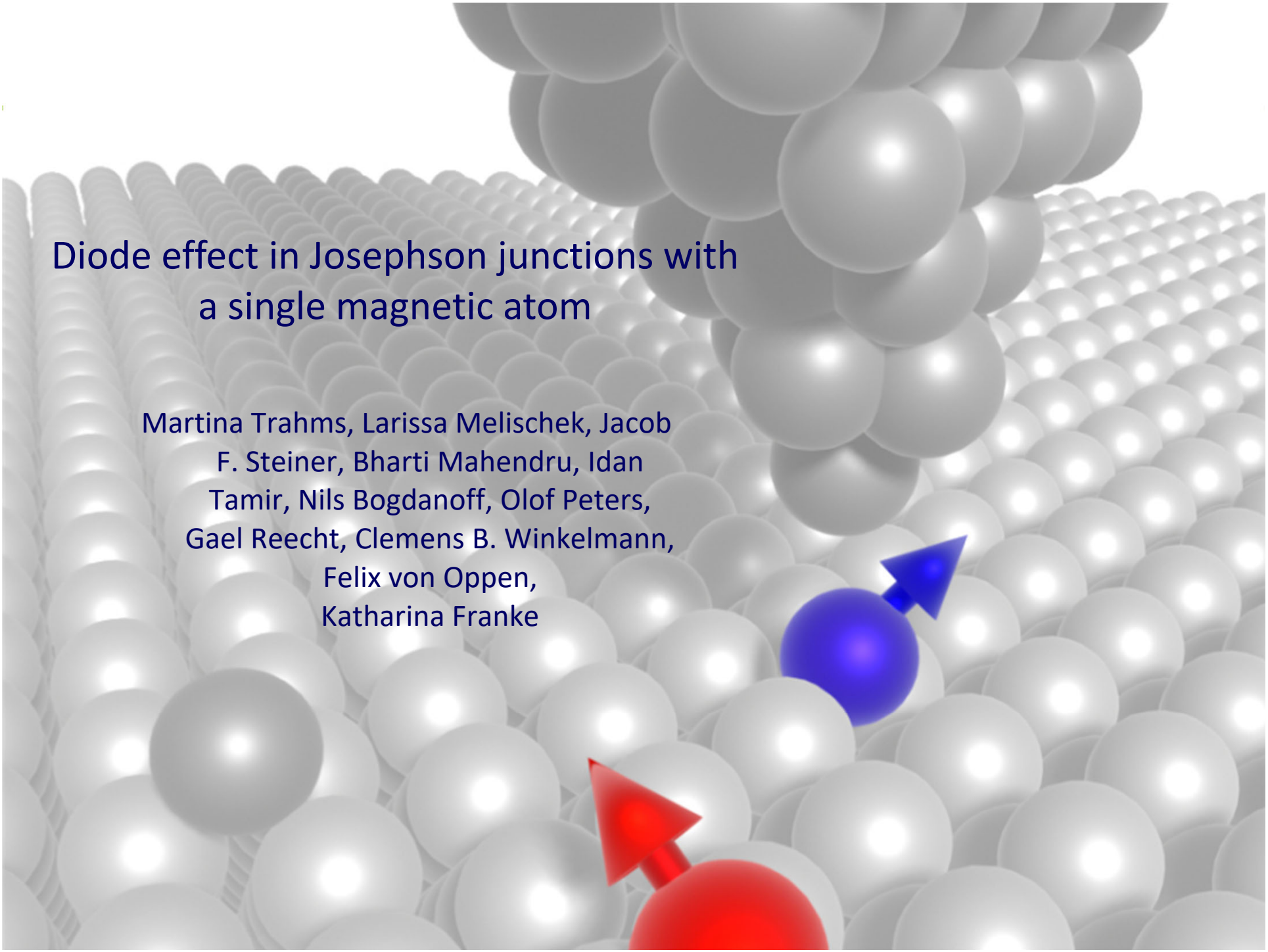


Diode effect in Josephson junctions with a single magnetic atom

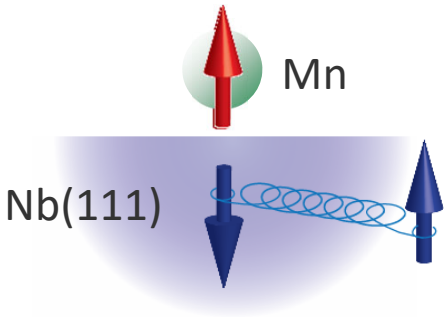
Martina Trahms, Larissa Melischek, Jacob F. Steiner, Bharti Mahendru, Idan Tamir, Nils Bogdanoff, Olof Peters, Gael Reecht, Clemens B. Winkelmann, Felix von Oppen, Katharina Franke

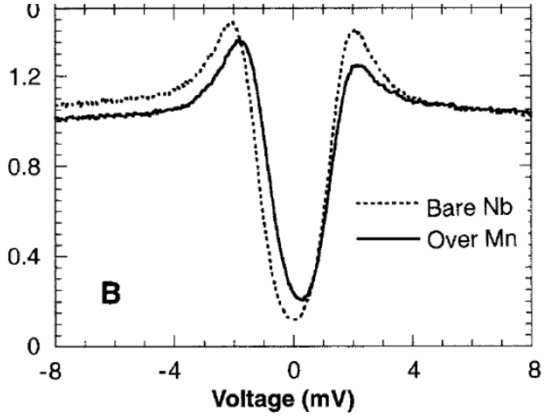
Yu-Shiba-Rusinov states

Freie Universität Berlin

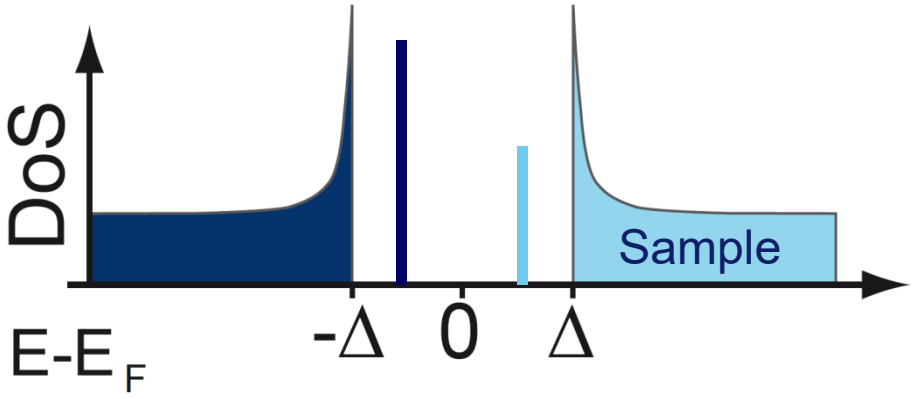
On superconductors:

- Yu-Shiba-Rusinov states





Yazdani et al., Science (1997)



- Spins exchange scatter at a magnetic center:

$$\epsilon_S = \Delta \frac{1 - A^2 + B^2}{\sqrt{4A^2 + (1 - A^2 + B^2)}}$$

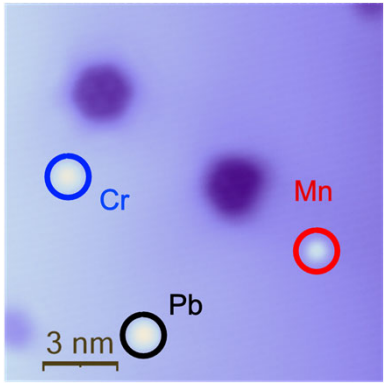
$$A = \frac{\pi}{2} J S \nu_0 \qquad B = \pi K \nu_0$$

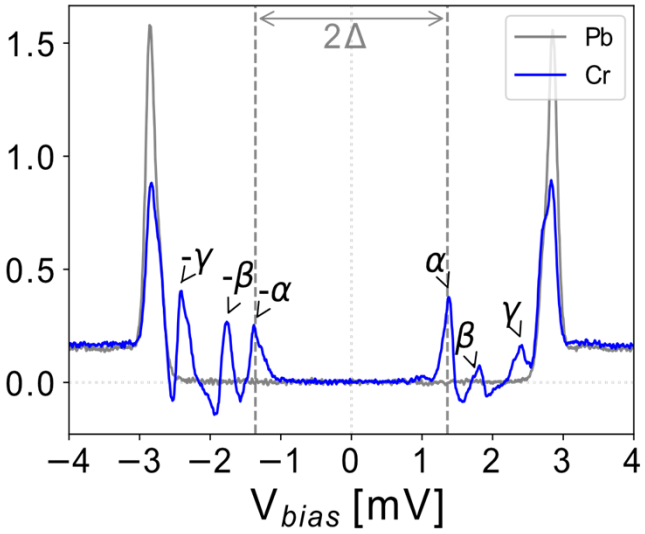
- Yu-Shiba-Rusinov states

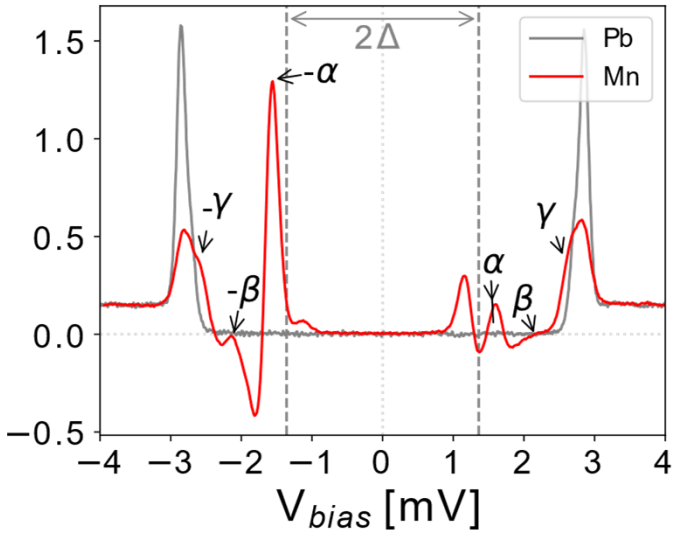
L. Yu, Acta Phys. Sin. 21, 75 (1965)
H. Shiba, Prog. Theor. Phys. 40, 435 (1968)
A.I. Rusinov, JETP Lett. 9, 85 (1969)

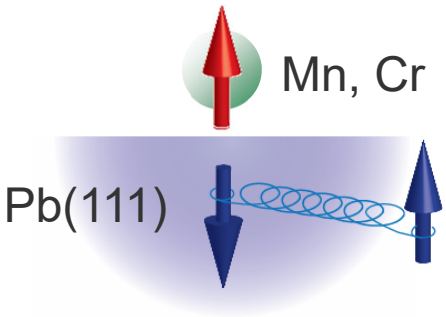
YSR states of Mn and Cr on Pb(111)

- Voltage bias









- Yu-Shiba-Rusinov states:

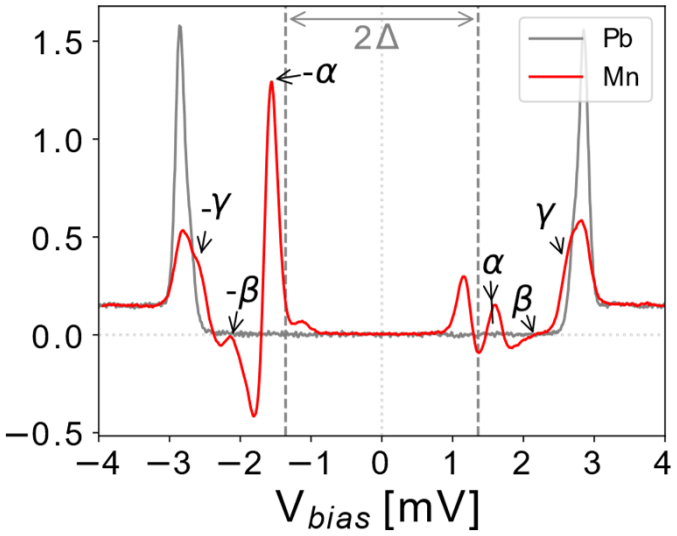
$$\epsilon_S = \Delta \frac{1 - A^2 + B^2}{\sqrt{4A^2 + (1 - A^2 + B^2)}}$$

