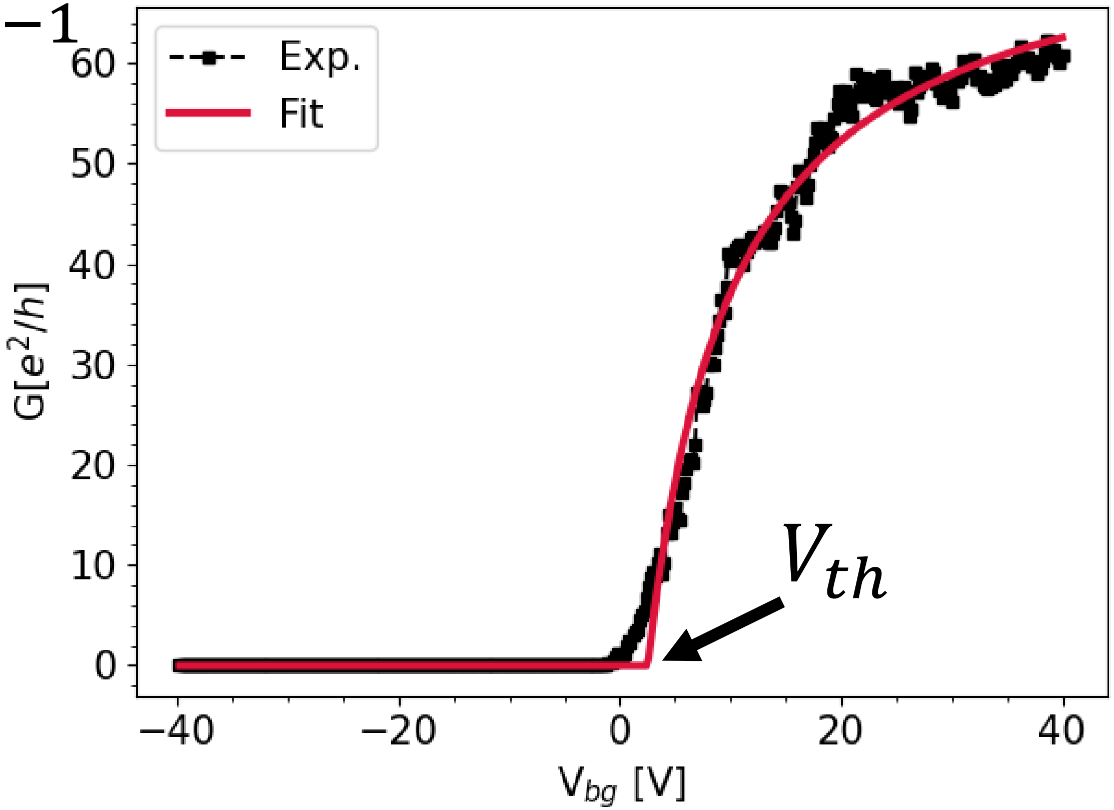
$V_{th2} = 8$ V
$\mu_2 = 10000\ \mathrm{cm^2V^{-1}s^{-1}}$

$R_c = 200\ \Omega$

Symmetric SQUID conductance

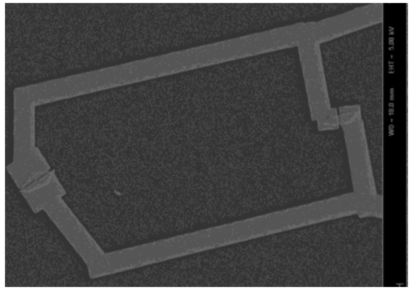


- $V_{th} = 2.5 \pm 0.1$ V
- $\mu = 8200 \pm 200$ cm^{2}V^{-1}s^{-1}
- $R_c = 342 \pm 3\ \Omega$

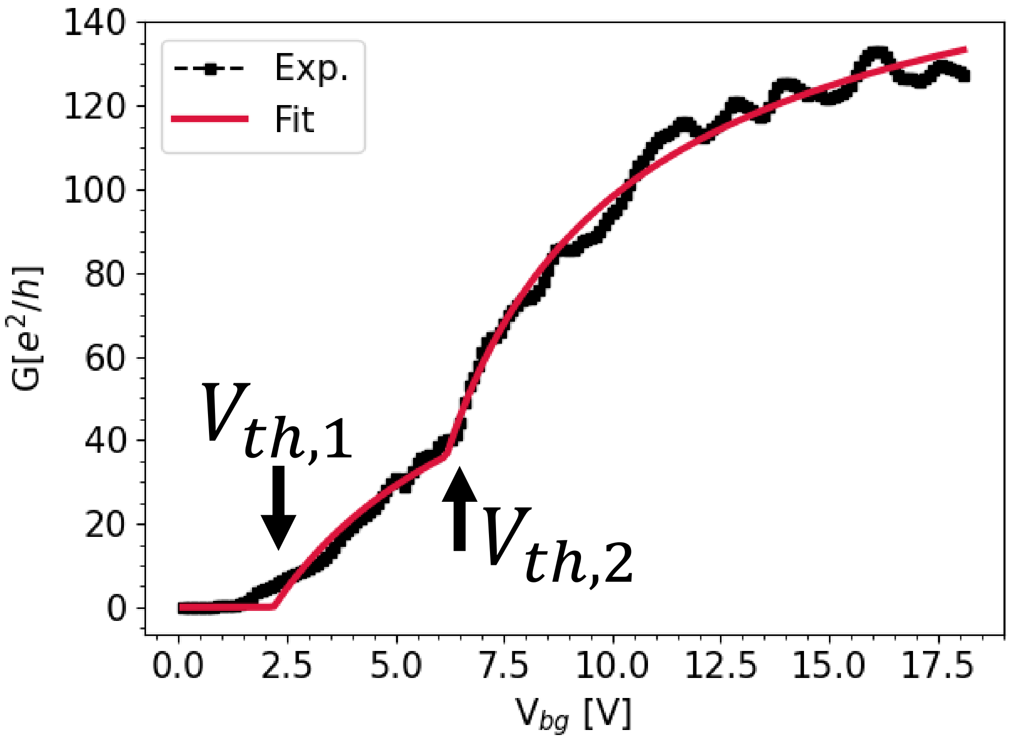


$$l_{MFP} = \frac{\hbar\mu}{e}\sqrt{2\pi n_{2d}} = 150 \text{ nm @ BG} = 20 \text{ V}$$

Asymmetric SQUID conductance



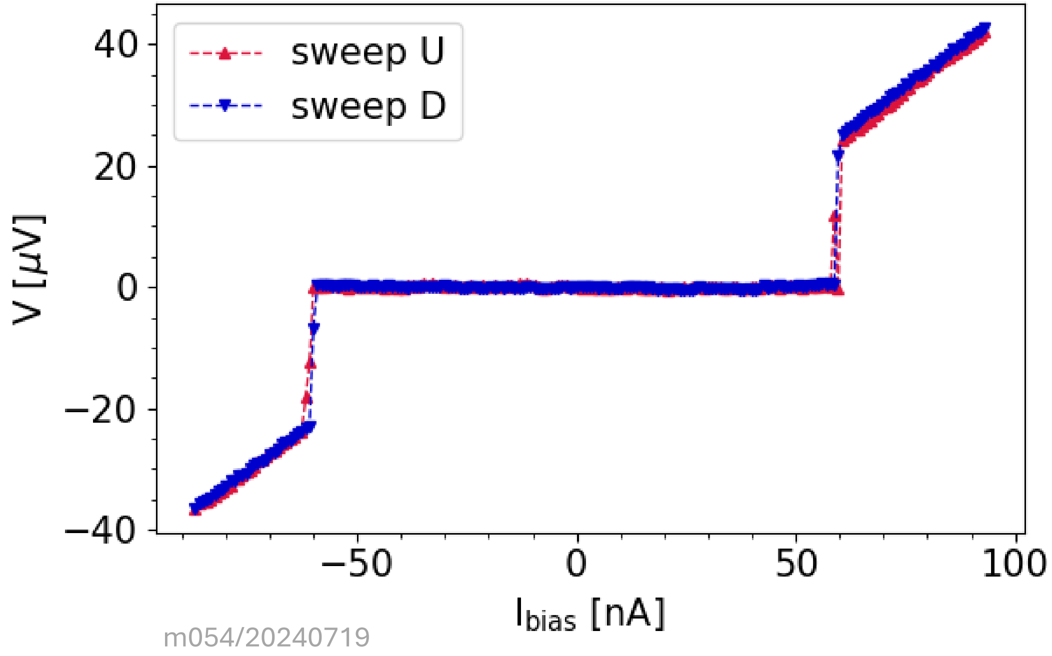
- $V_{th,1} = 2.2 \pm 0.1$ V
- $V_{th,2} = 6.2 \pm 0.1$ V
- $\mu_1 = 18600 \pm 950$ cm^{2}V^{-1}s^{-1}
- $\mu_2 = 9700 \pm 500$ cm^{2}V^{-1}s^{-1}
- $R_c = 147 \pm 2\ \Omega$
- At $V_{bg} = 15$ V $\quad l_{MFP,1} = 300$ nm, $l_{MFP,2} = 140$ nm



VI traces @ $T = 350$ mK

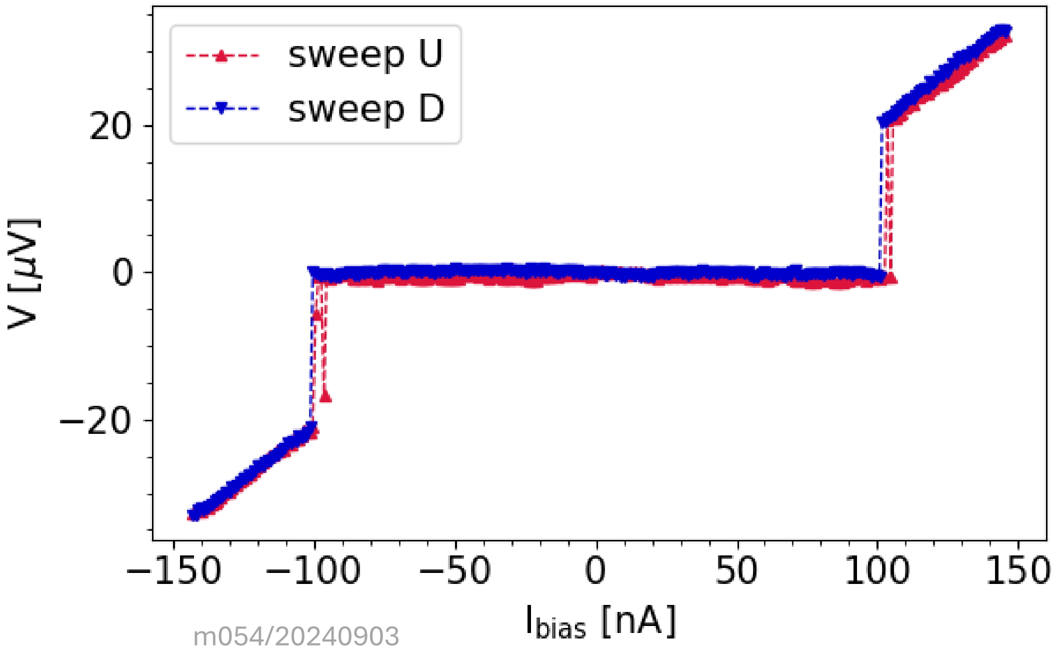
Symmetric SQUID

$V_{BG} = 20.0$ V $I_{sw} \cong 60$ nA



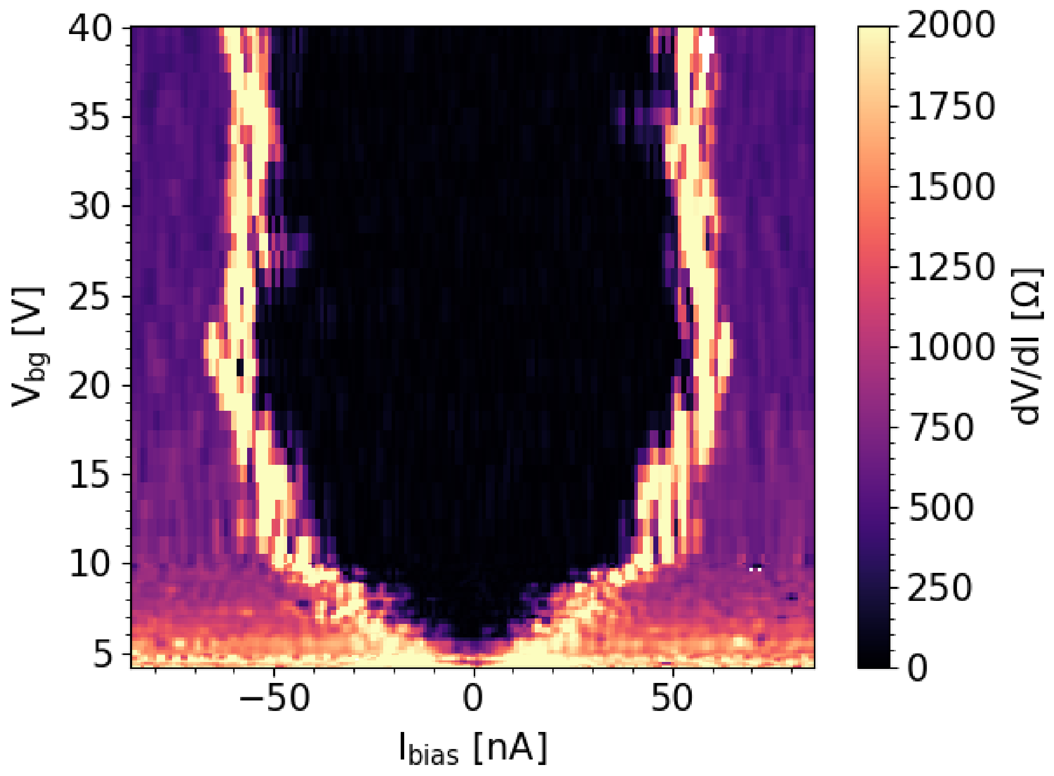
Asymmetric SQUID

$V_{BG} = 18.0$ V $I_{sw} \cong 100$ nA



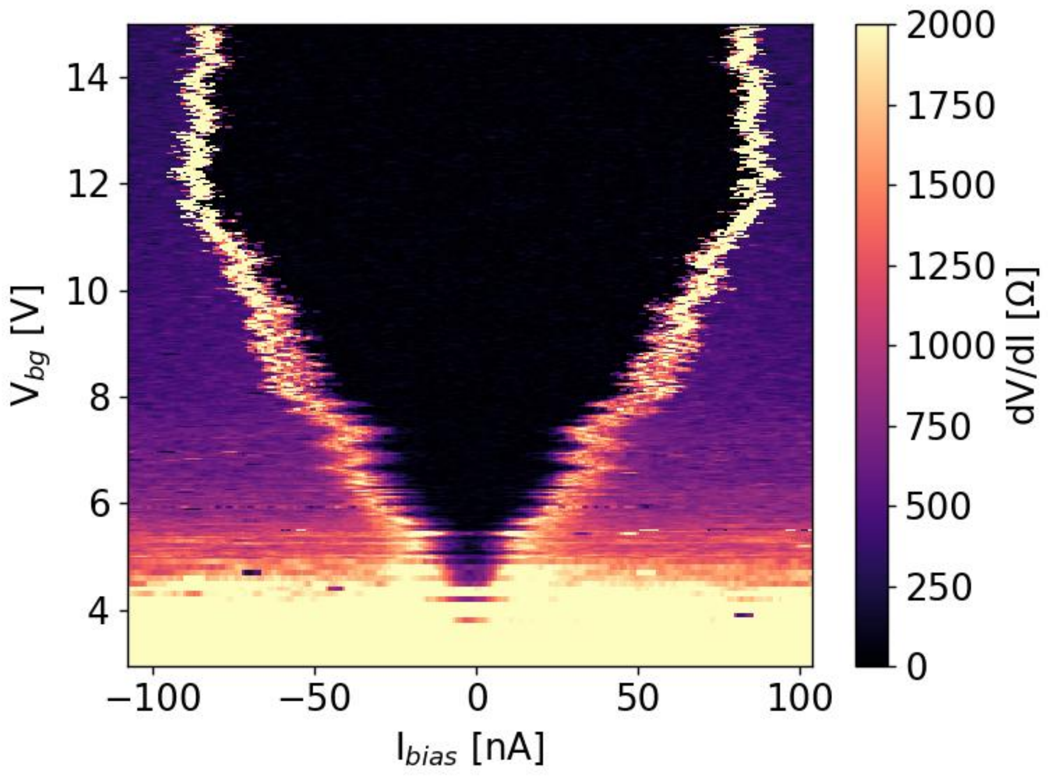
Backgate control of supercurrent $@ T = 350\ \mathrm{mK}$

Symmetric SQUID



m030 to m037 folder 2024-07-11 C2S4

Asymmetric SQUID



m123 to m130 2024-09-03 H6S4

Interference on Symmetric SQUID

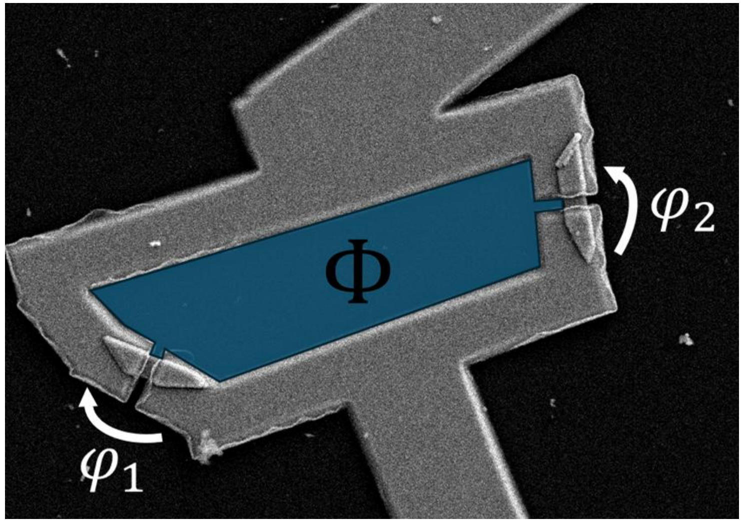
Basic Theory

- $I_{SQUID} = I_1(\varphi_1) + I_2(\varphi_2)$

- $\varphi_1 - \varphi_2 = \frac{2\pi\Phi}{\Phi_0} + 2\pi n$

- Interference properties depend on the relations $I_1(\varphi_1)$, $I_2(\varphi_2)$ (Current Phase Relationships, CPRs)

$$\Phi = \Phi_{ext} - LI_{circ}$$
$$L = L_{geo} + L_{kin}$$



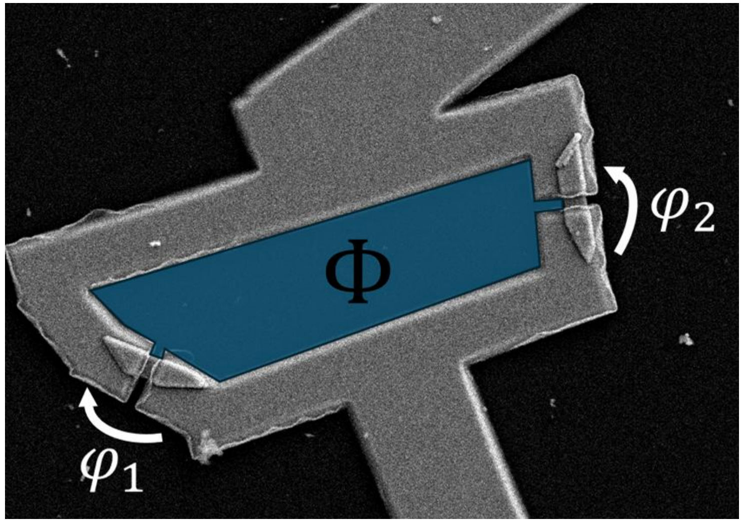
Basic Theory for Sinusoidal CPR

- $I_1(\varphi_1) = I_{c1}\sin(\varphi_1)$ $\quad$ $I_2(\varphi_2) = I_{c2}\sin(\varphi_2)$
- $I_c = \sqrt{(I_{c1} - I_{c2})^2 + 4I_{c1}I_{c2}\cos\left(\pi\frac{\Phi}{\Phi_0}\right)^2}$

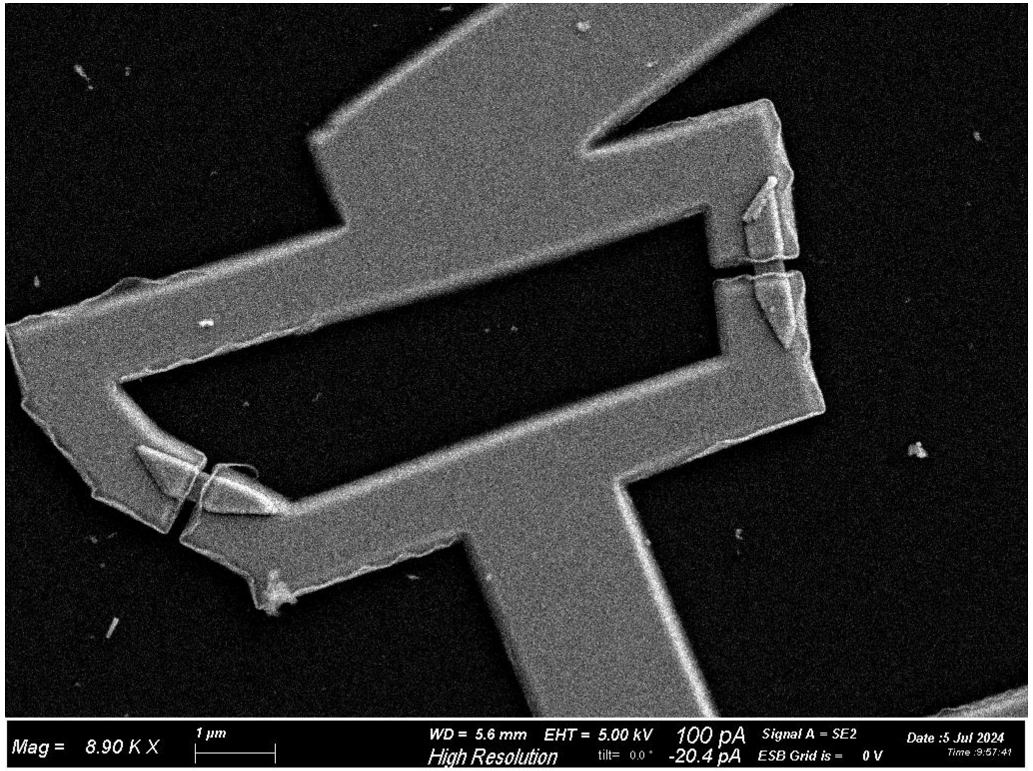
$$\Phi = \Phi_{ext} - LI_{circ}$$
$$L = L_{geo} + L_{kin}$$

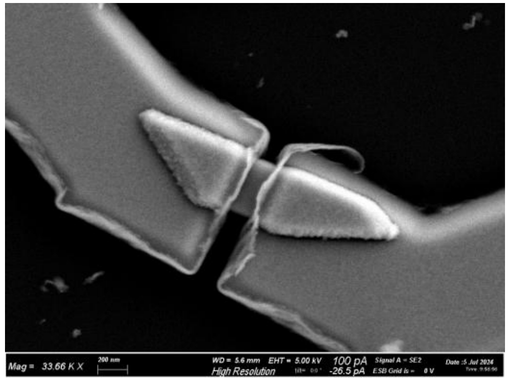
$\Phi = n\Phi_0 \quad \rightarrow I_c = |I_{c1} + I_{c2}|$

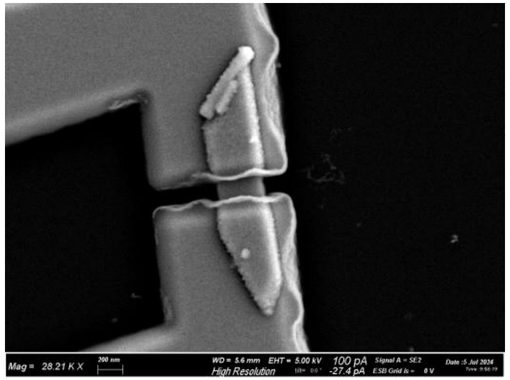
$\Phi = \Phi_0/2 + n\Phi_0 \rightarrow I_c = |I_{c1} - I_{c2}|$



Symmetric SQUID: C2S4







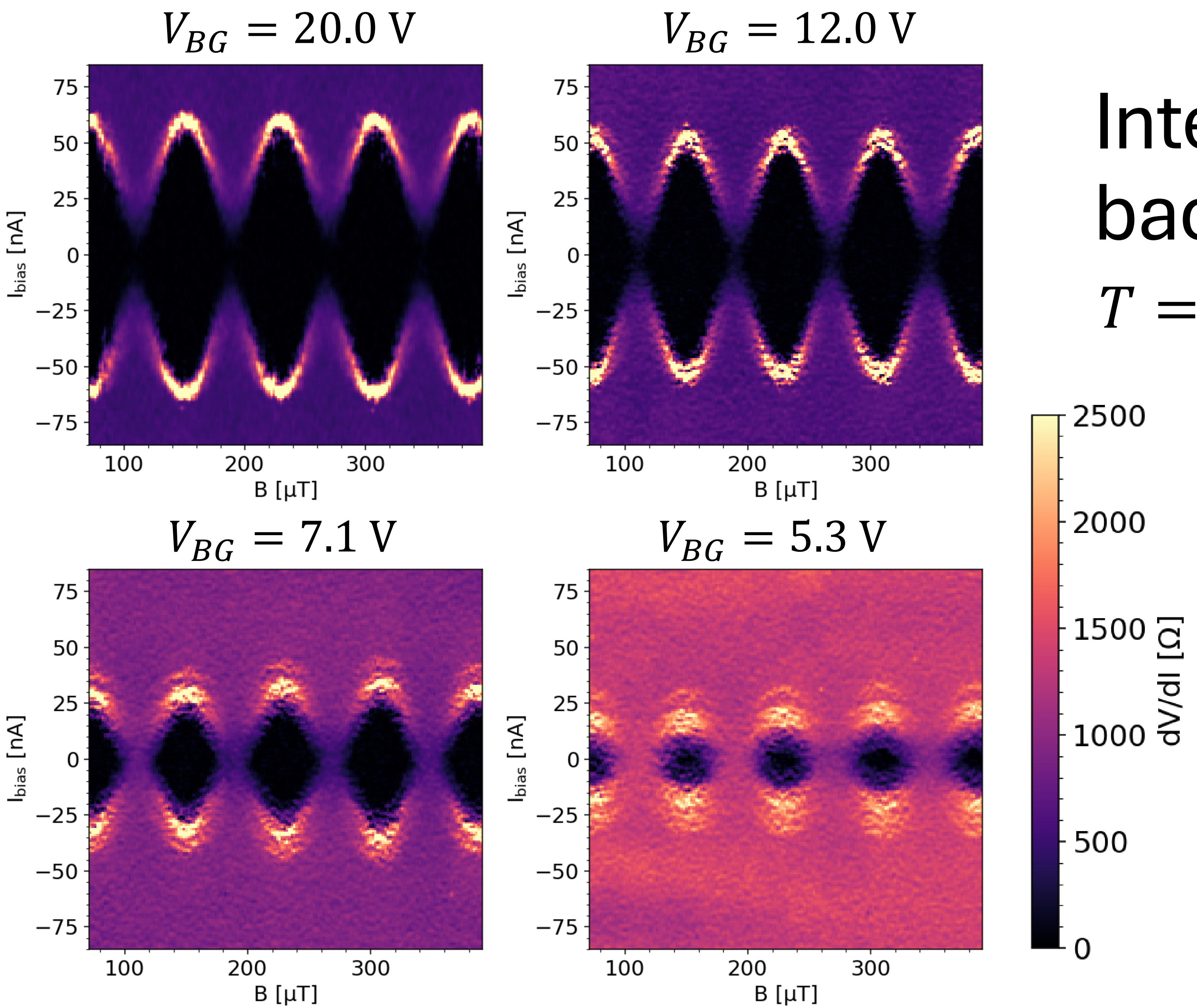
$A_{geo} = 13.6\ \mu m^2$

$L_1 = 200\ \text{nm}$
$W_1 = 380\ \text{nm}$

$L_2 = 200\ \text{nm}$
$W_2 = 380\ \text{nm}$

Interference vs backgate

$T = 350\ \mathrm{mK}$



Interference vs backgate

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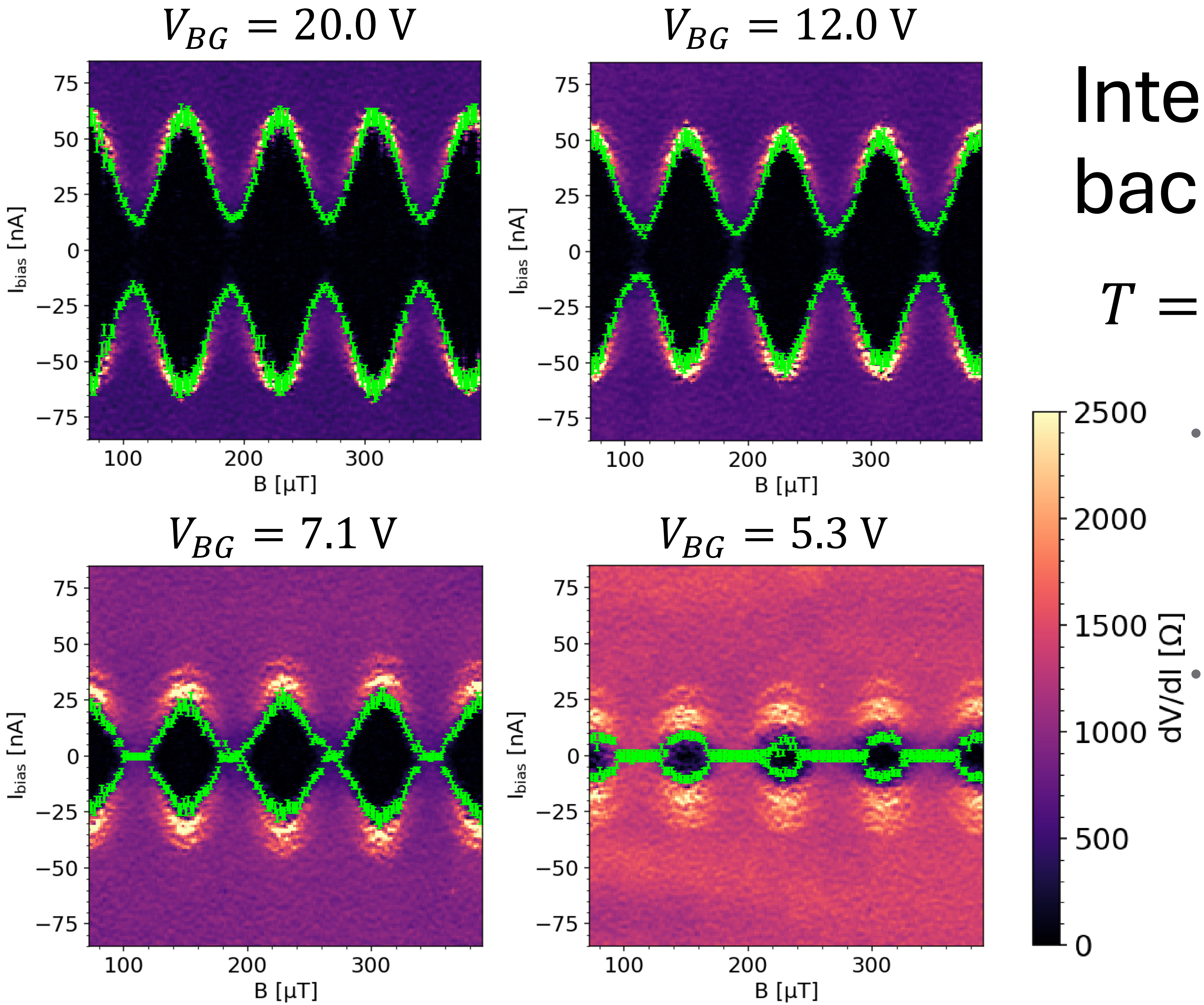
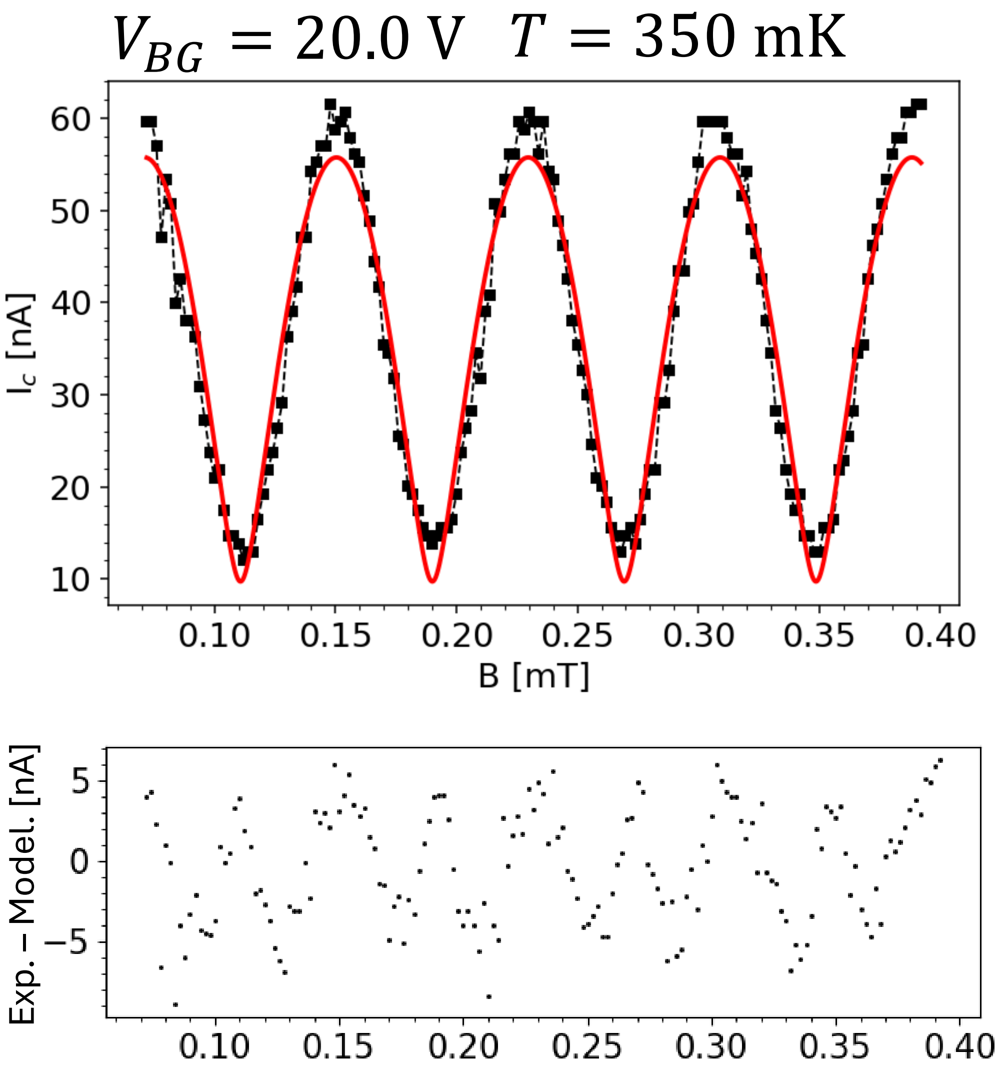