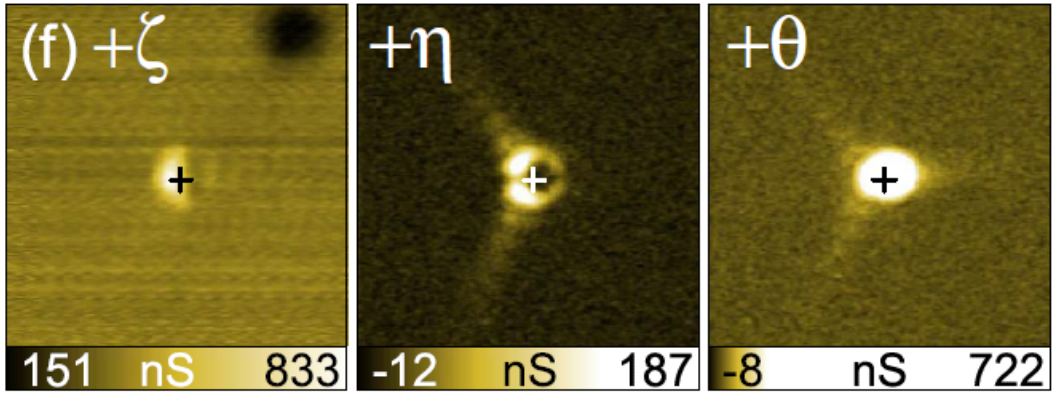
$$A = \frac{\pi}{2} J S \nu_0 \qquad B = \pi K \nu_0$$

- Different electron and hole weight

L. Yu, Acta Phys. Sin. 21, 75 (1965)
H. Shiba, Prog. Theor. Phys. 40, 435 (1968)
A.I. Rusinov, JETP Lett. 9, 85 (1969)

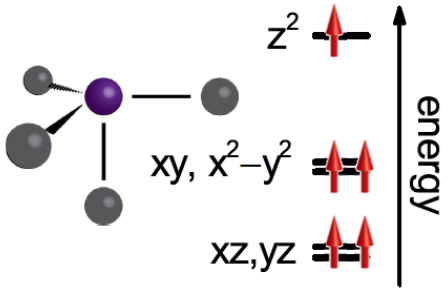
Crystal-field split YSR states





dI/dV maps, 8.8 x 8.8 nm^2

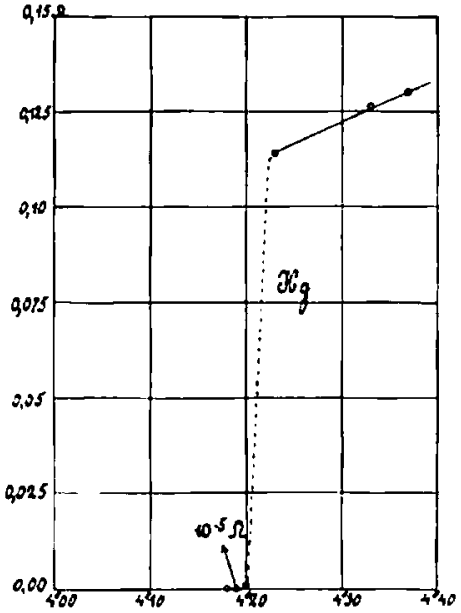
- different adsorption sites yield different YSR splittings
- crystal field splitting

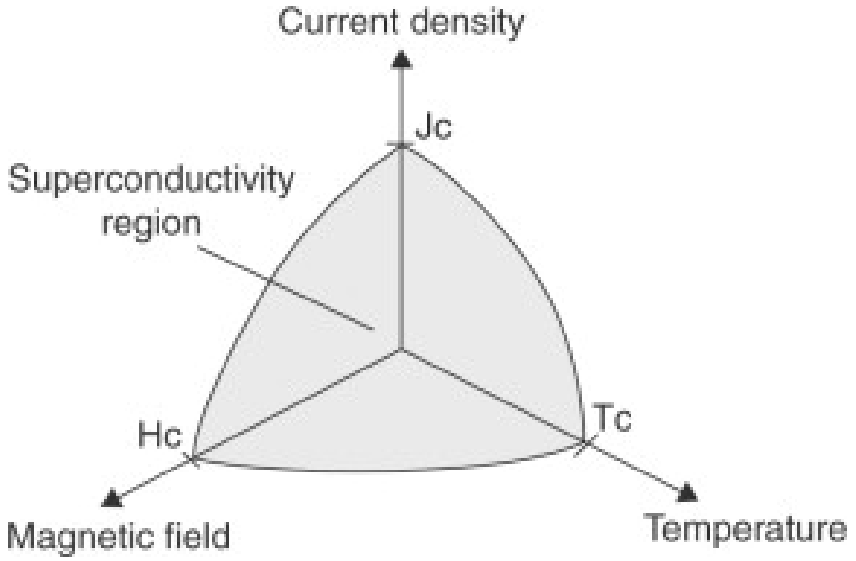


M. Ruby et al., Phys. Rev. Lett. 117, 186801 (2016)

Superconductivity

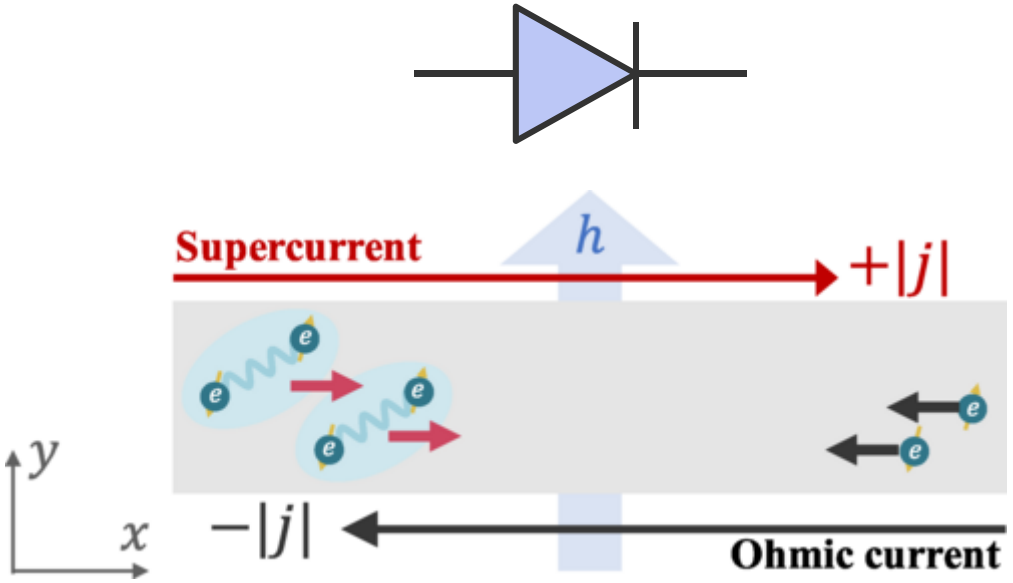
► Current flow with zero resistance
(1911 Kamerlingh Onnes)





Control of dissipationless vs. resistive regime?

Superconducting diode

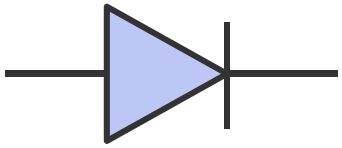


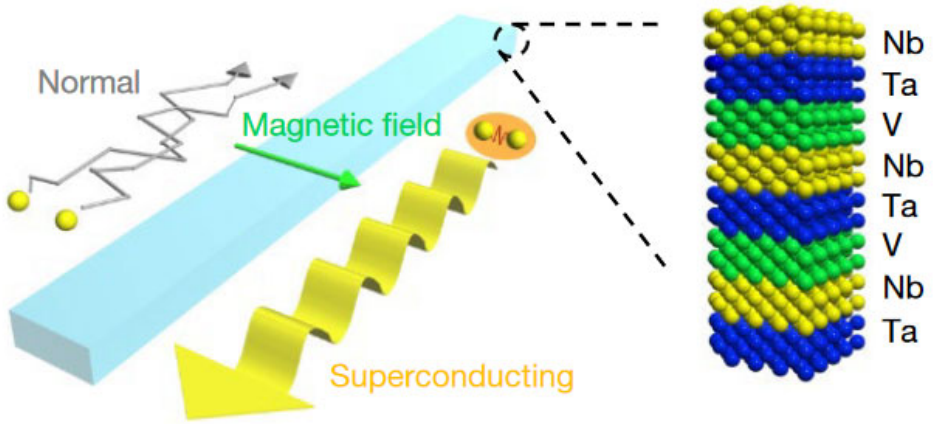
Daido, et al., Phys. Rev. Lett. 128, 037001 (2022)

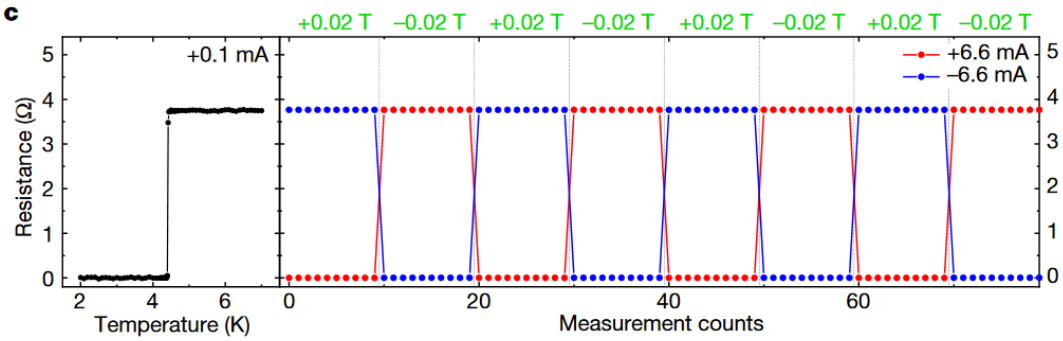
- Supercurrent in one direction
- Resistive current in reverse direction

Superconducting diode

Superconducting diode







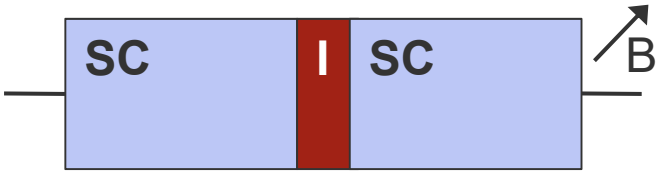
Ando, …Ono, Nature 584, 373 (2020)

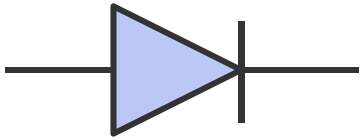
- Supercurrent in one direction
- Resistive current in reverse direction
- Magnetochiral anisotropy

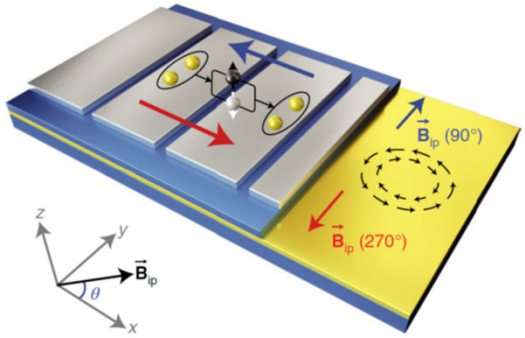
$$R = R_0[1 + \gamma \hat{\mathbf{e}}_z(\mathbf{B} \times \mathbf{I})]$$

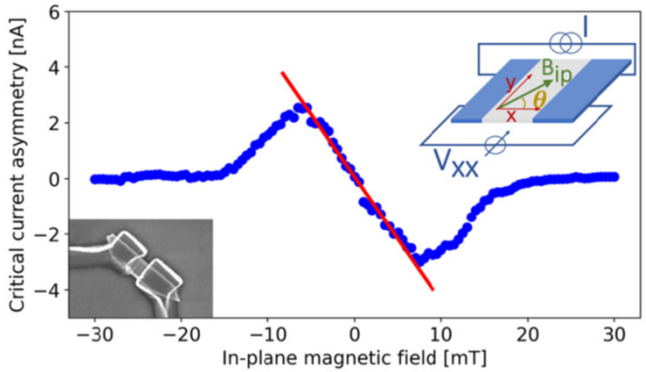
Superconducting diode

Josephson diode: realization









- Proximity-coupled two-dimensional electron gas/material with strong spin-orbit interaction

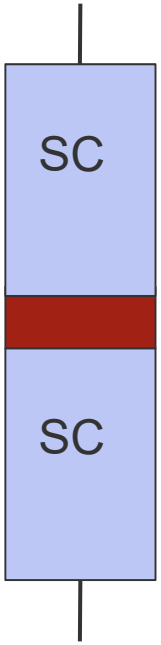
- Spatial-inversion symmetry broken
- Time-reversal symmetry broken in B field
- Anomalous current-phase relationship $I(\phi) \neq -I(-\phi)$

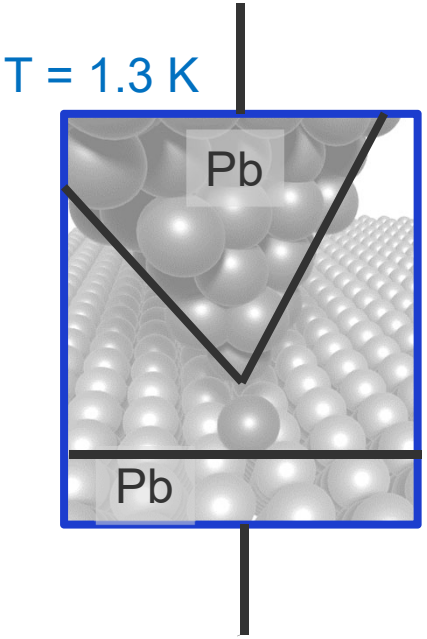
- Typical diode behavior in critical current

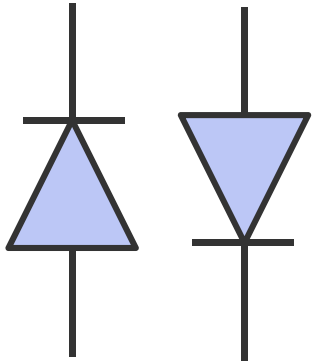
Baumgartner, et al., Nature Nanotech. 17, 39 (2022)
Turini, et al., Nano Lett. 22, 8502 (2022)

Atomic Josephson junctions as diodes?

Freie Universität Berlin







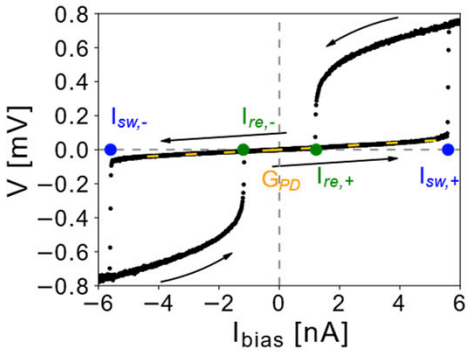
- So far:

  layered structures

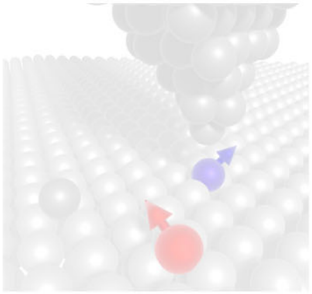
- Atomic-scale Josephson junction in an STM

- Diode behavior?

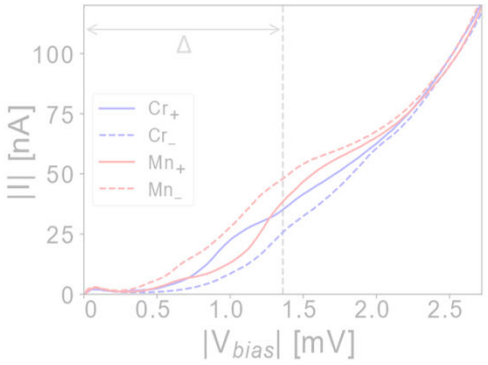
Outline



- Current-biased spectroscopy in a STM
- Switching and retrapping currents



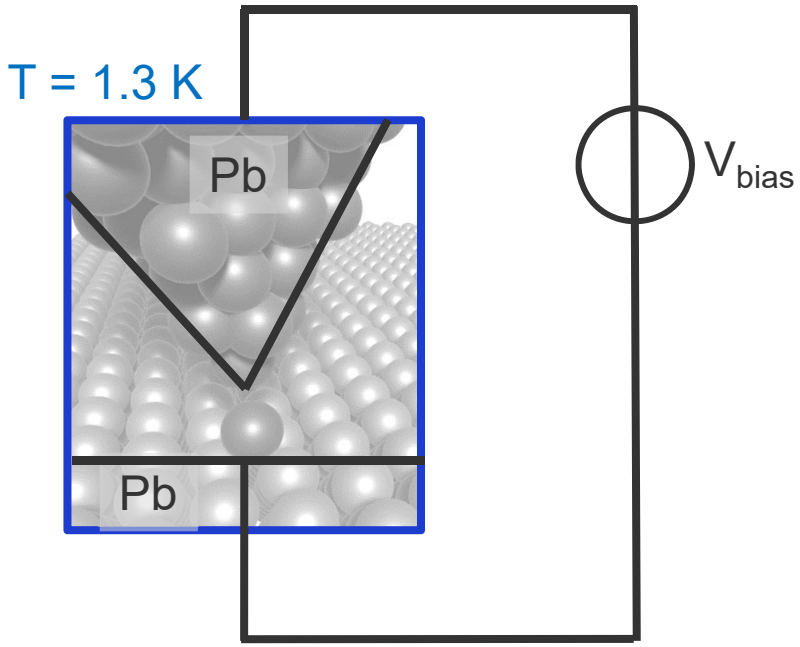
- Magnetic adatoms on superconductors
- Asymmetry of retrapping currents
  - Diode behavior



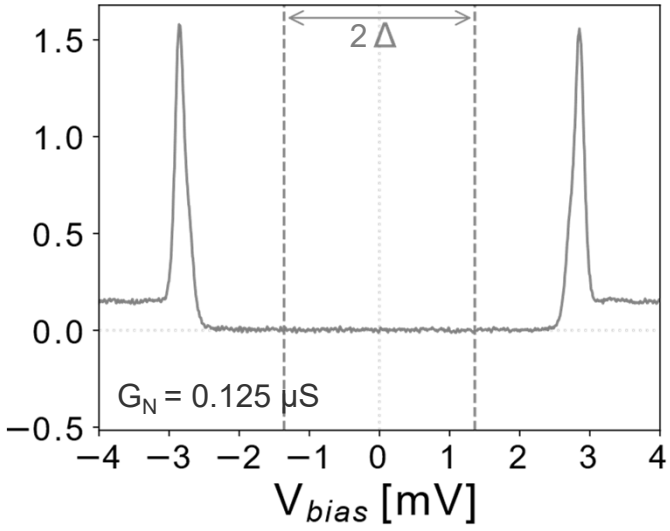
- Origin of diode behavior

Voltage-biased STM

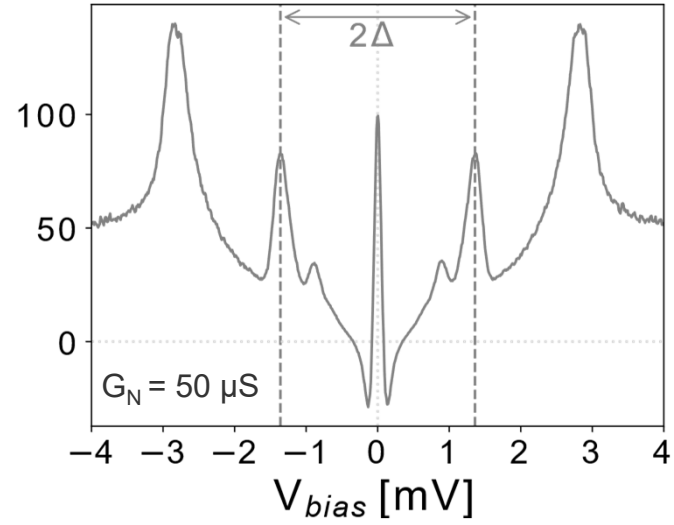
- Superconducting tip and superconducting substrate