- SQUID pattern is not symmetric for all the backgate values → **JJ are not identical**
- At low V_{BG} destructive interference is obtained for a range of magnetic field.

First Model

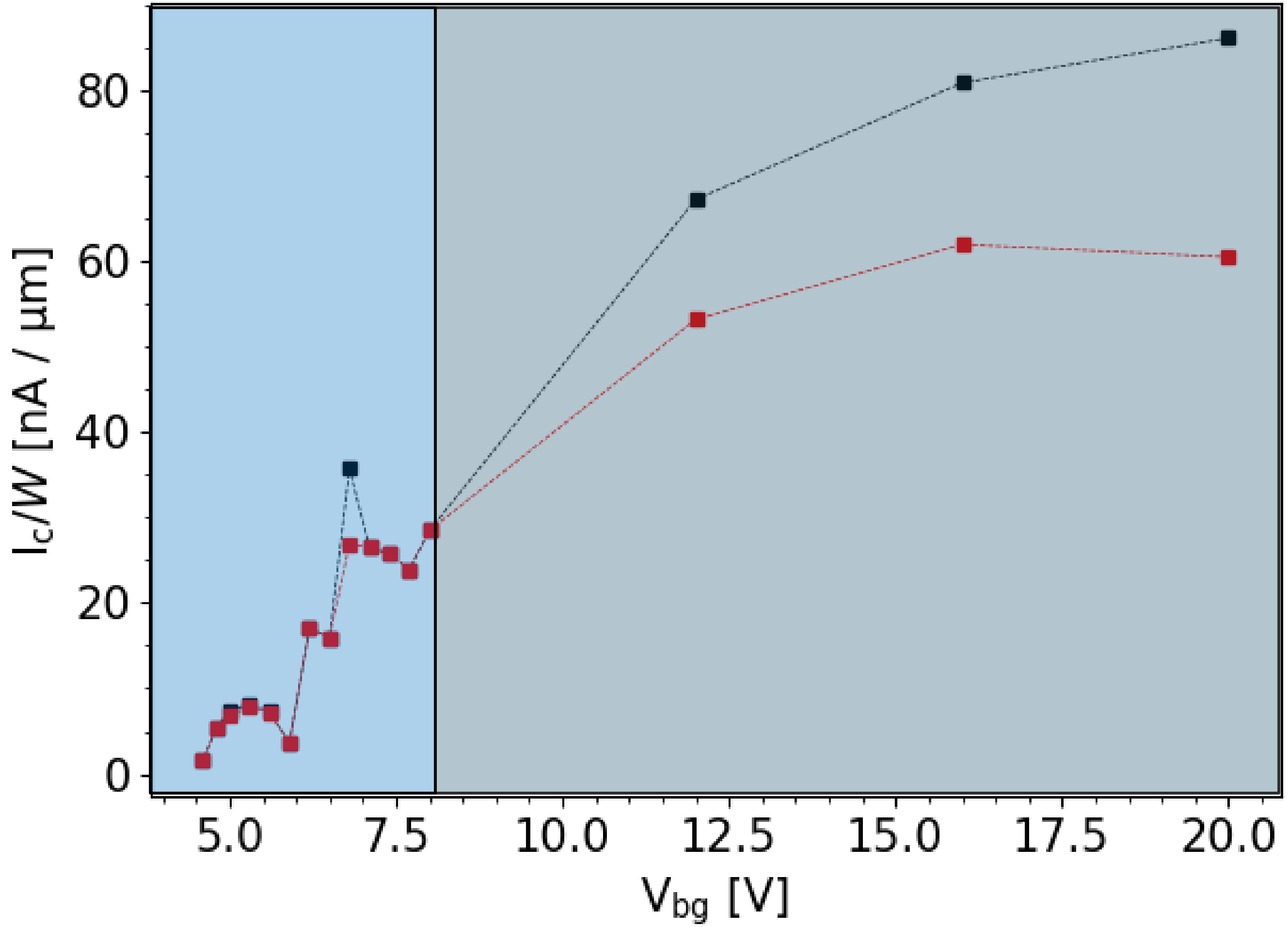
- $I_c = \sqrt{(I_{c1} - I_{c2})^2 + 4 I_{c1} I_{c2} \cos\left(\pi \frac{\boldsymbol{BA}}{\Phi_0} + \text{phase}\right)^2}$
- $I_{c1} = 32.8 \pm 0.4$ nA
- $I_{c2} = 23.0 \pm 0.5$ nA
- $A_{eff} = 26.10 \pm 0.1\ \mu m^2$
- $A_{geo} = 13.6\ \mu m^2$
- $\rightarrow F = 1.9$



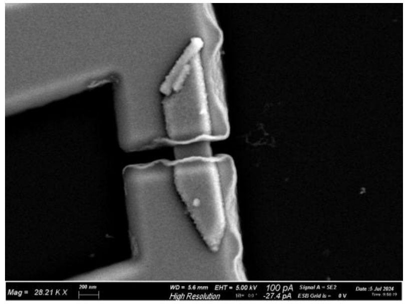
20240711/m054_a

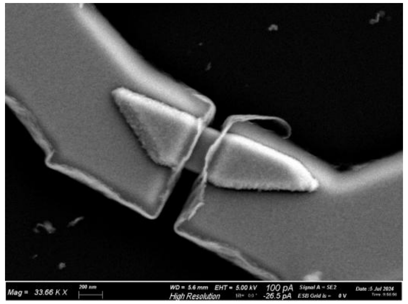
SQUID regimes vs backgate

Symmetric Asymmetric



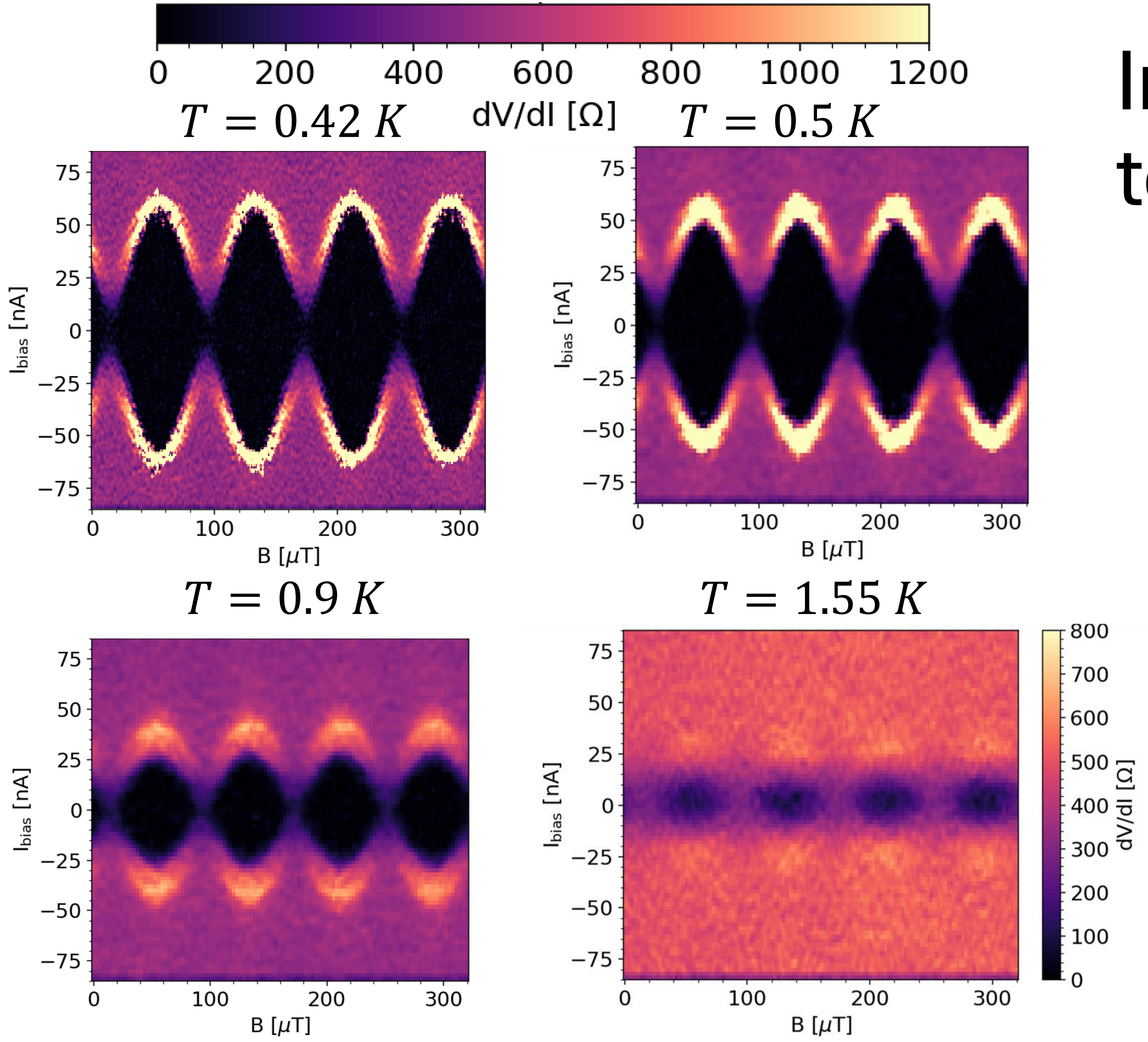
- $I_{c1}/W = 86 \text{ nA } \mu\text{m}^{-1}$
- $I_{c2}/W = 61 \text{ nA } \mu\text{m}^{-1}$
- Different interface transparency?