- Tunnel junction: tip far away

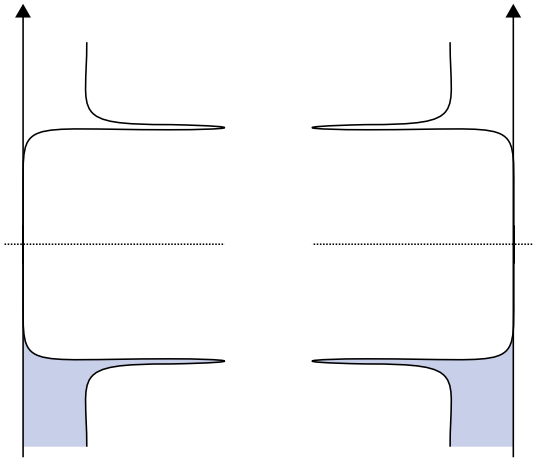


- Josephson junction: tip close to substrate

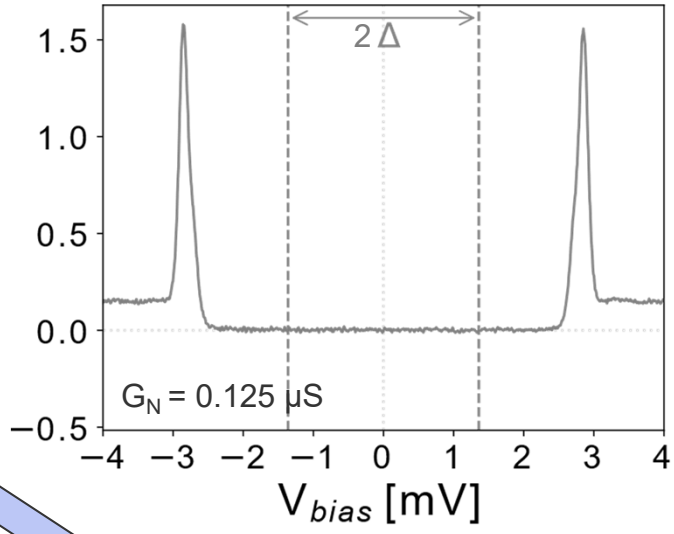


Voltage-biased STM

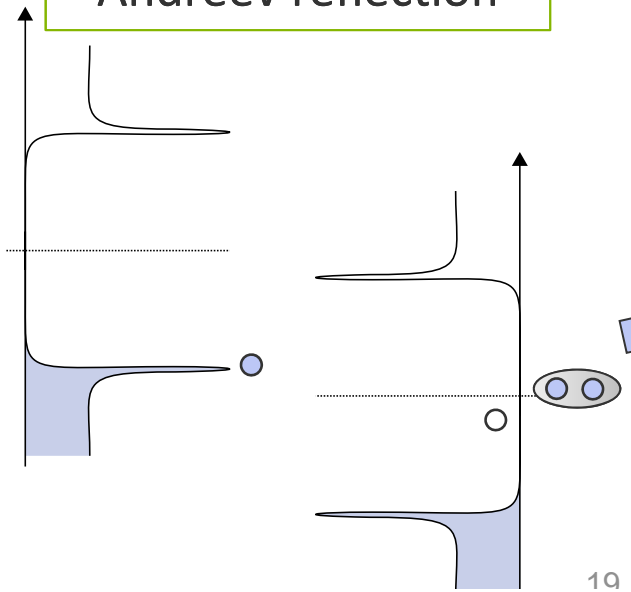
Josephson peak



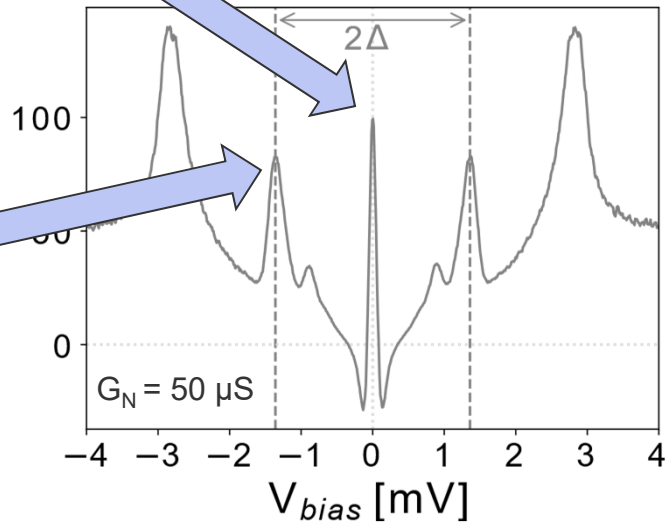
- Tunnel junction: tip far away



Andreev reflection

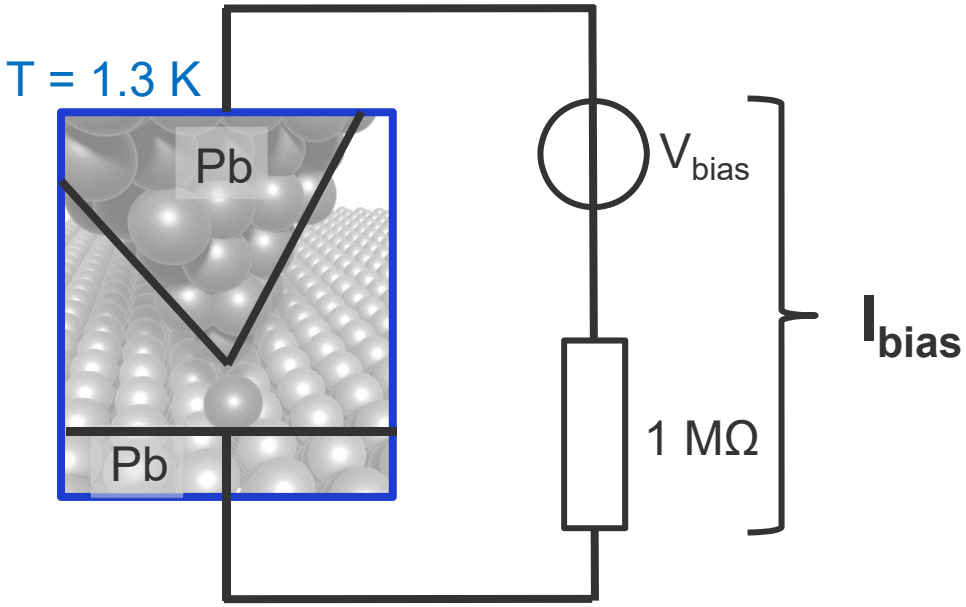


- Josephson junction: tip close to substrate



19

Current-biased Josephson spectroscopy in STM



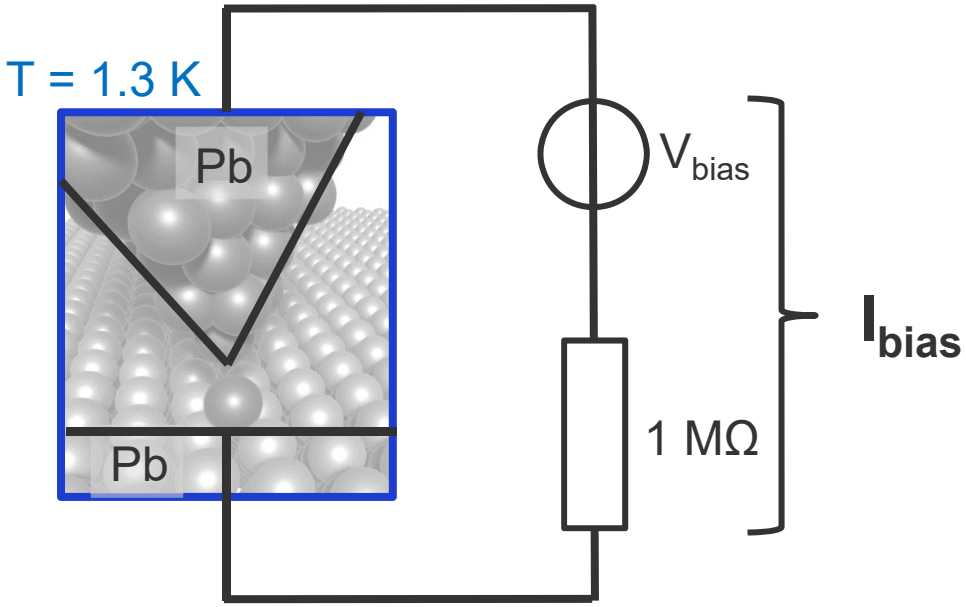
- Josephson equations

$$I_S(t) = I_{c0}\sin(\phi(t))$$

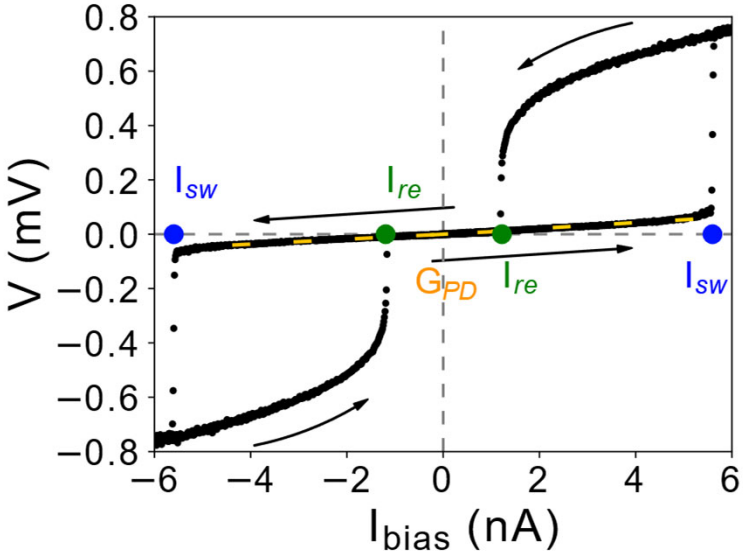
$$V_J = \frac{\hbar}{2e}\frac{d\phi}{dt}$$

- Effective current control by large resistor

Current-biased Josephson spectroscopy in STM



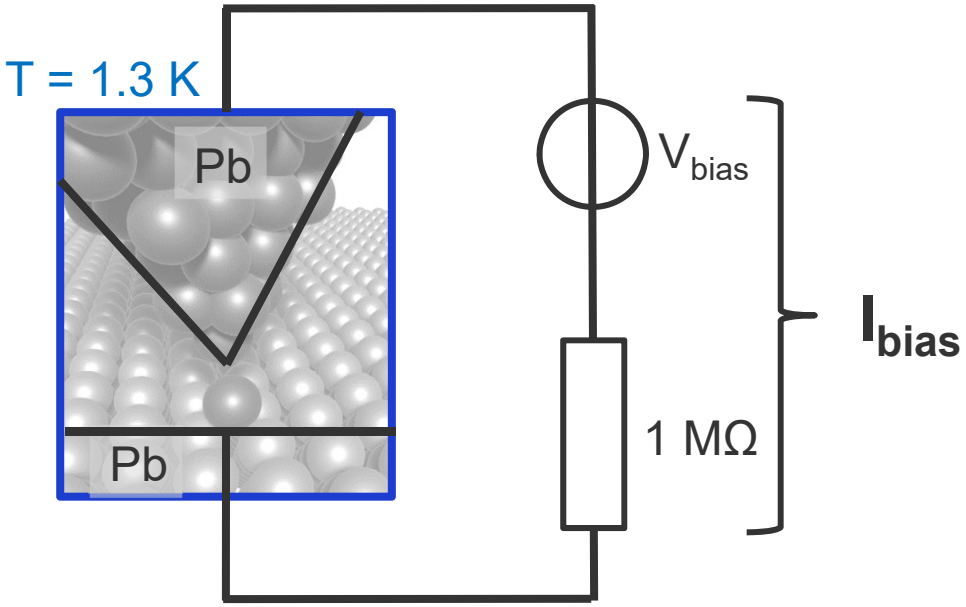
Current biased Pb-Pb junction:

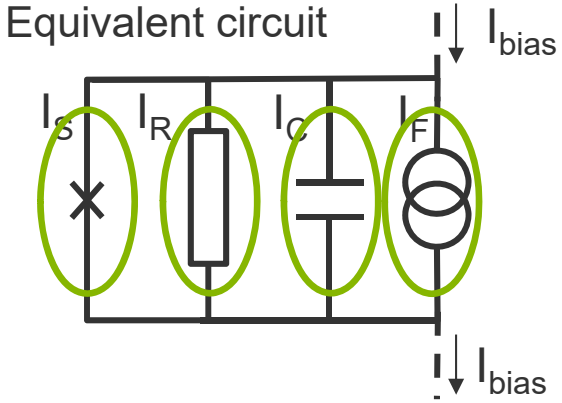


- Effective current control by large resistor

- Switching current (~ 5.8 nA)
- Retrapping current (~ 1.2 nA)
  - Hysteretic behavior

RCSJ model: current contributions





- Resistively and capacitively shunted Josephson junction (RCSJ)

$$I(t) = I_{c0}\sin(\phi(t)) + \frac{V}{R_N} + C\frac{dV}{dt} + \delta I$$

$$I(t) = I_{c0}\sin(\phi(t)) + \frac{\hbar}{2e}\frac{1}{R_N}\dot{\phi} + \frac{\hbar}{2e}C\ddot{\phi} + \delta I$$

- Josephson equations

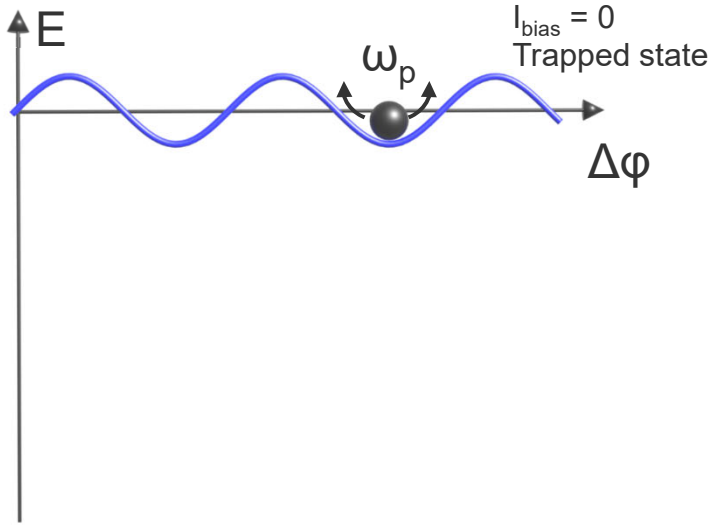
$$I_S(t) = I_{c0}\sin(\phi(t))$$

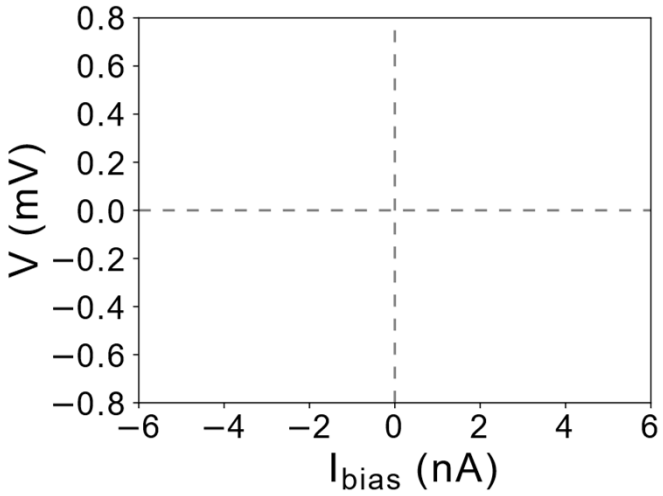
$$V_J = \frac{\hbar}{2e}\frac{d\phi}{dt}$$

RCSJ model: trapped state

- Resistively and capacitively shunted Josephson junction (RCSJ)

$$I(t) = I_{c0}\sin\big(\phi(t)\big) + \frac{\hbar}{2e}\frac{1}{R_N}\dot{\phi} + \frac{\hbar}{2e}C\ddot{\phi} + \delta I$$



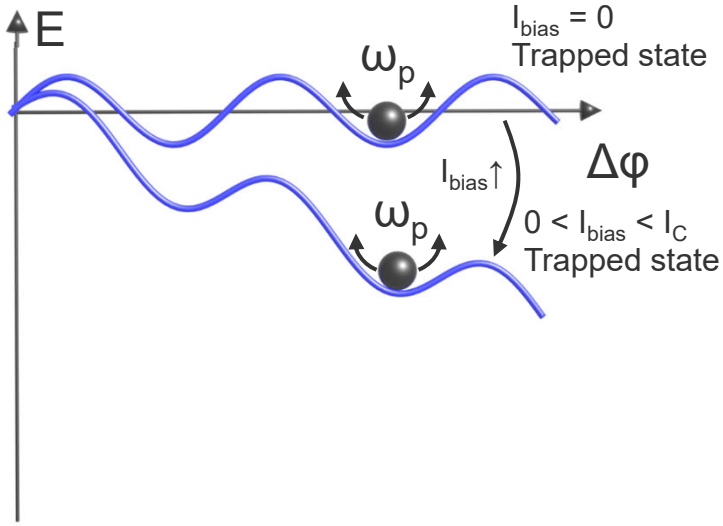


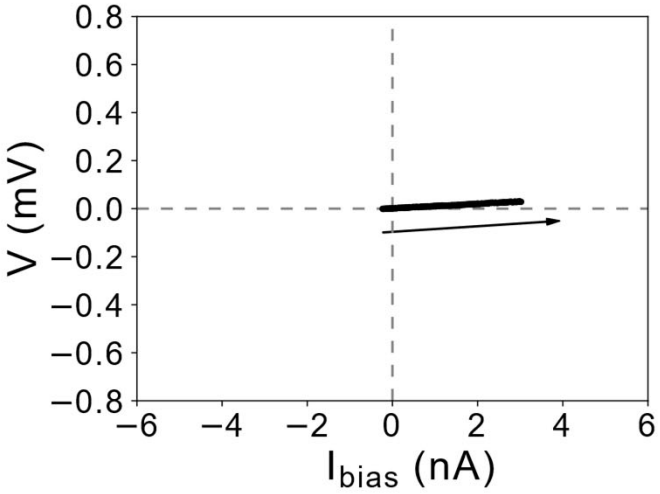
RCSJ model: trapped state

Freie Universität Berlin

- Resistively and capacitively shunted Josephson junction (RCSJ)

$$I(t) = I_{c0}\sin\big(\phi(t)\big) + \frac{\hbar}{2e}\frac{1}{R_N}\dot{\phi} + \frac{\hbar}{2e}C\ddot{\phi} + \delta I$$





RCSJ model: switching into running state

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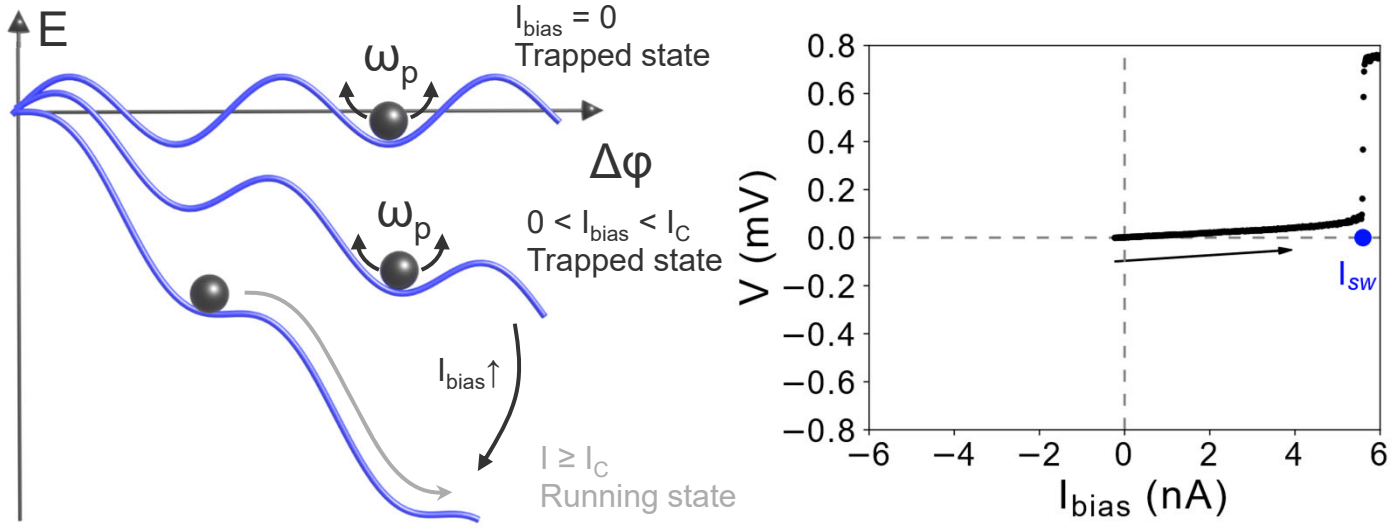
- Resistively and capacitively shunted Josephson junction (RCSJ)

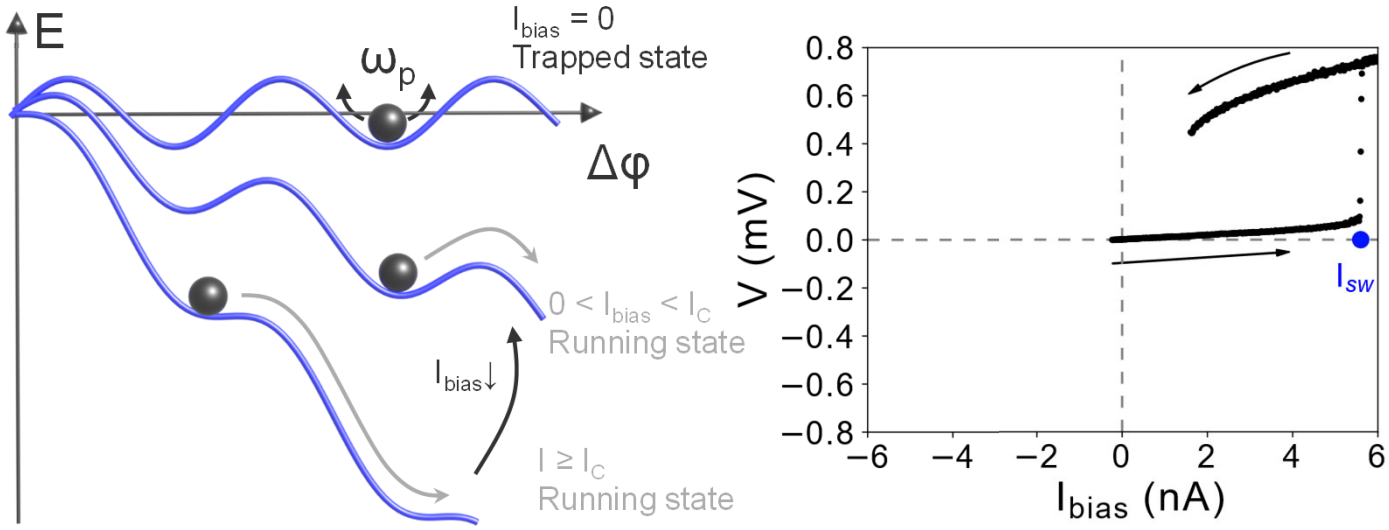
$$I(t) = I_{c0}\sin\big(\phi(t)\big) + \frac{\hbar}{2e}\frac{1}{R_N}\dot{\phi} + \frac{\hbar}{2e}C\ddot{\phi} + \delta I$$



RCSJ model: running state

- Resistively and capacitively shunted Josephson junction (RCSJ)

$$I(t) = I_{c0}\sin\big(\phi(t)\big) + \frac{\hbar}{2e}\frac{1}{R_N}\dot{\phi} + \frac{\hbar}{2e}C\ddot{\phi} + \delta I$$

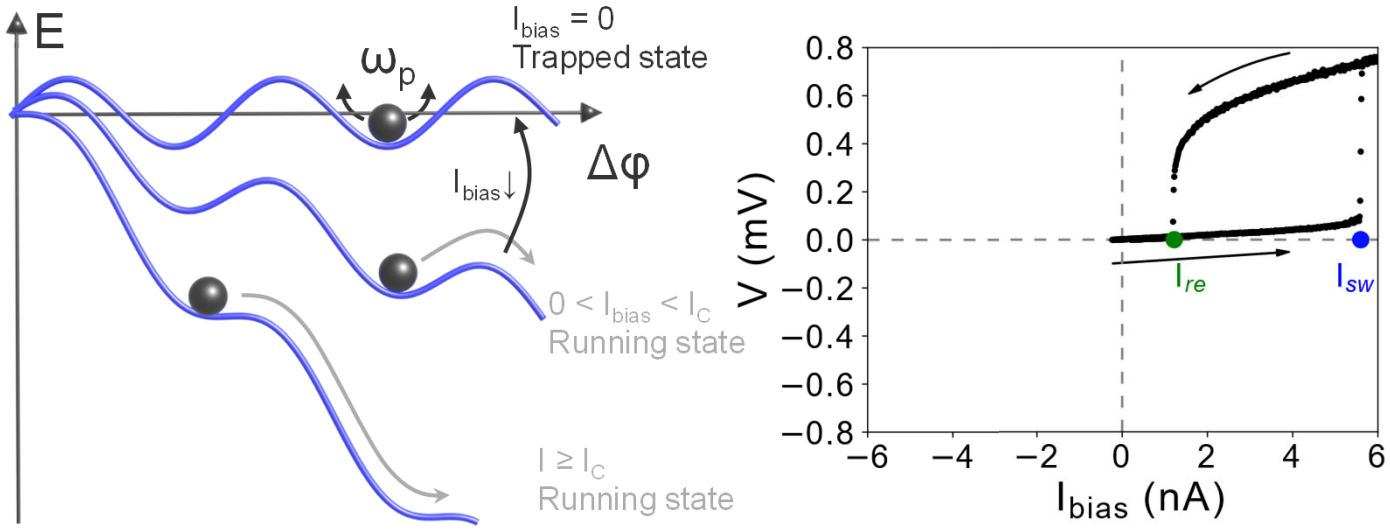


RCSJ model: retrapping of phase particle

Freie Universität Berlin

- Resistively and capacitively shunted Josephson junction (RCSJ)