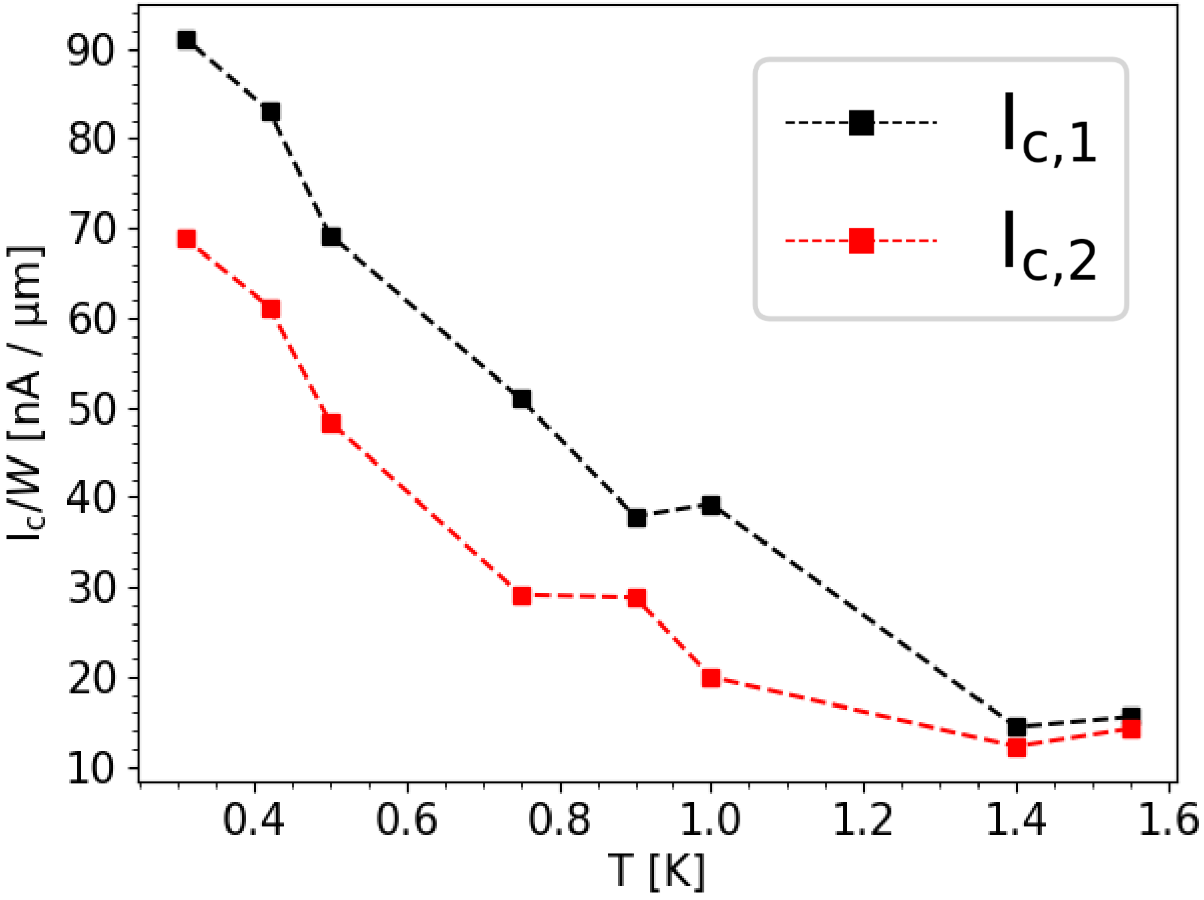
Interference vs temperature

- $V_{BG} = 20.0\ \mathrm{V}$
- Asymmetry in critical currents up to 1.5 K

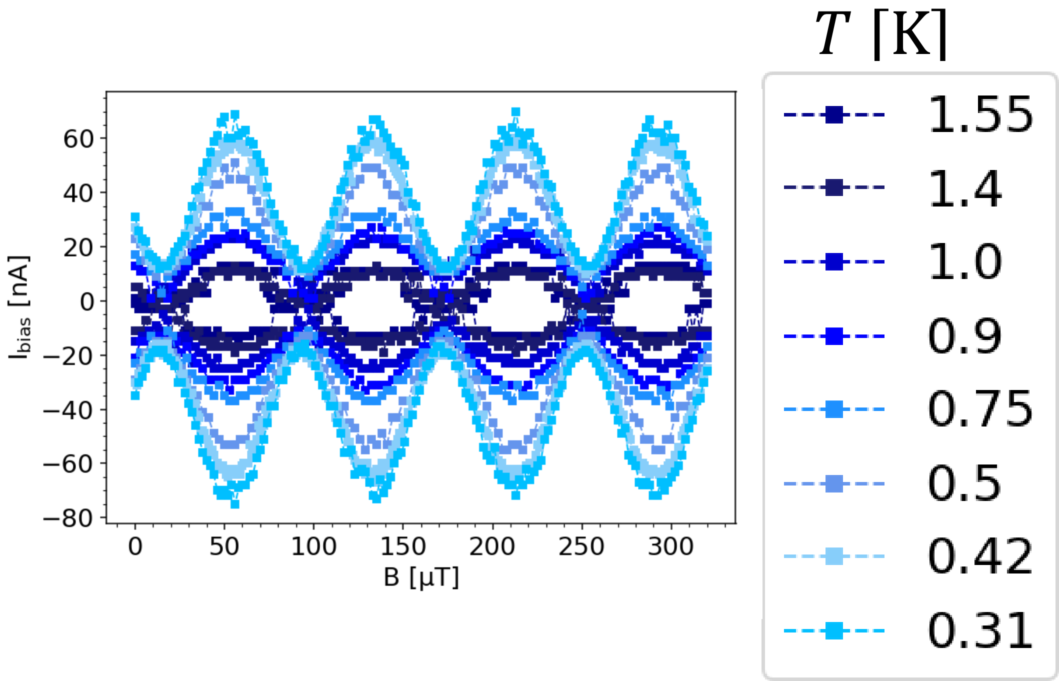


Temperature Behaviour

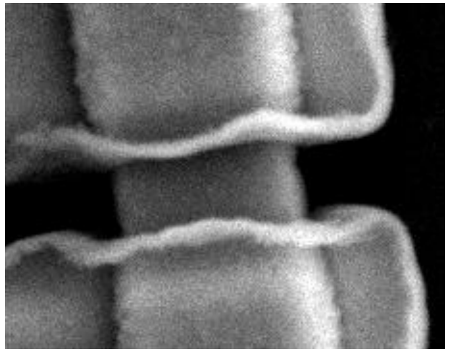
$V_{BG} = 20.0$ V



- Similar decay in temperature for both supercurrents.
- Slow decay above 1 K

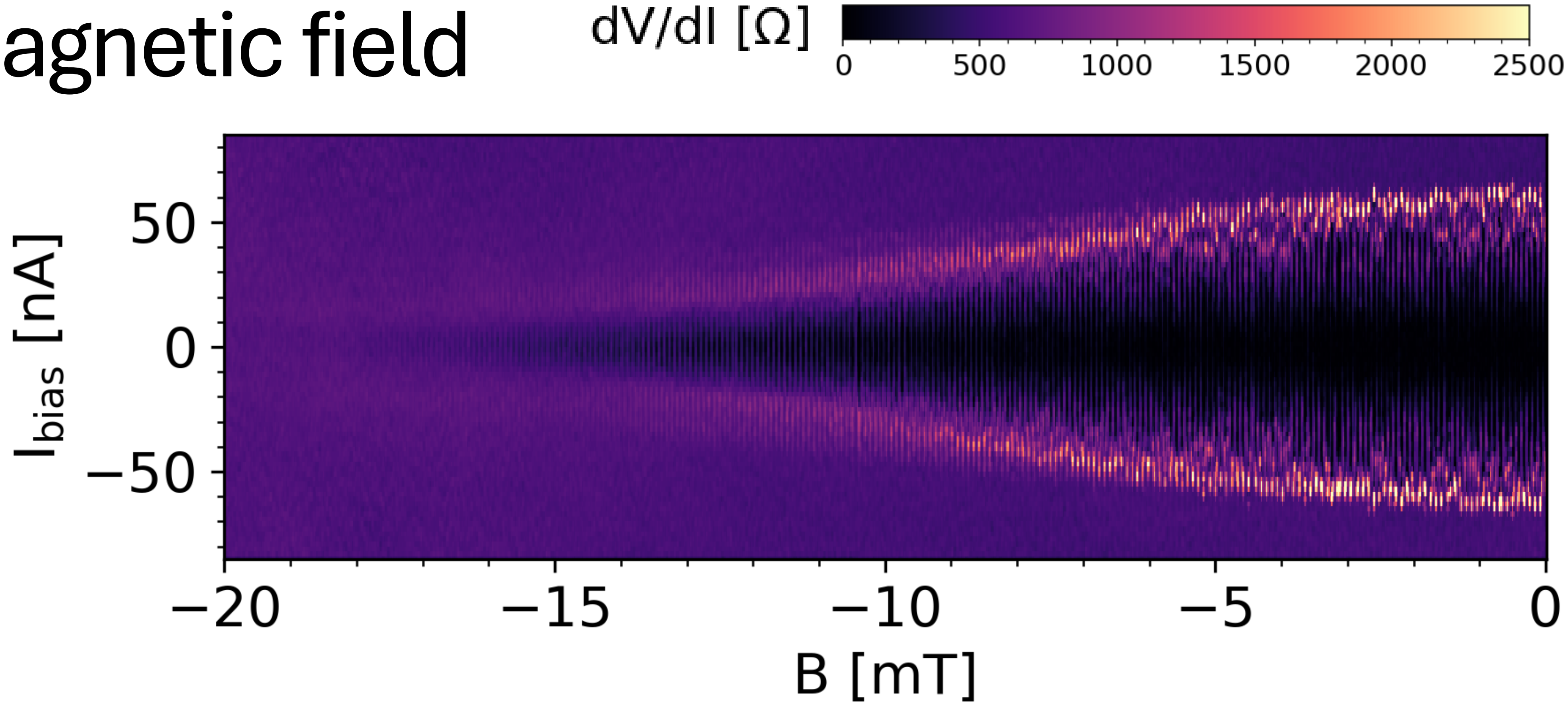


“High” magnetic field

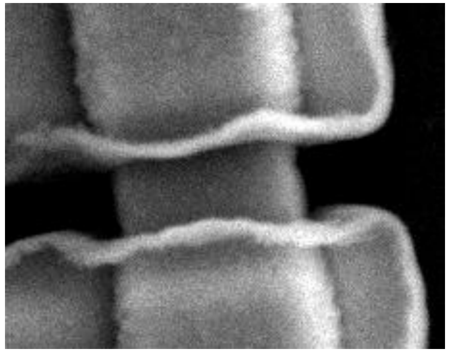


L = 200 nm
W = 380 nm
λ_L = 40 nm

$V_{BG} = 20.0$ V
$T = 350$ mK



“High” magnetic field



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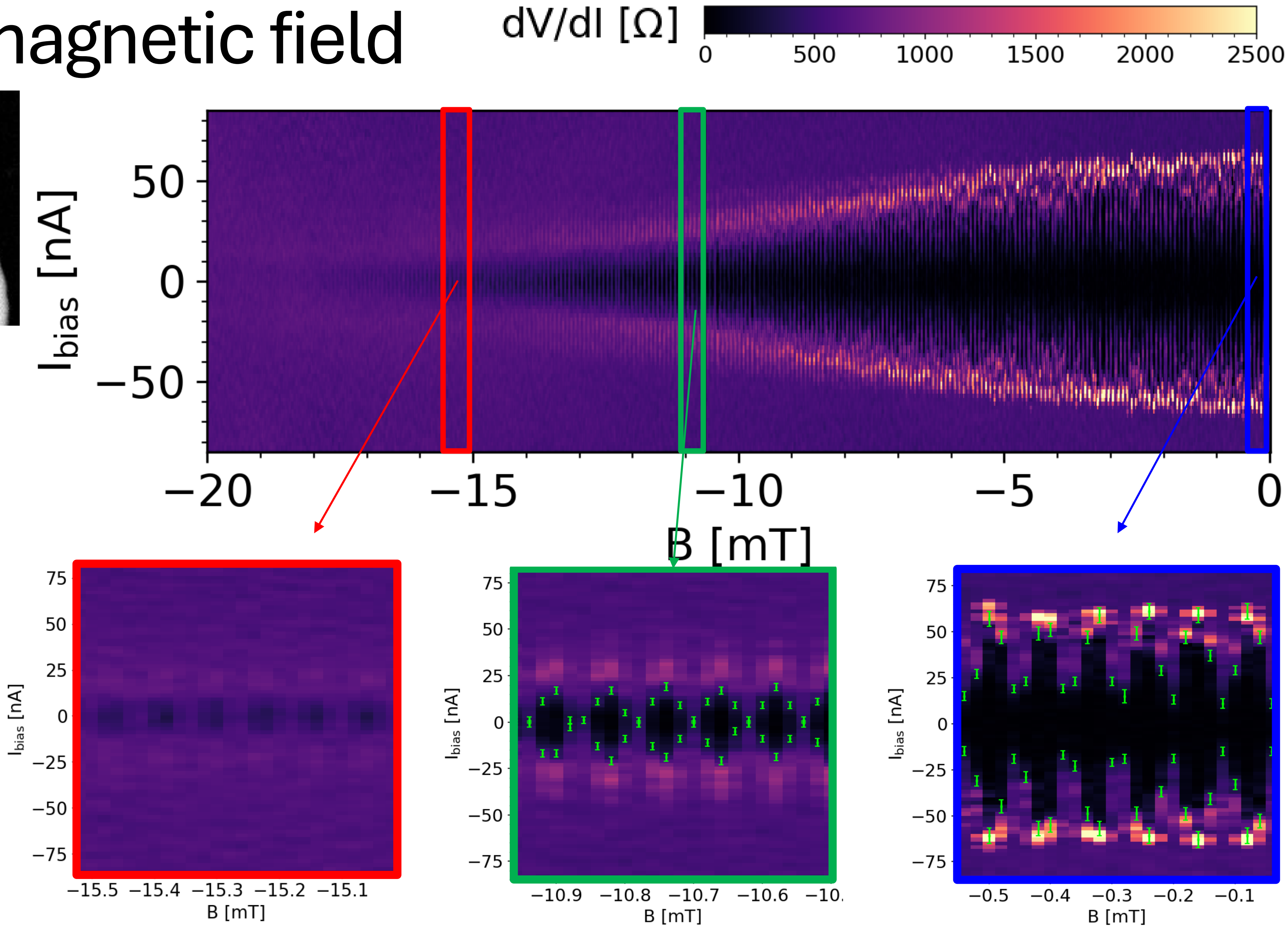

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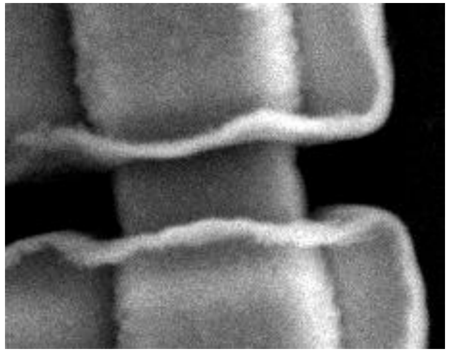
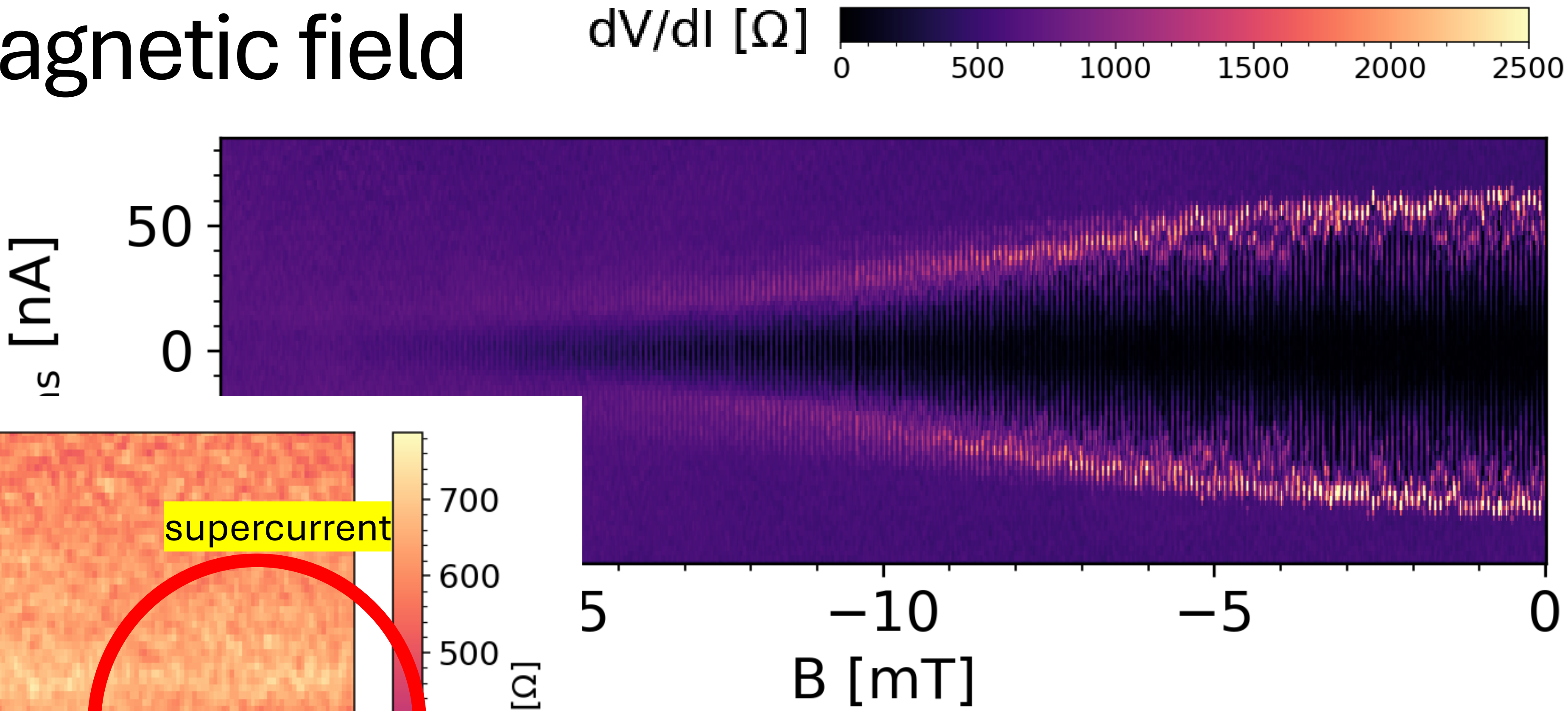
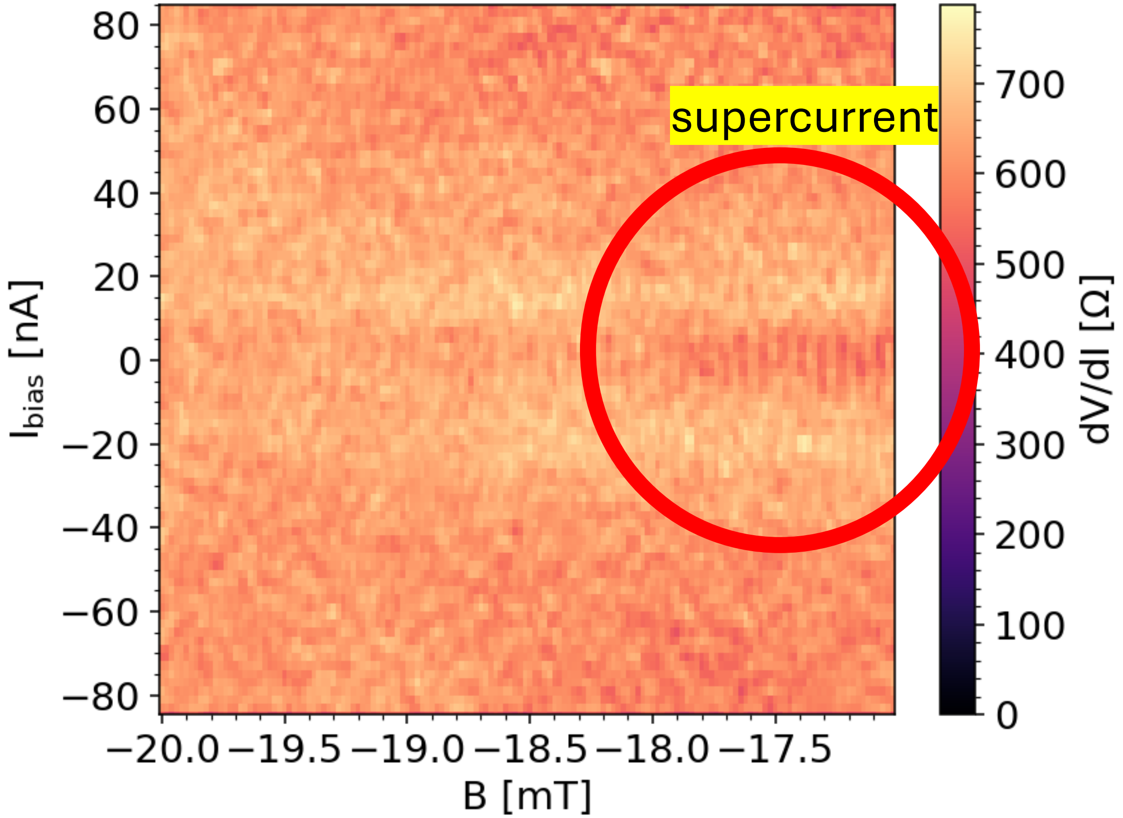






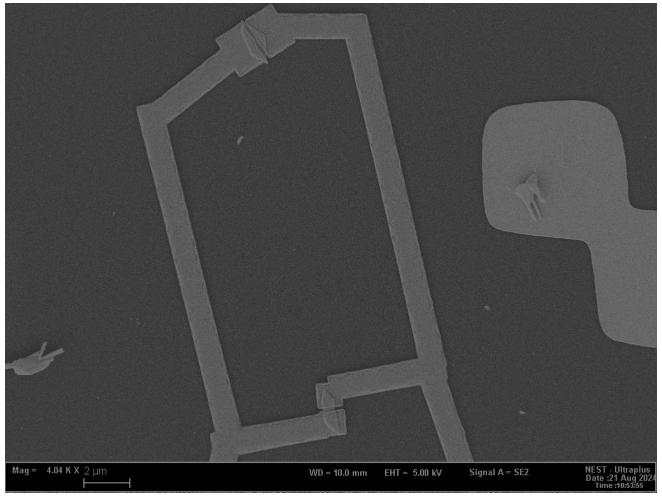
$\Phi_0 = 2.07\ \text{mT}\ \mu\text{m}^2$

$I_c(18.5\ \text{mT}) \cong 0\ \text{nA} \rightarrow A = 0.11\ \mu\text{m}^2$

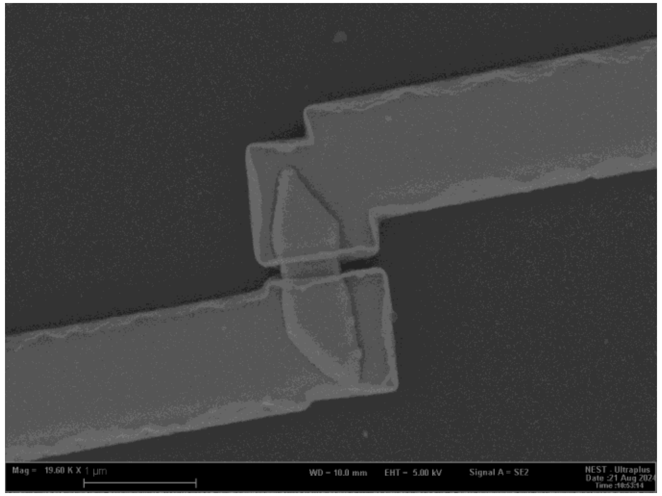
$A_{JJ1} = (L + 2\lambda_L) \times W = 0.11\ \mu m^2$

Results Asymmetric SQUID

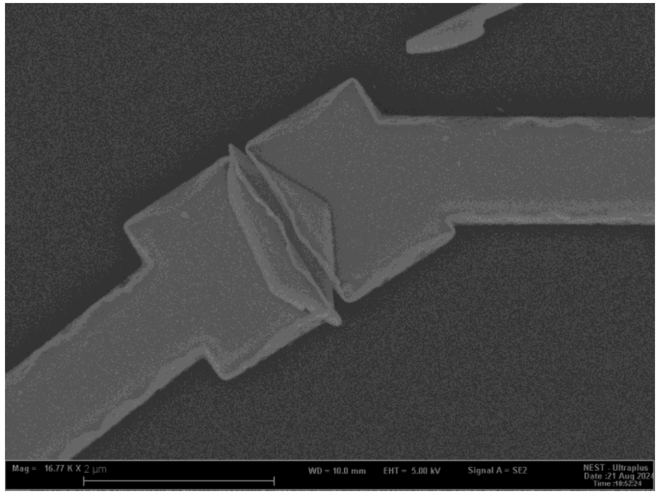
SEM: H6S4



A = 60 μm^2

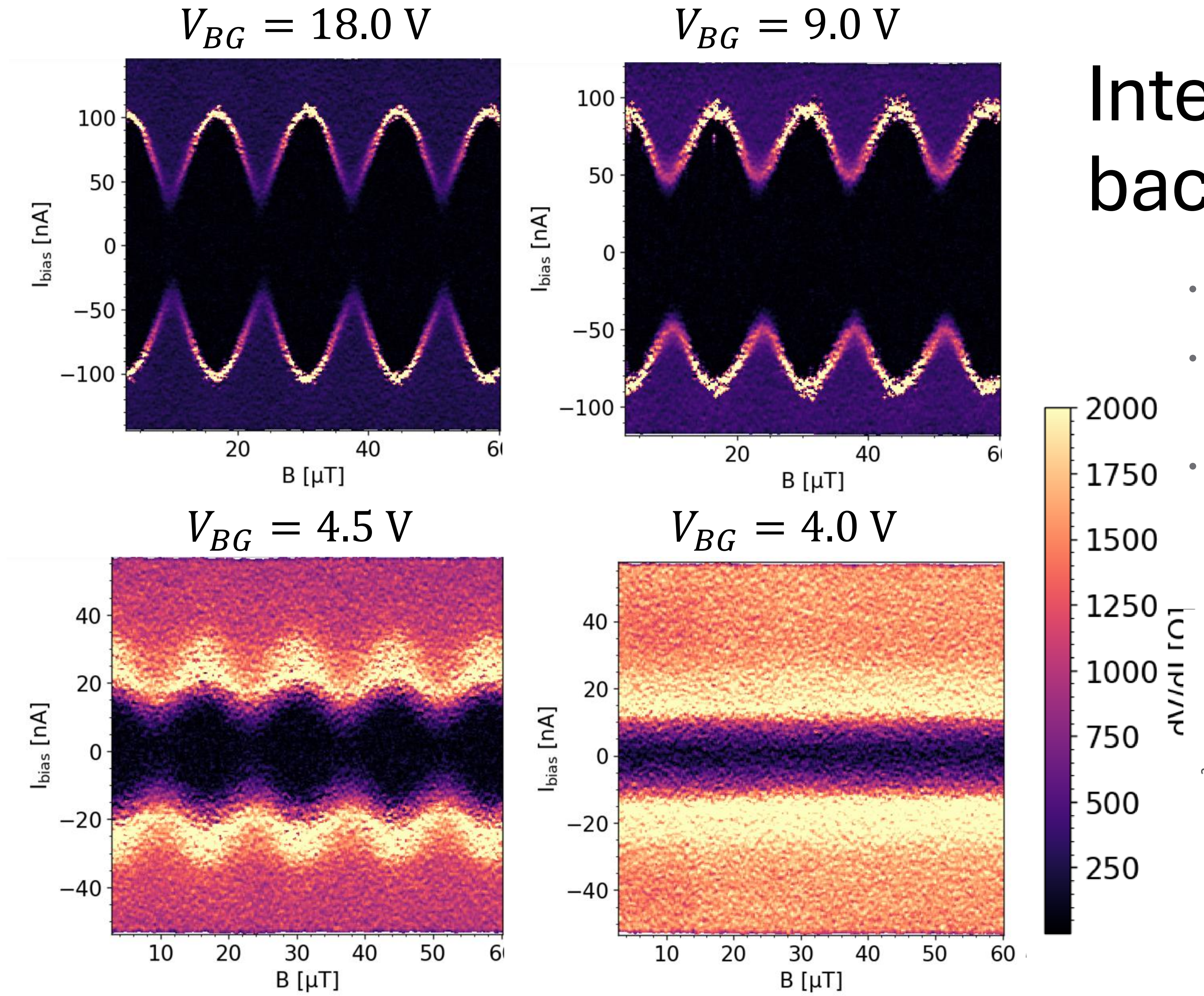


L = 190 nm
W = 530 nm
A = 0.10 μm^2

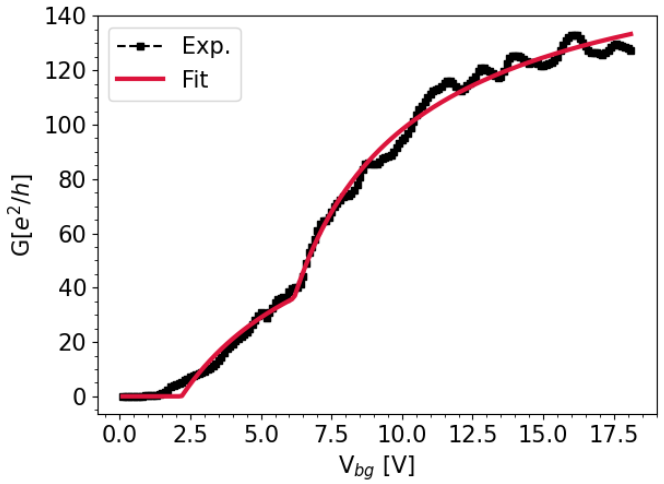


L = 180 nm
W = 1.7 um
A = 0.30 μm^2

Interference vs backgate

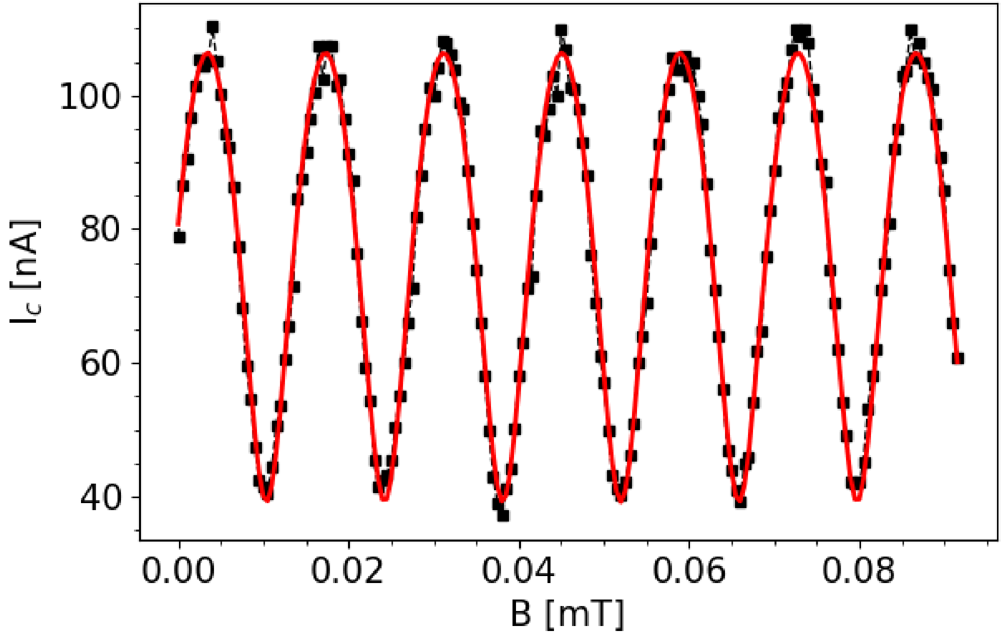


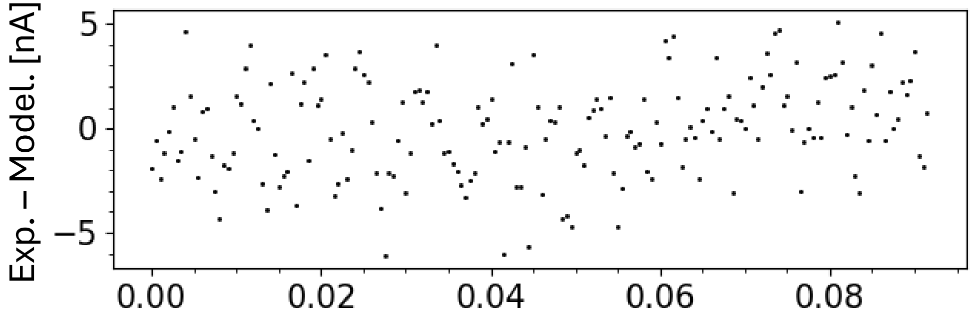
- $T = 350$ mK
- Always in the asymmetric regime
- Loss of interference for $V_{BG} = 4.0$ V



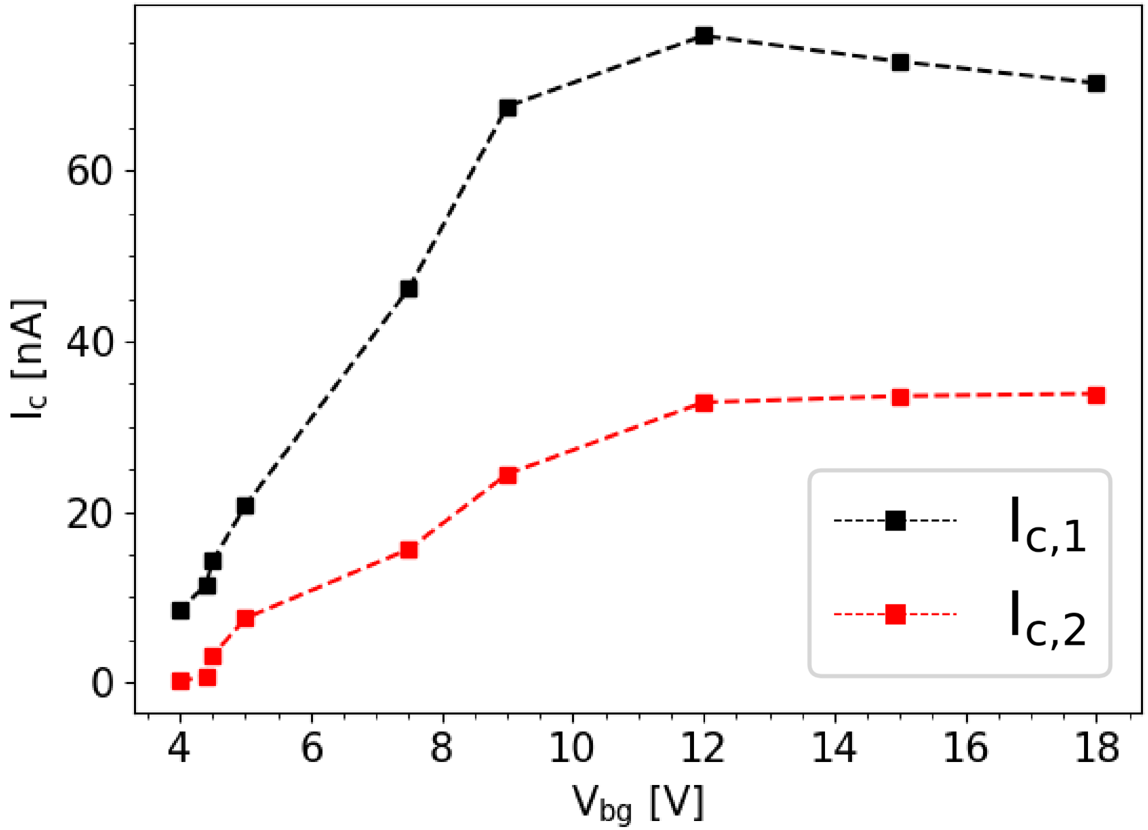
First Model

- $I_c = \sqrt{(I_{c1} - I_{c2})^2 + 4I_{c1}I_{c2}\cos\left(\pi\frac{\boldsymbol{B}A}{\Phi_0} + \text{phase}\right)^2}$
- $I_{c1} = 72.8 \pm 0.2$ nA
- $I_{c2} = 33.6 \pm 0.3$ nA
- $A_{\text{eff}} = 149.0 \pm 0.1\ \mu\text{m}^2$
- $A_{\text{geo}} = 60\ \mu\text{m}^2$
- $\rightarrow$ F = 2.5