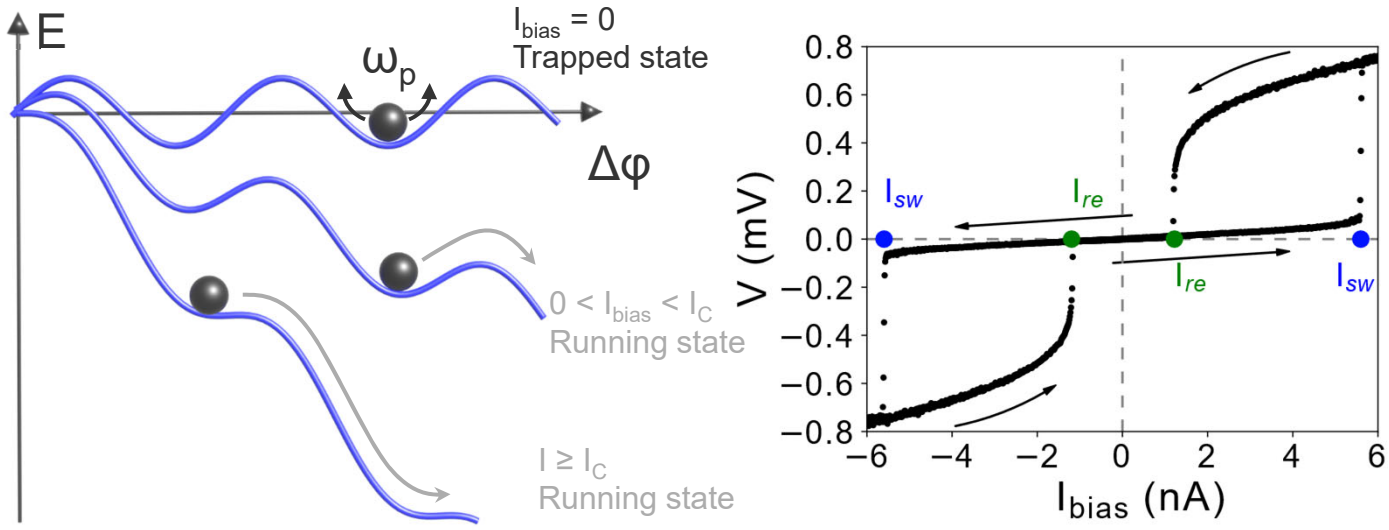
$$I(t) = I_{c0}\sin\big(\phi(t)\big) + \frac{\hbar}{2e}\frac{1}{R_N}\dot{\phi} + \frac{\hbar}{2e}C\ddot{\phi} + \delta I$$



RCSJ model

- Resistively and capacitively shunted Josephson junction (RCSJ)

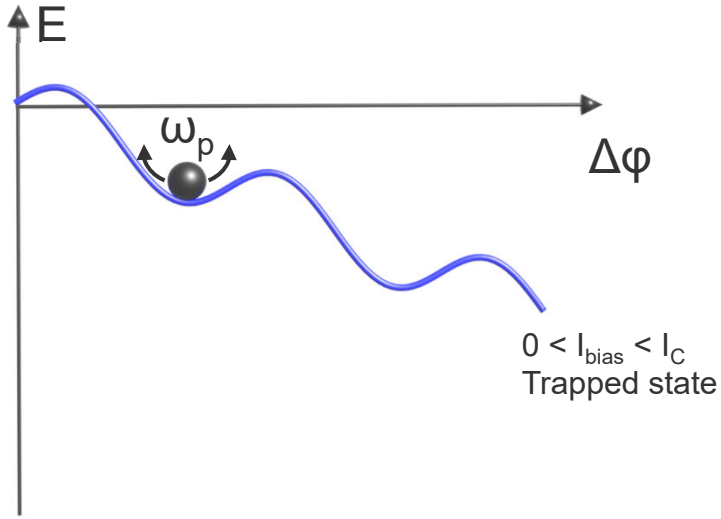
$$I(t) = I_{c0}\sin\big(\phi(t)\big) + \frac{\hbar}{2e}\frac{1}{R_N}\dot{\phi} + \frac{\hbar}{2e}C\ddot{\phi} + \delta I$$

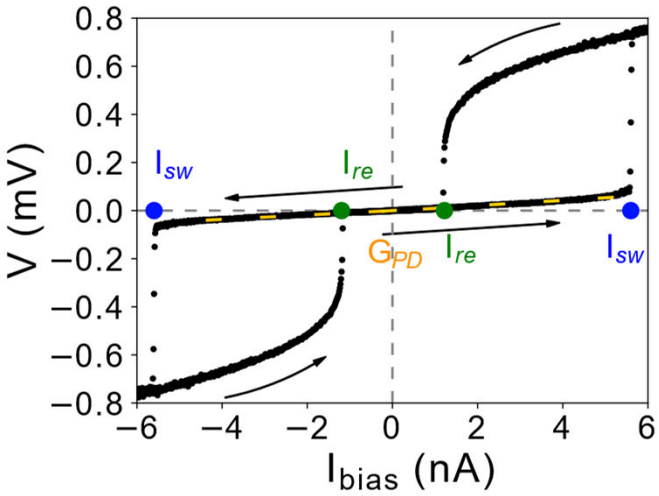


RCSJ model

- Resistively and capacitively shunted Josephson junction (RCSJ)

$$I(t) = I_{c0}\sin\big(\phi(t)\big) + \frac{\hbar}{2e}\frac{1}{R_N}\dot{\phi} + \frac{\hbar}{2e}C\ddot{\phi} + \delta I$$

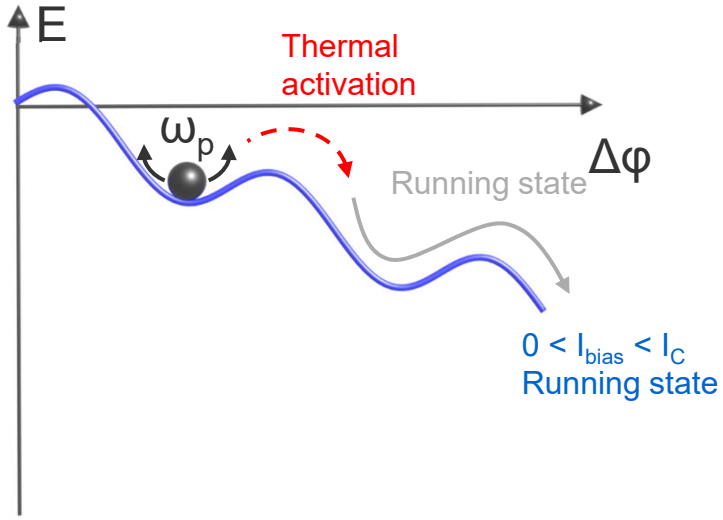


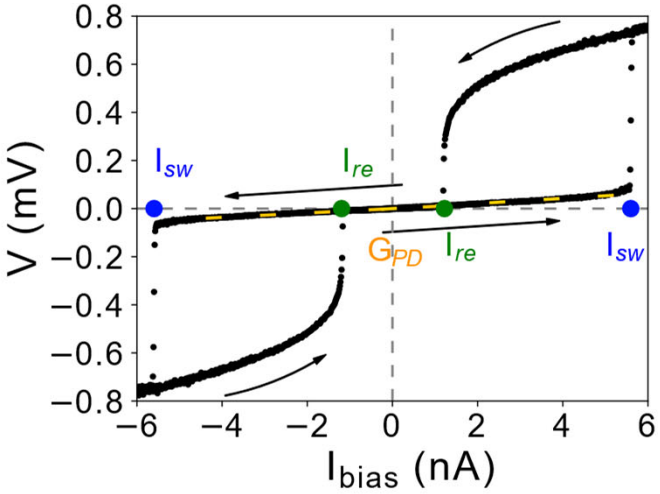


RCSJ model: phase diffusion

- Resistively and capacitively shunted Josephson junction (RCSJ)

$$I(t) = I_{c0}\sin\big(\phi(t)\big) + \frac{\hbar}{2e}\frac{1}{R_N}\dot{\phi} + \frac{\hbar}{2e}C\ddot{\phi} + \delta I$$

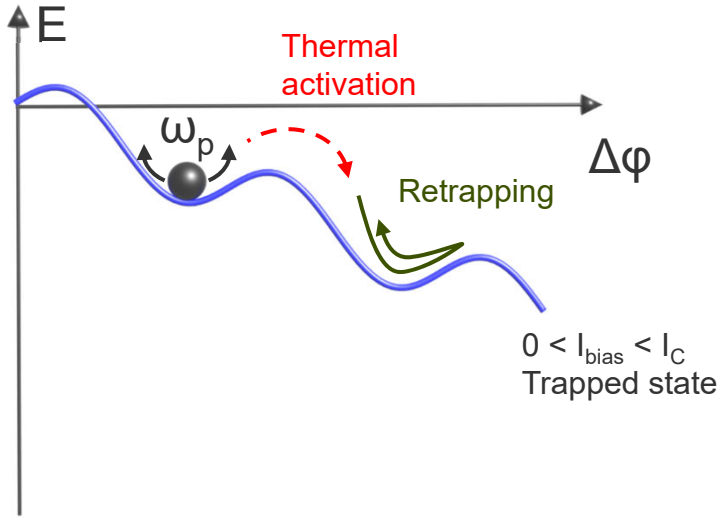


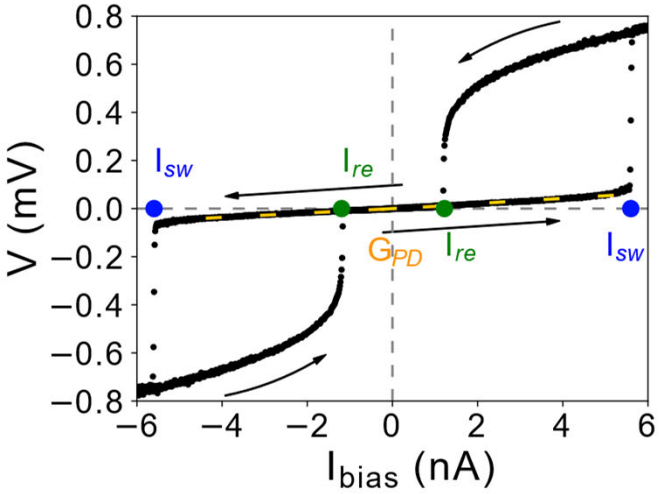


RCSJ model: phase diffusion

- Resistively and capacitively shunted Josephson junction (RCSJ)

$$I(t) = I_{c0}\sin\big(\phi(t)\big) + \frac{\hbar}{2e}\frac{1}{R_N}\dot{\phi} + \frac{\hbar}{2e}C\ddot{\phi} + \delta I$$

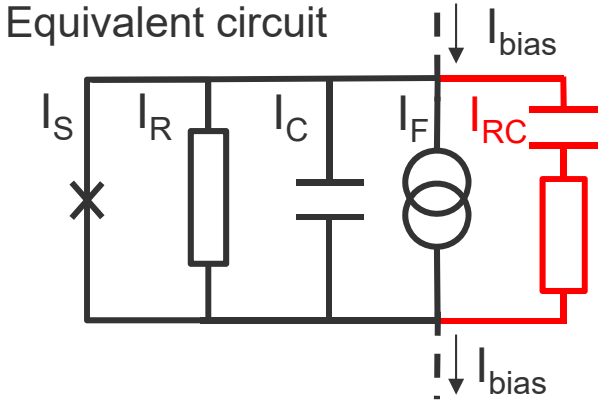


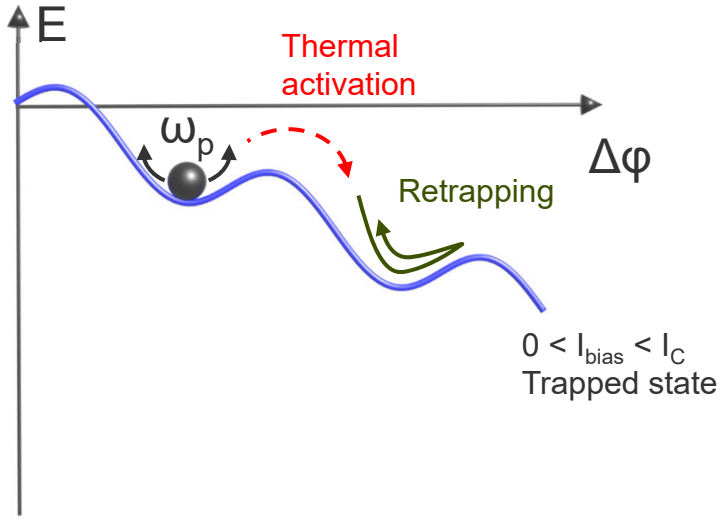


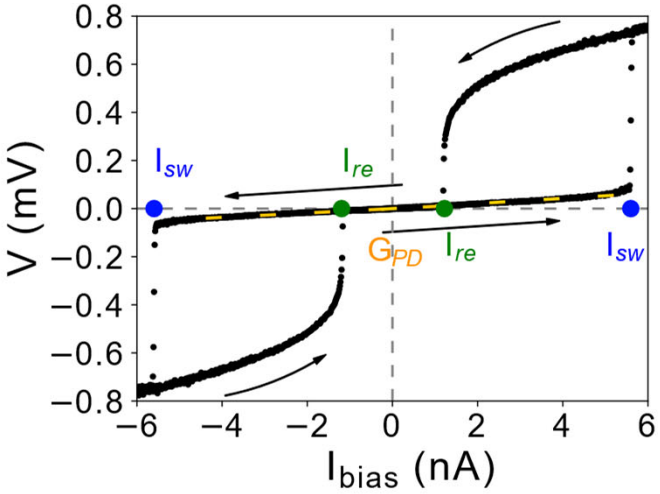
RCSJ model with frequency-dependent damping