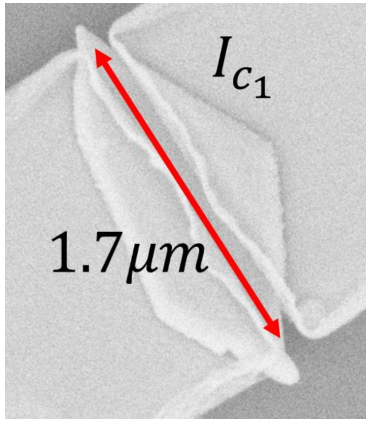


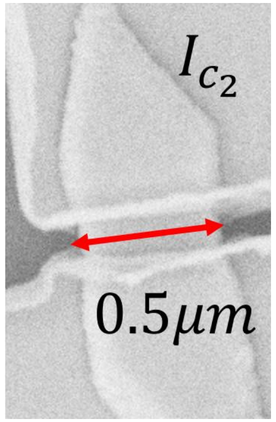


Critical Current vs backgate



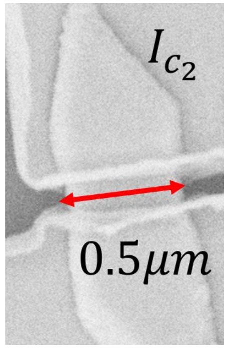
- I associate the higher critical current to the wider flag.

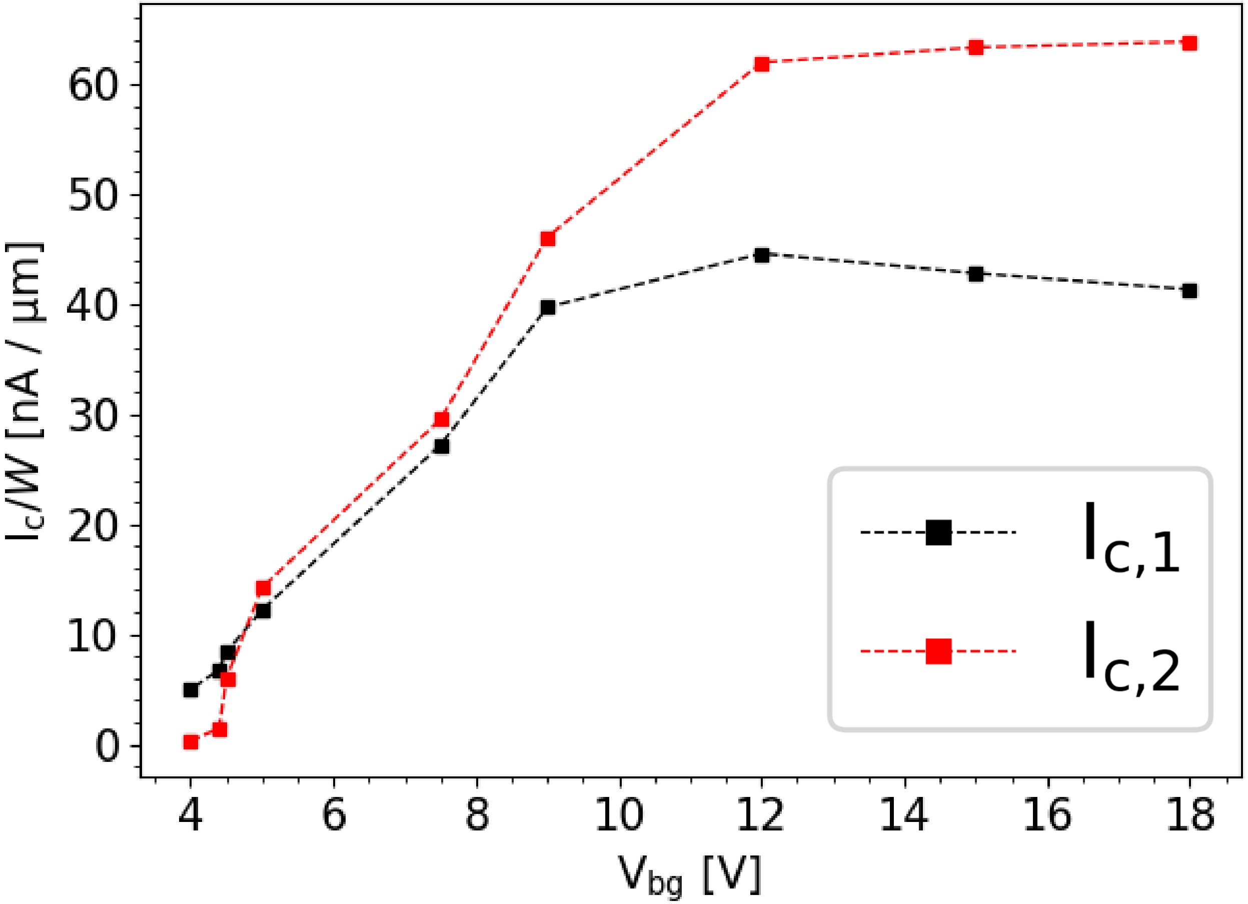




Critical current density versus backgate

- $I_{c1}/W_1 = 40$ nA µm^{-1}
- $I_{c2}/W_2 = 62$ nA µm^{-1}
- The narrow flag has higher supercurrent density
- The narrow flag is the one that show pinch off at $V_{BG} = 4.0$ V





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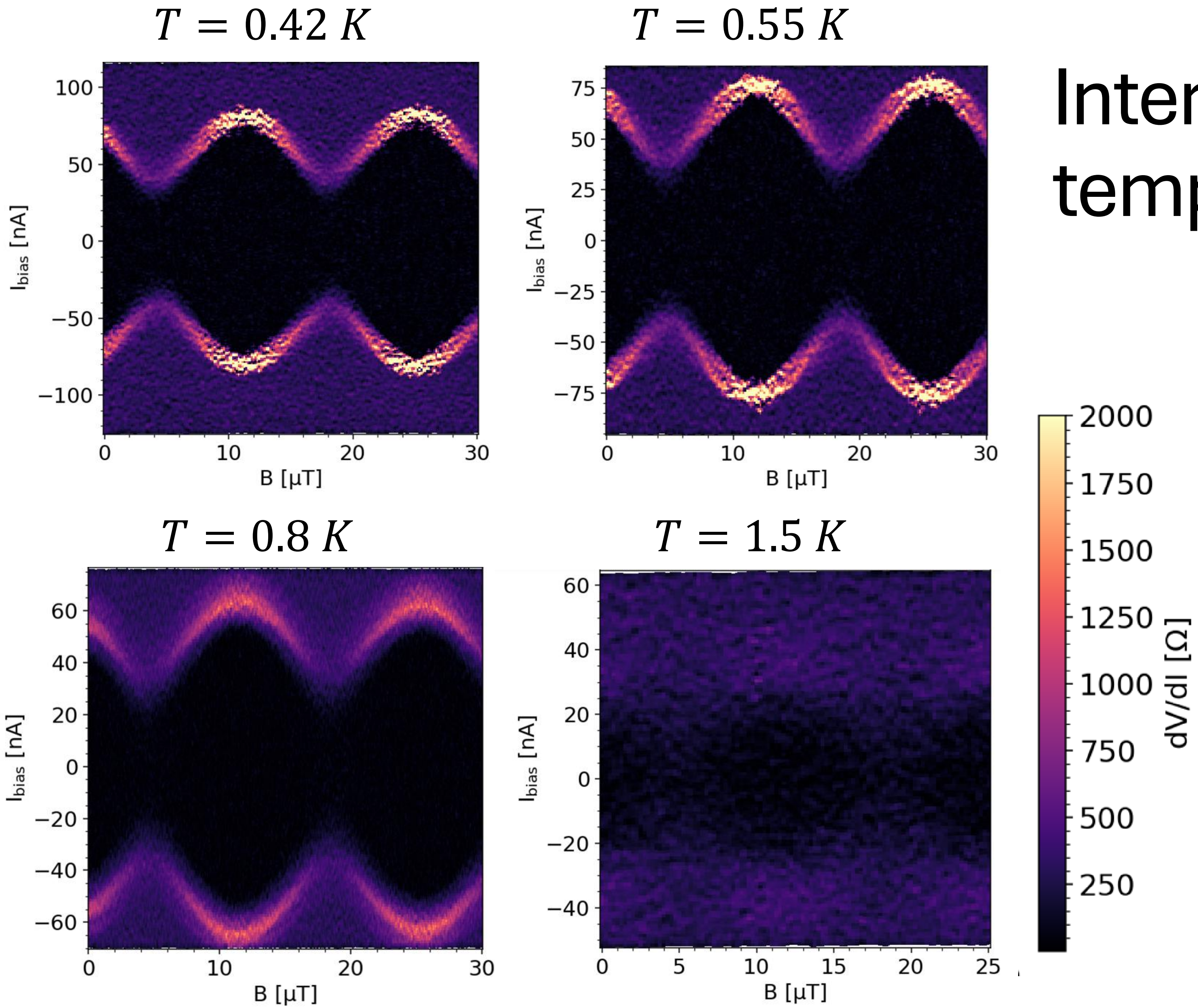
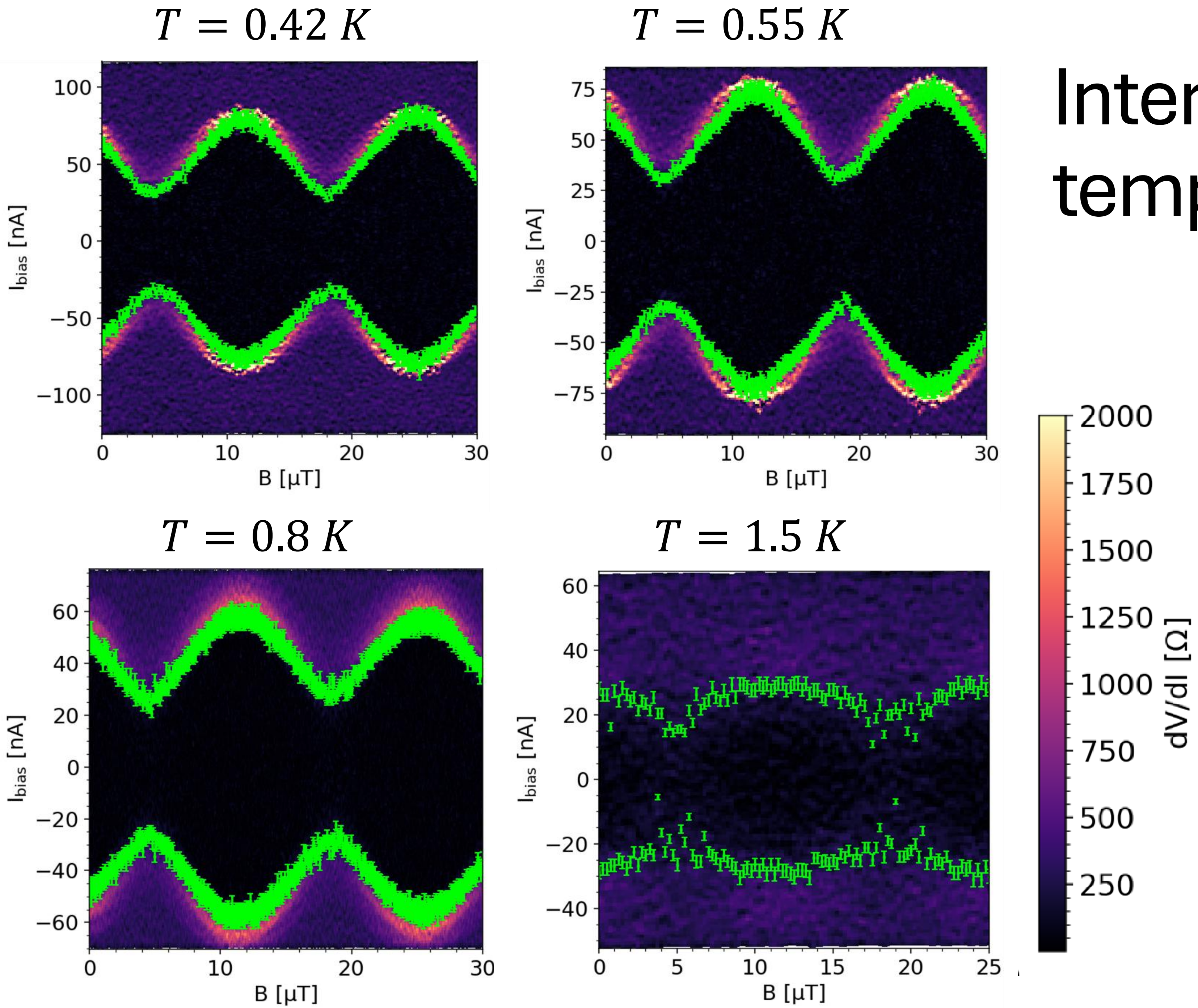
Interference vs temperature

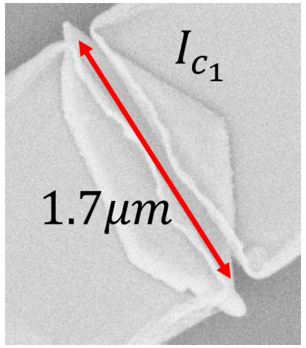


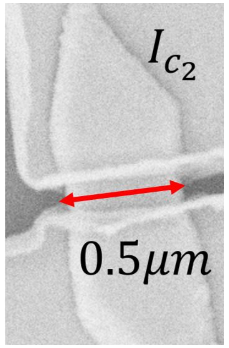
Interference vs temperature



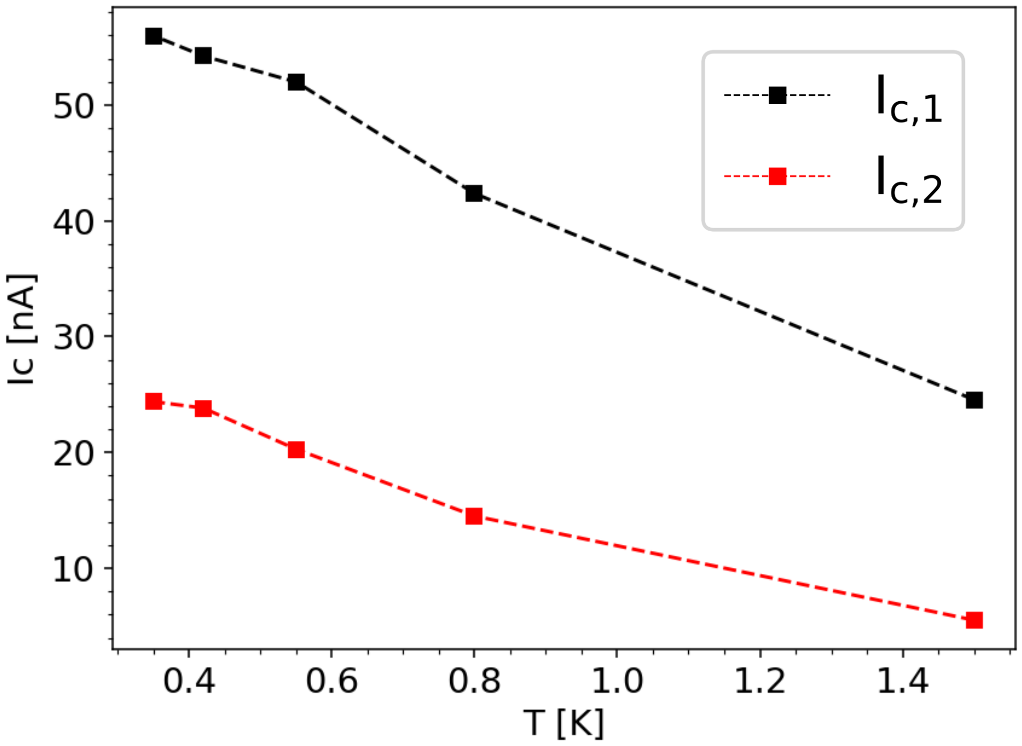
- Interference is visible also at 1.5 K

Critical Currents vs temperature

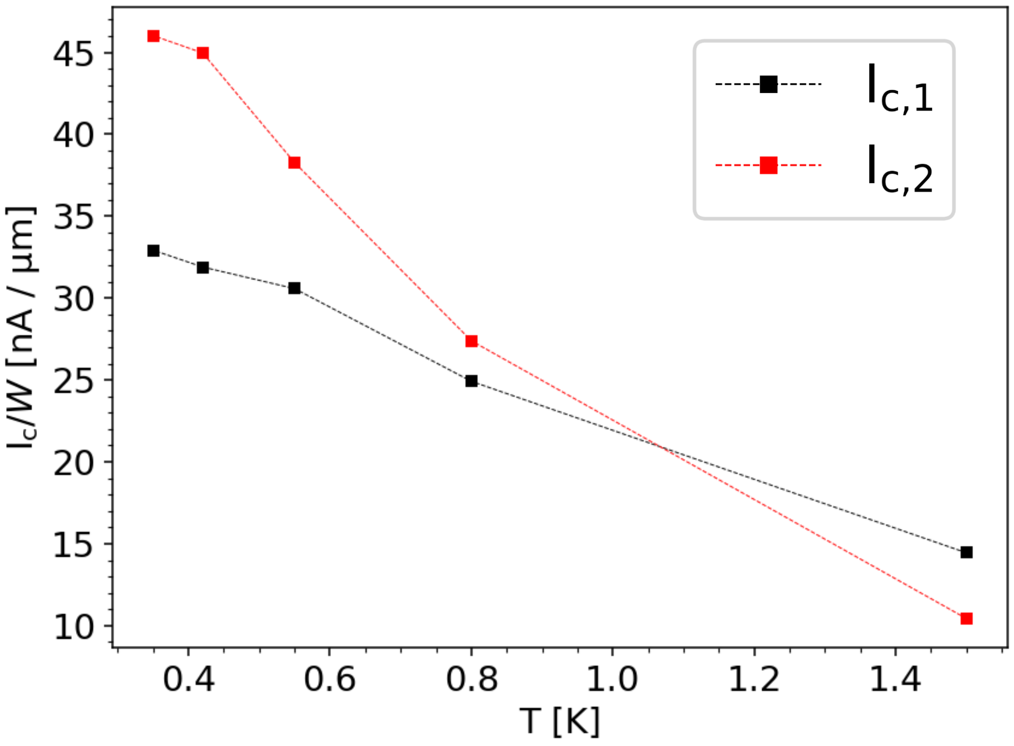




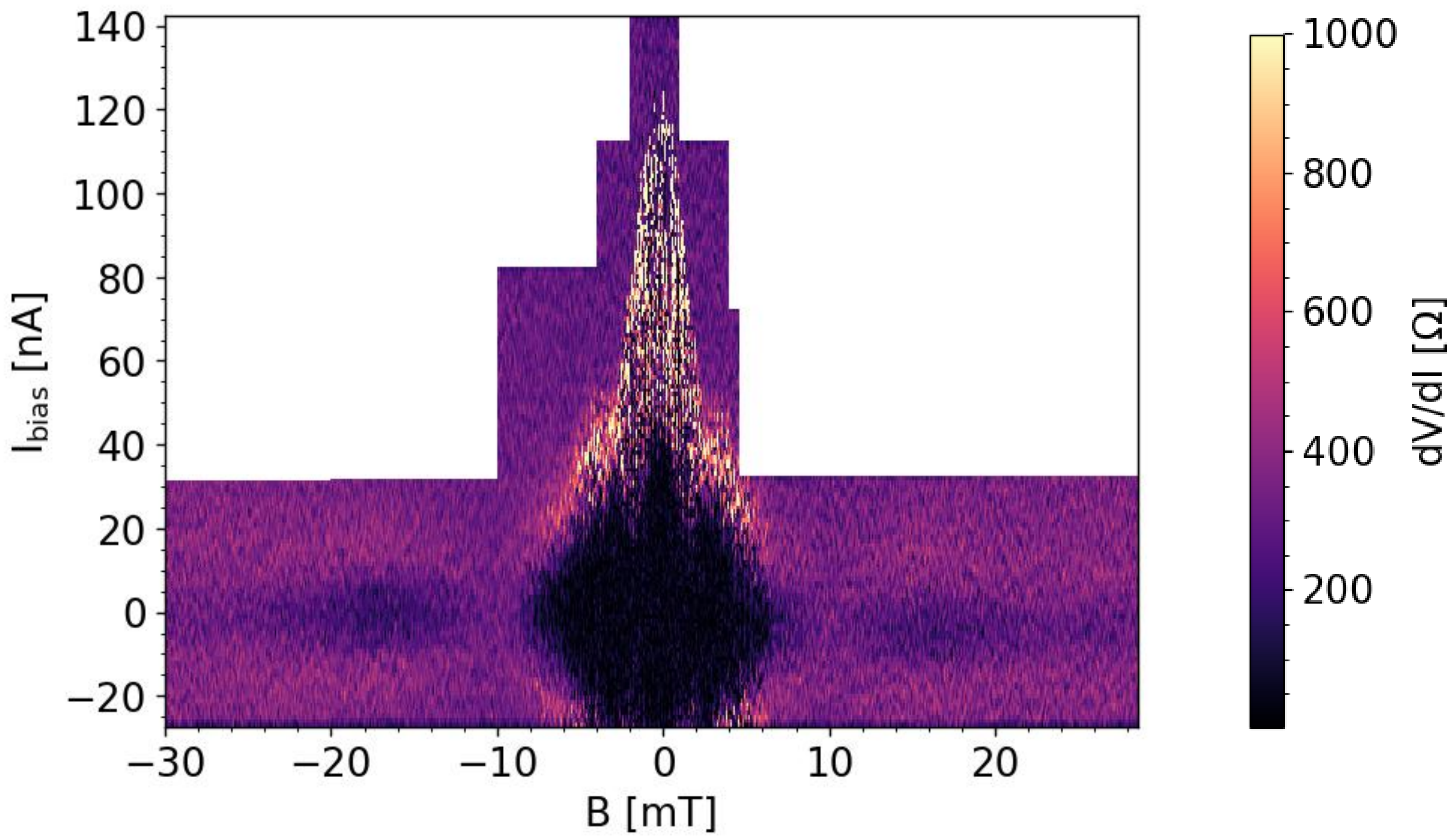
Critical Current



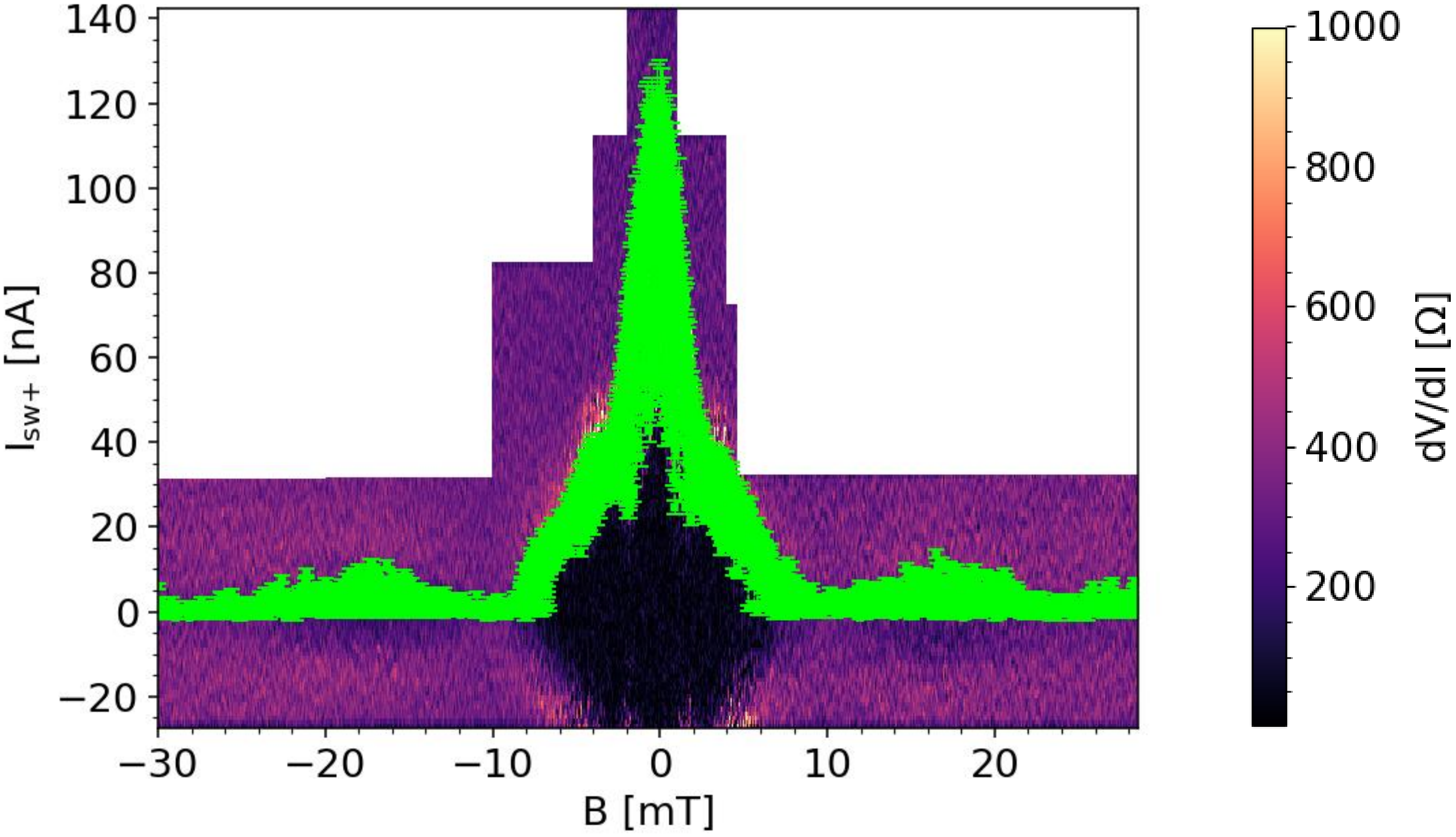
Critical Current Density



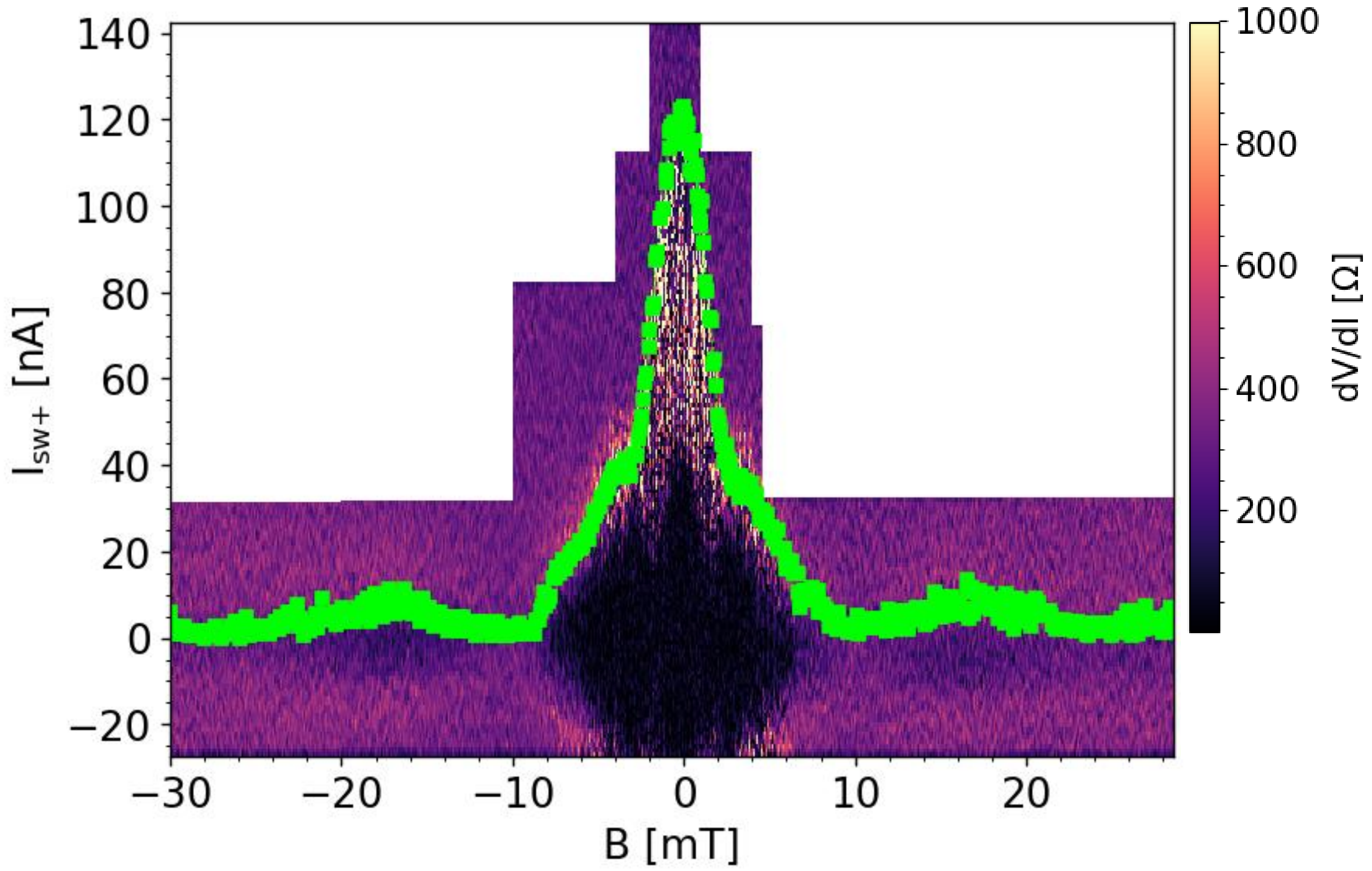
Single Junction Interference



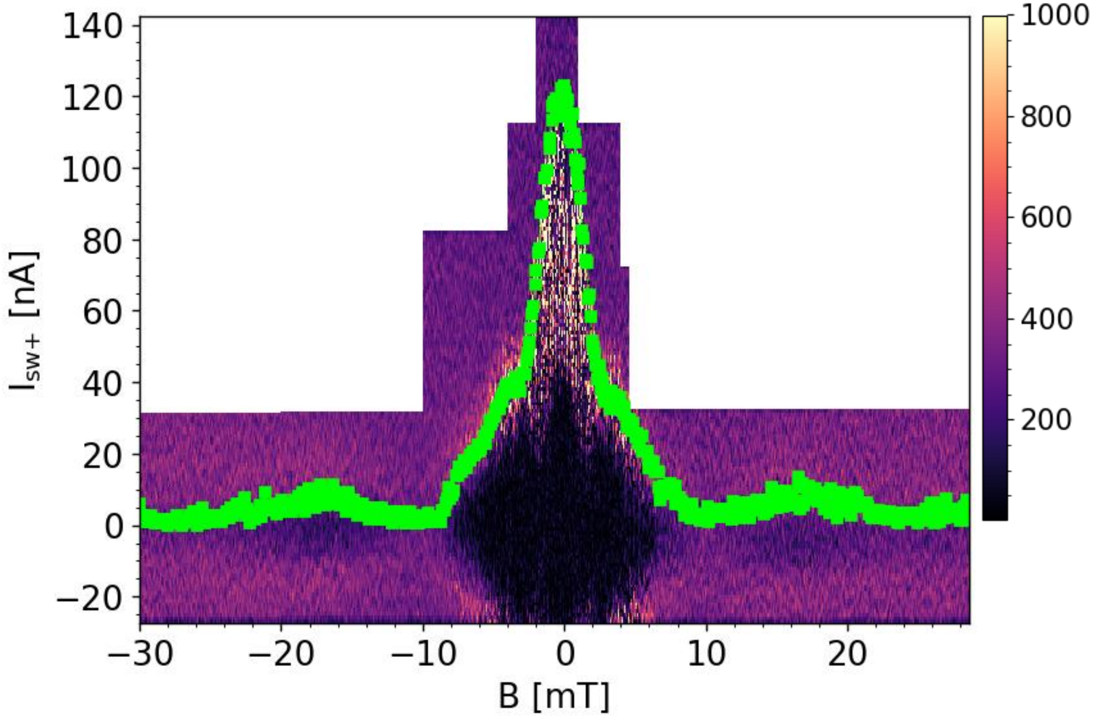
Single Junction Interference

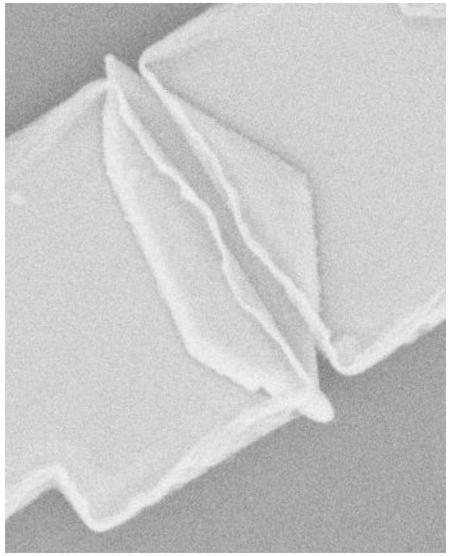


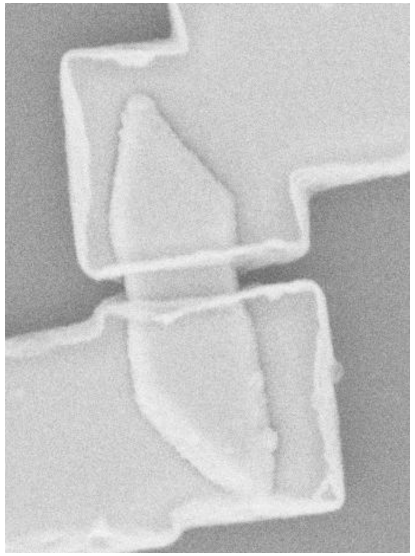
Single Junction Interference