- Resistively and capacitively shunted Josephson junction (RCSJ)

$$I(t) = I_{c0}\sin\big(\phi(t)\big) + \frac{\hbar}{2e}\frac{1}{R_N}\dot{\phi} + \frac{\hbar}{2e}C\ddot{\phi} + \delta I$$







- Frequency-dependent damping (Kautz, Martinis, Phys. Rev B 42, 16 (1990))

RCSJ model of Pb-Pb Josephson junction

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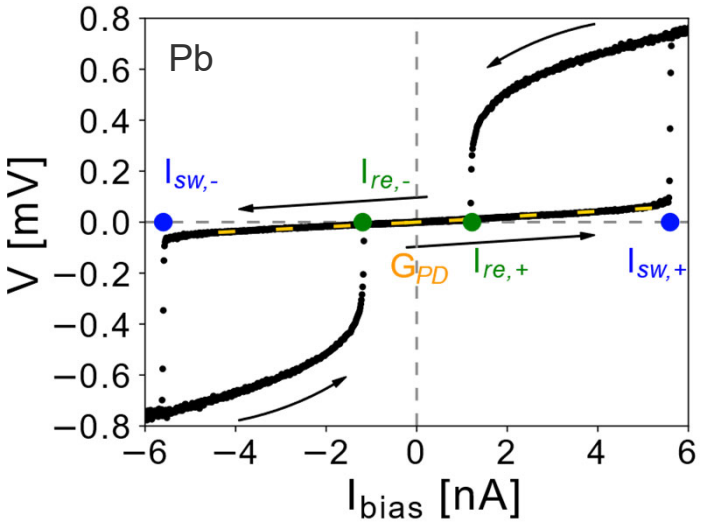
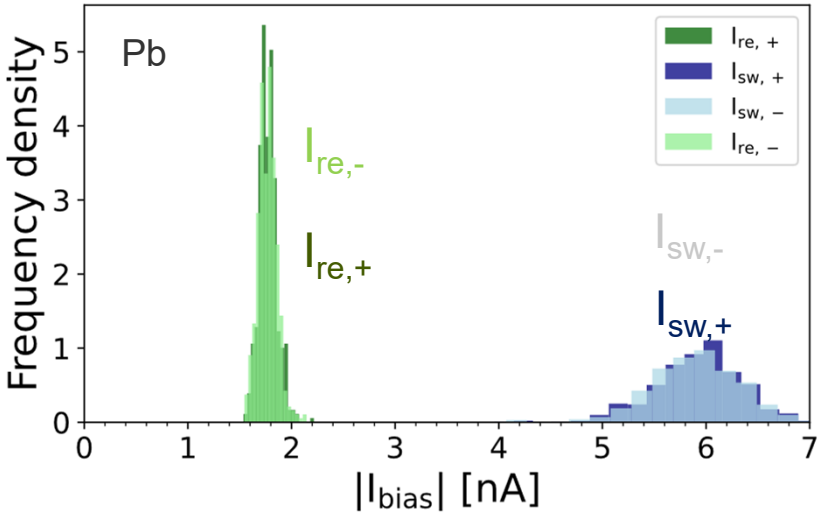
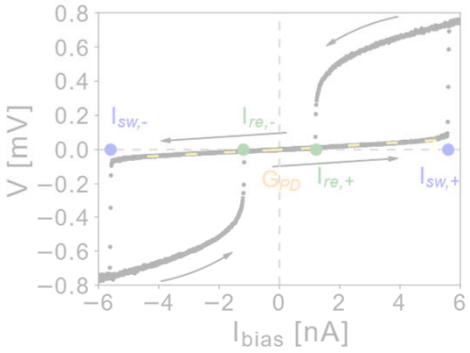
- Resistively and capacitively shunted Josephson junction (RCSJ)



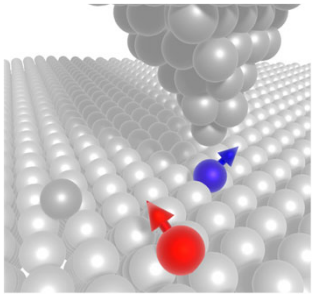


- Statistical distribution of switching and retrapping currents due to fluctuations

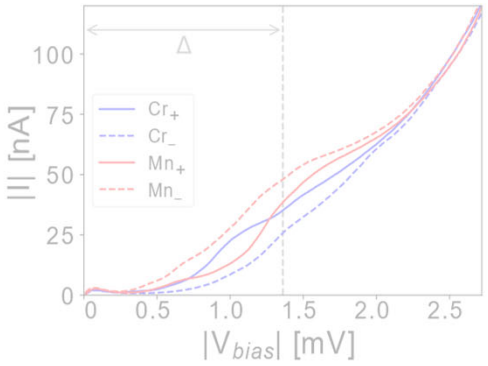
Outline



- Current-biased spectroscopy in a STM
- Switching and retrapping currents

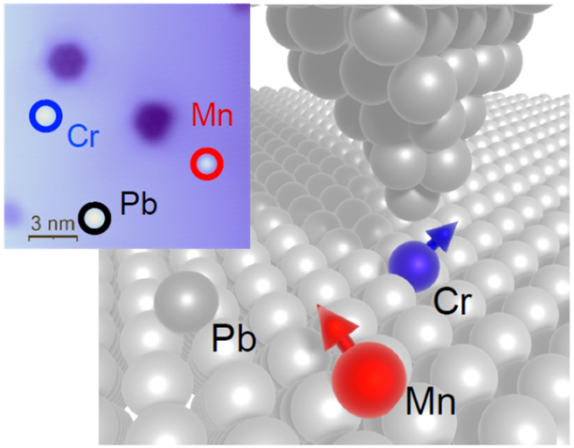


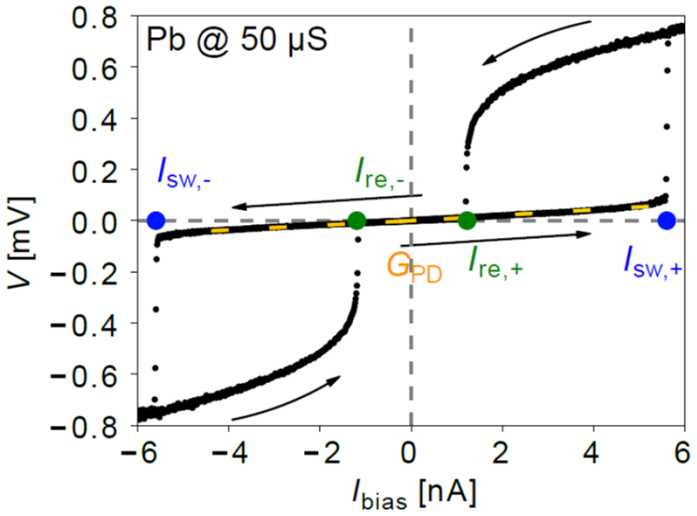
- Magnetic adatoms on superconductors
- Asymmetry of retrapping currents
  - Diode behavior



- Origin of diode behavior

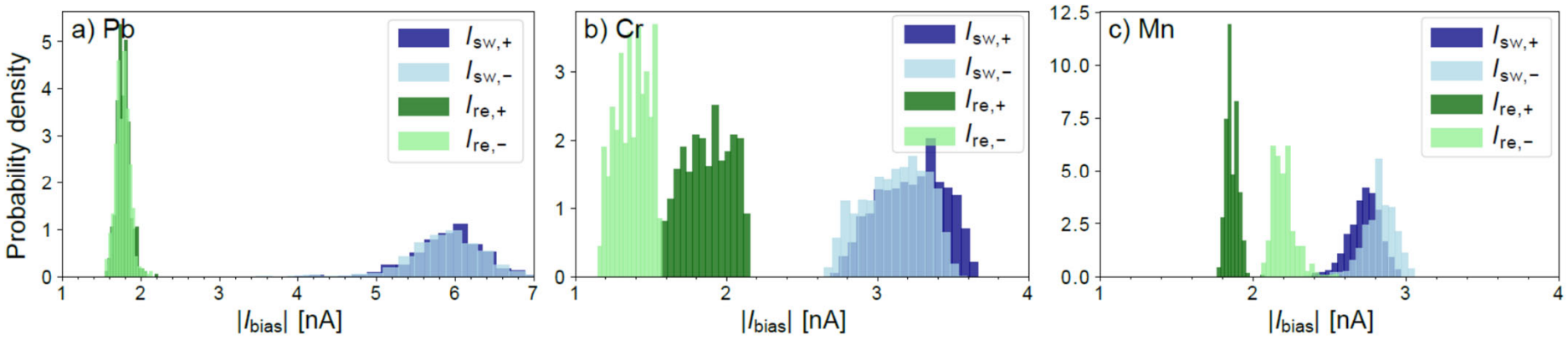
Josephson junctions with magnetic adatoms





- Asymmetric retrapping currents
- Asymmetry in opposite direction for Mn and Cr atoms