Single Junction Interference







$\lambda_L = 40$ nm

$A_1 = 0.44\ \mu\text{m}^2$ $A_2 = 0.14\ \mu\text{m}^2$

$I_c(3.3\ \text{mT}) \cong \text{local min} \rightarrow A_{\text{eff},1} = 0.62\ \mu\text{m}^2$

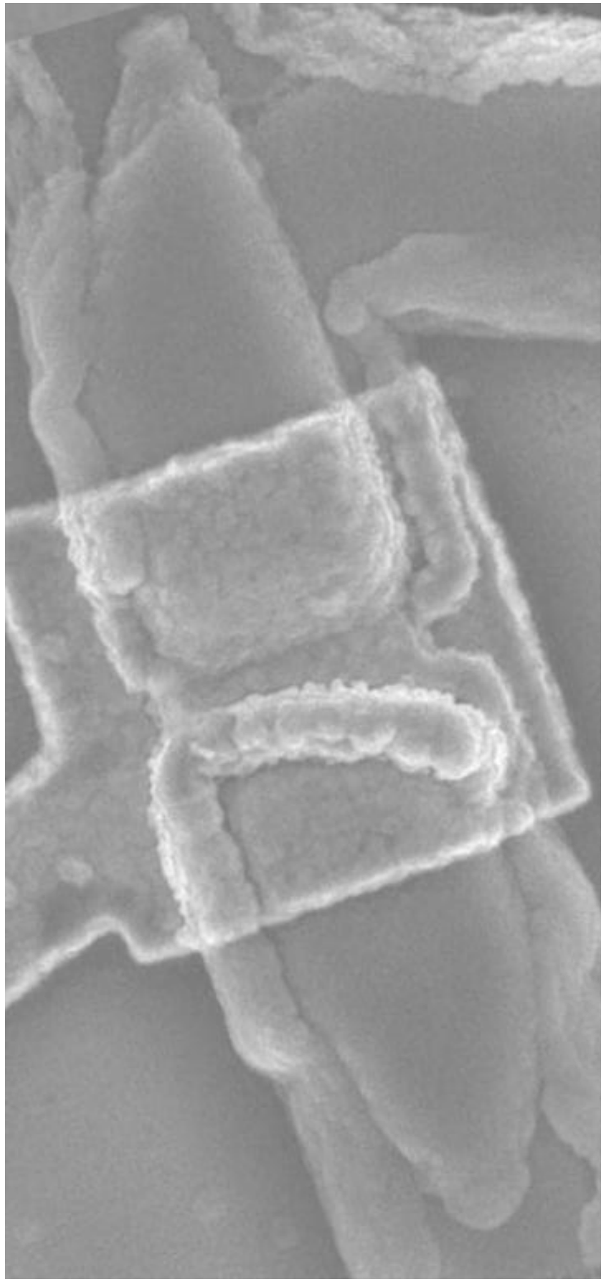
$I_c(10.6\ \text{mT}) \cong 0\ \text{nA} \rightarrow A_{\text{eff},2} = 0.19\ \mu\text{m}^2$

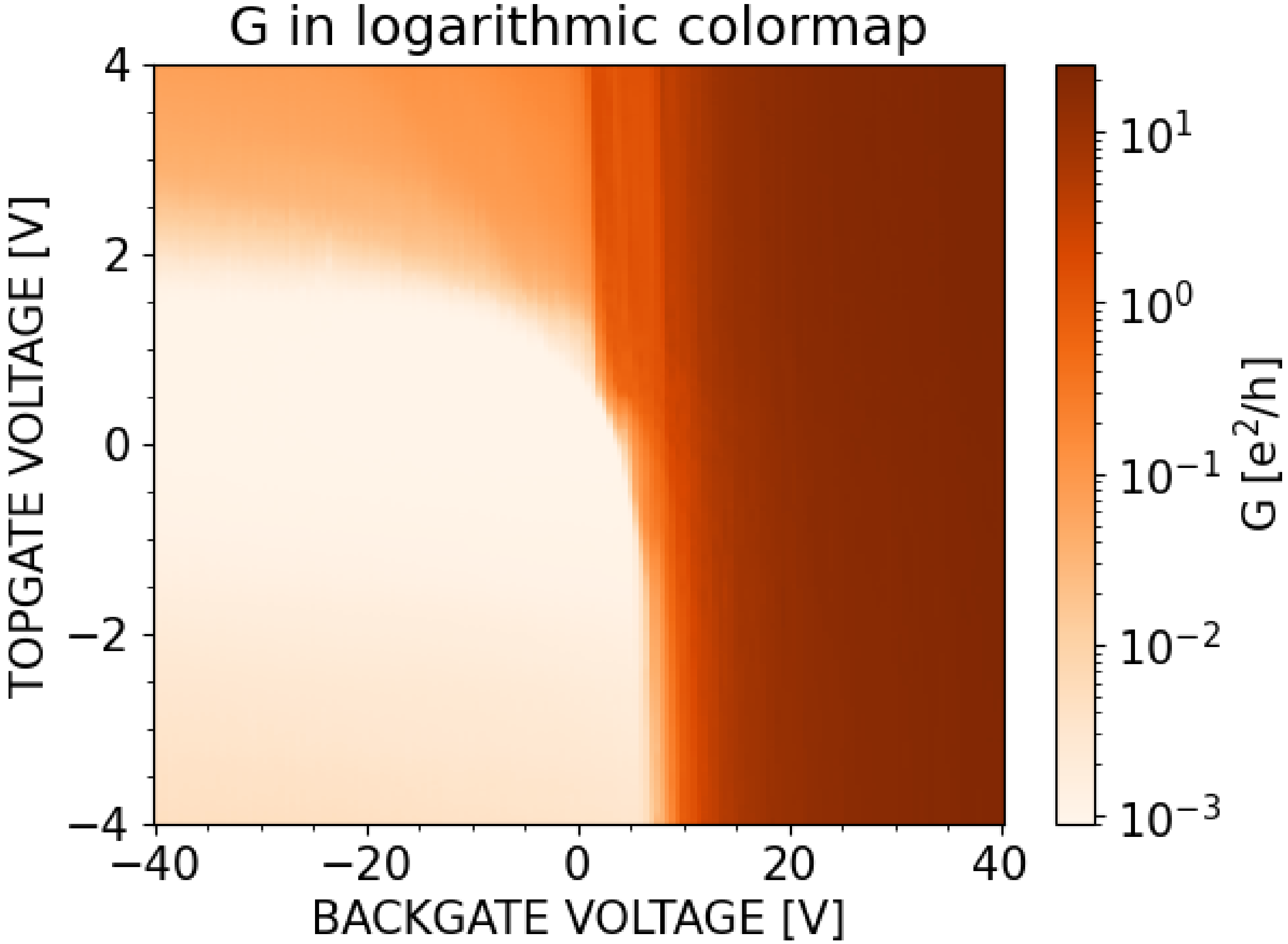
$A_1/A_2 = 3.14$

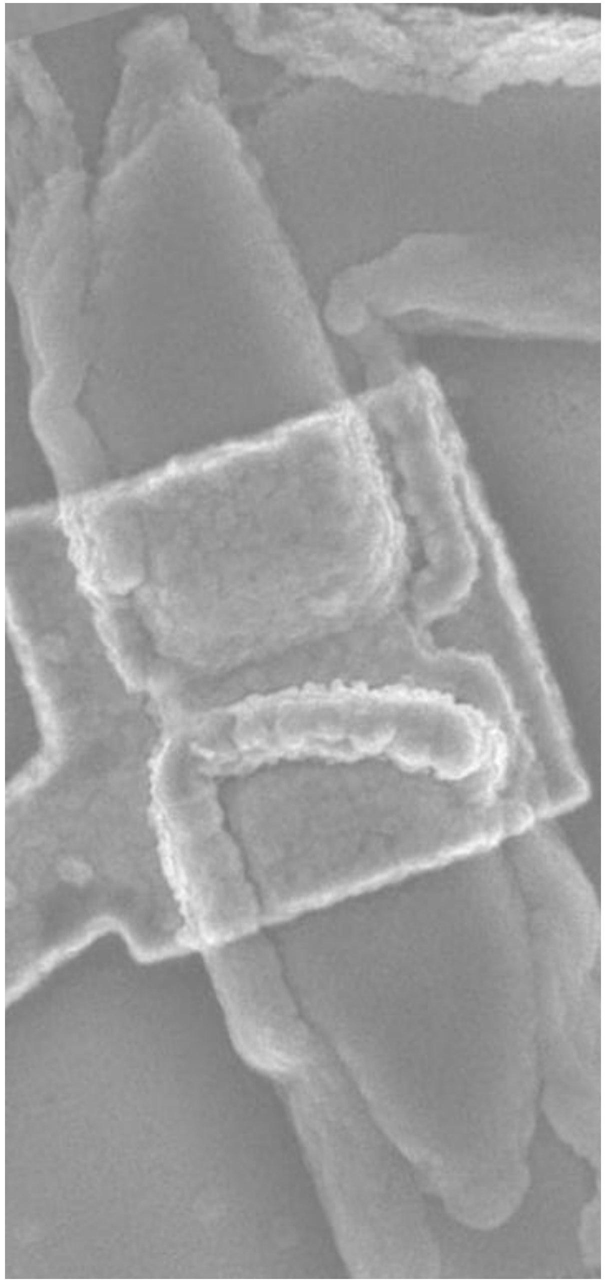
$A_{\text{eff},1}/A_{\text{eff},2} = 3.26$

Top Gates

Top Gate on single Josephson Junctions

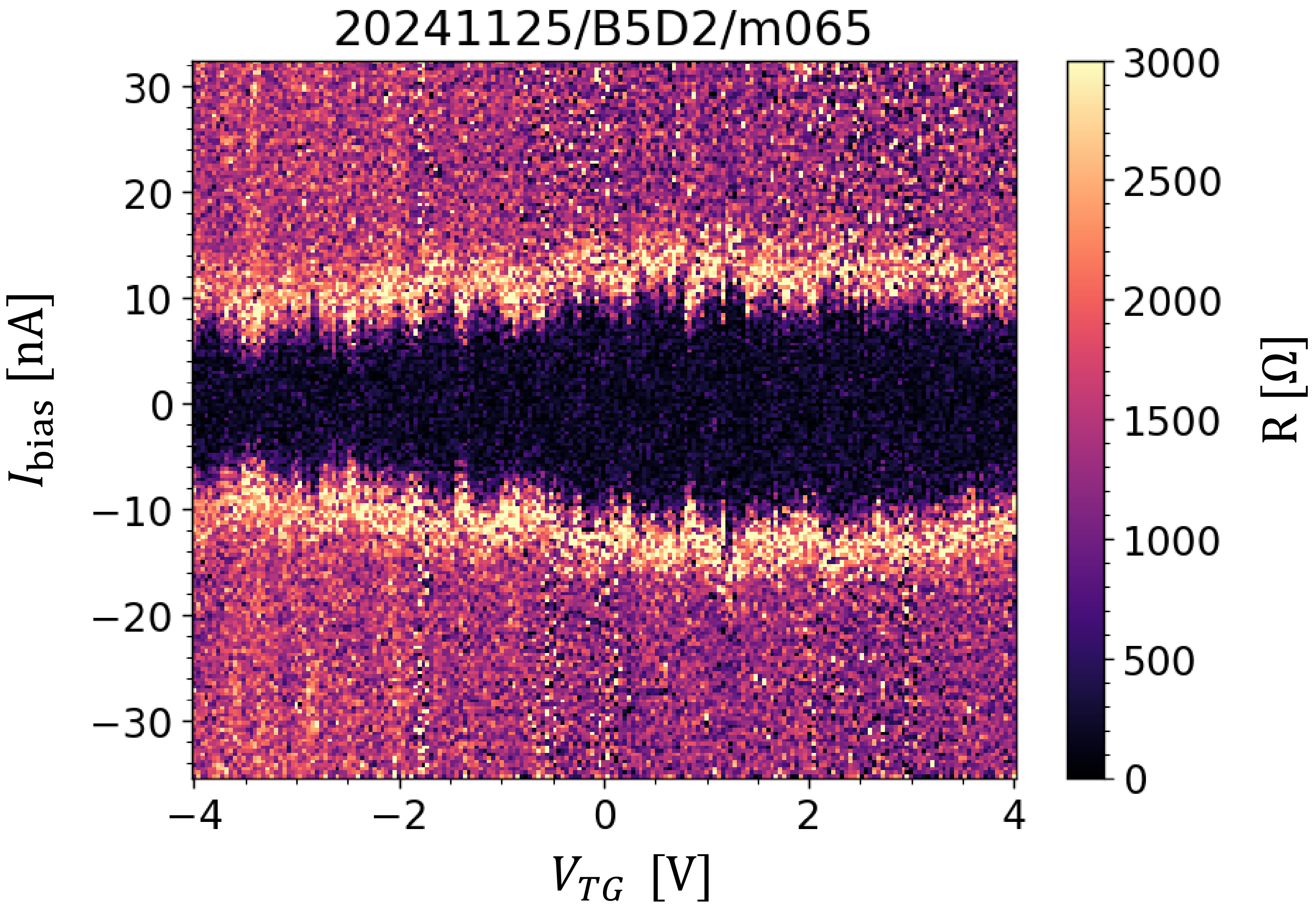






Top Gate control of supercurrent

$V_{BG} = 20.0$ V
$T = 350$ mK



Thanks for your attention!