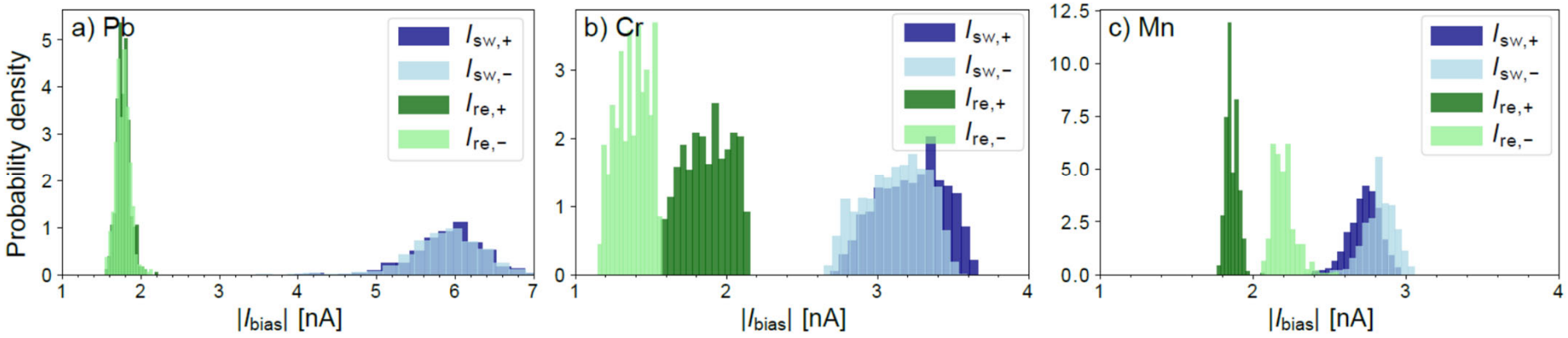
Statistics of asymmetry



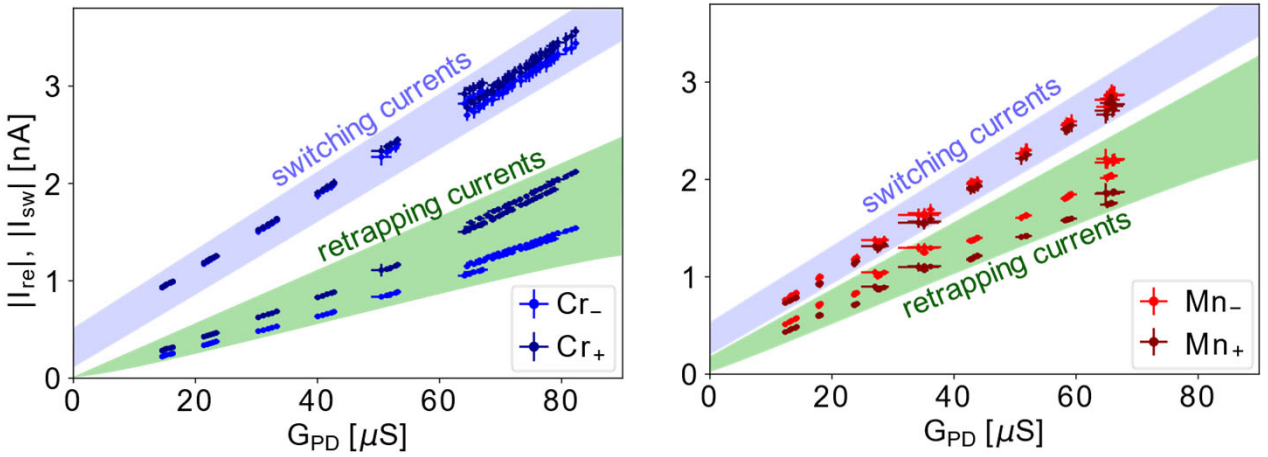
- Symmetric Pb-Pb junctions
- Strong asymmetry in retrapping currents
- Small asymmetry in switching currents

Diode behavior

Statistics of asymmetry

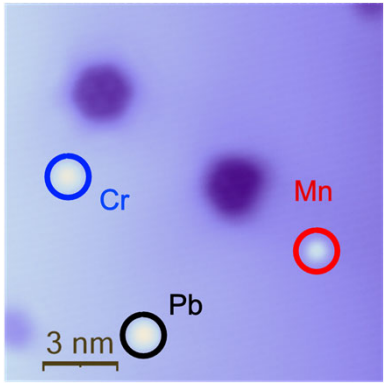


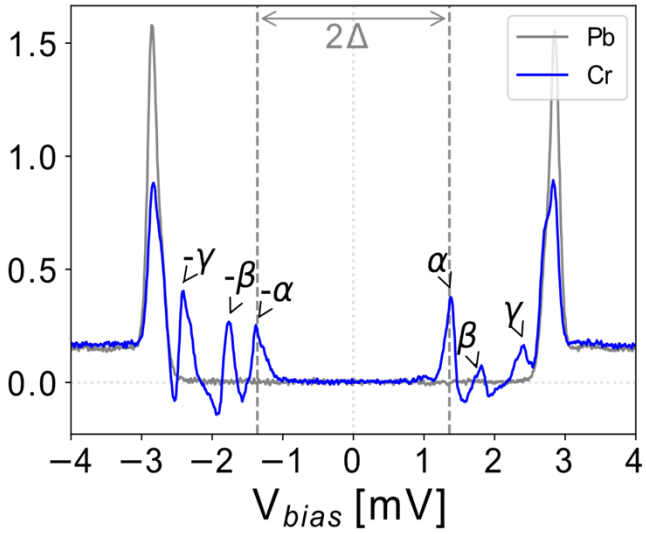
- Increase in asymmetry with increasing junction conductance
- Diode behavior

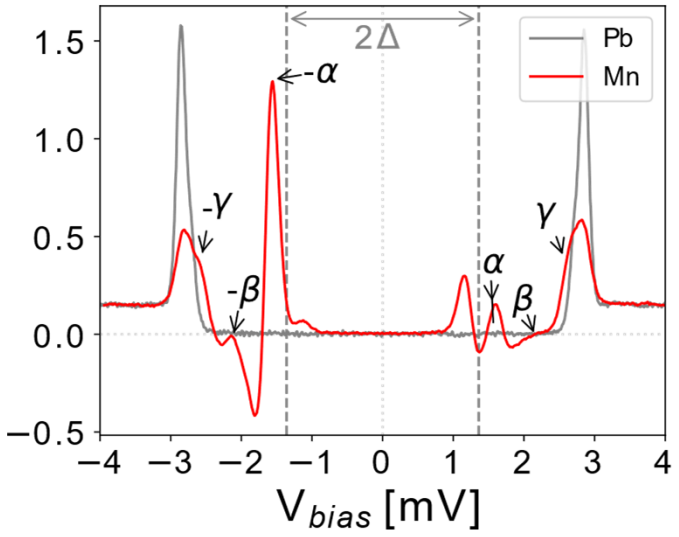


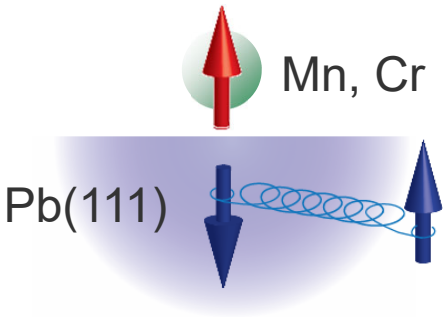
YSR states of Mn and Cr on Pb(111)

- Voltage bias









- Different electron and hole weight due to potential scattering

Influence of broken electron-hole symmetry on Josephson junction?

L. Yu, Acta Phys. Sin. 21, 75 (1965)
H. Shiba, Prog. Theor. Phys. 40, 435 (1968)
A.I. Rusinov, JETP Lett. 9, 85 (1969)

YSR states of Mn and Cr on Pb(111)

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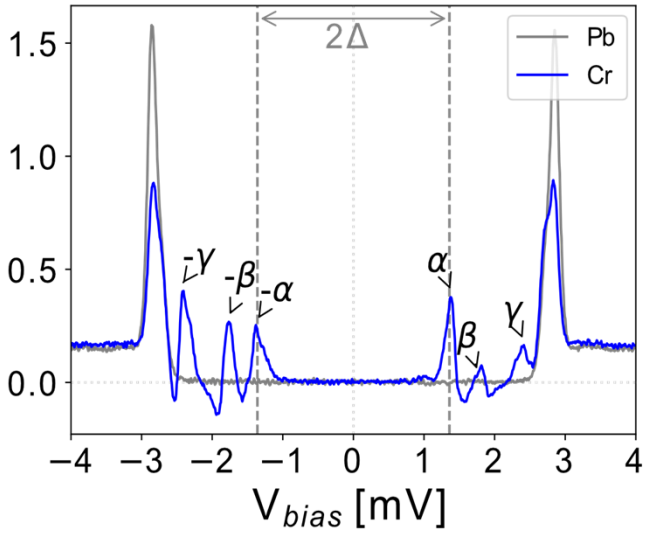
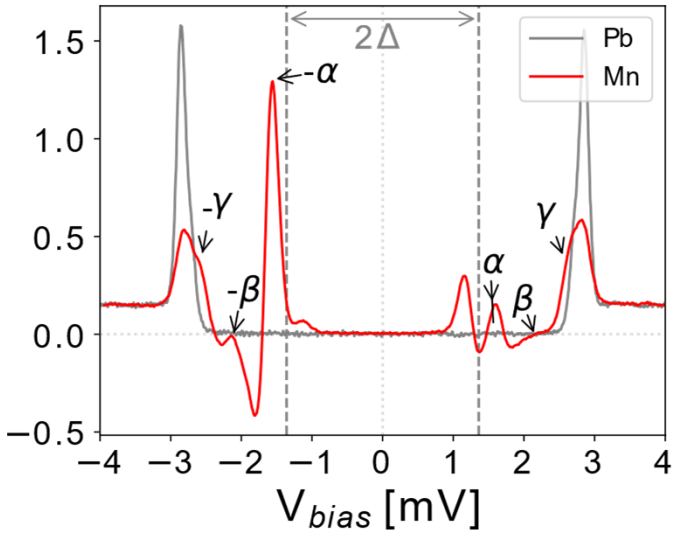
- Voltage bias

Far distance

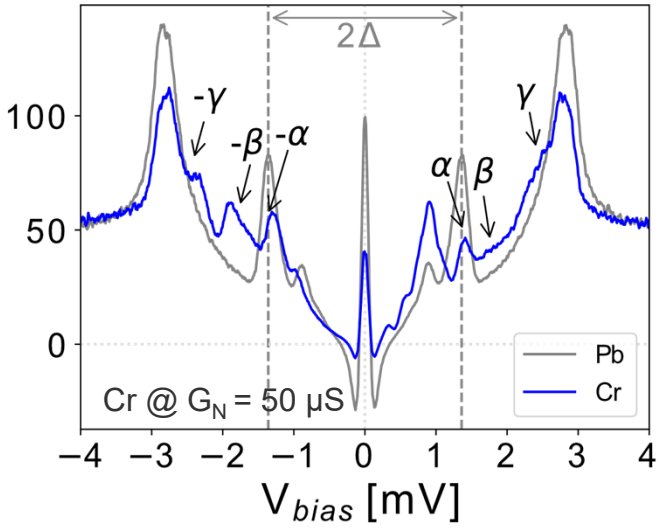
- Particle-hole asymmetric YSR states

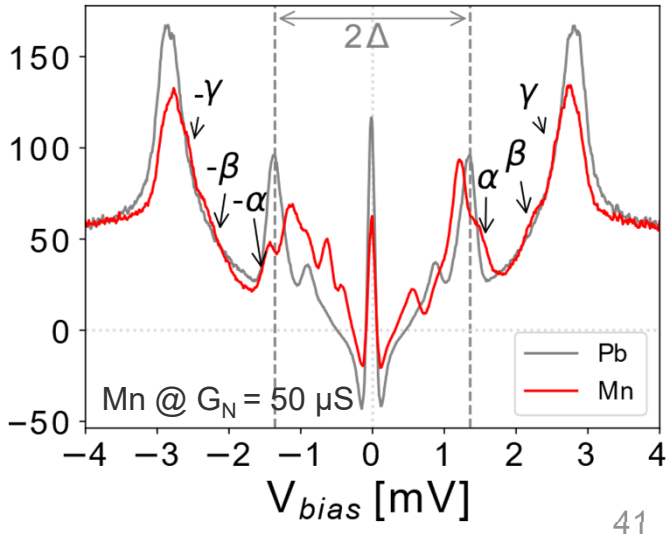




Josephson regime

- Particle-hole asymmetric dI/dV





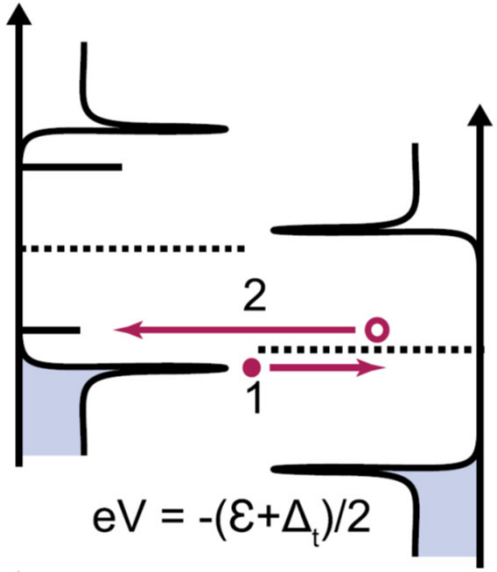
Excitation of YSR states by Andreev reflections

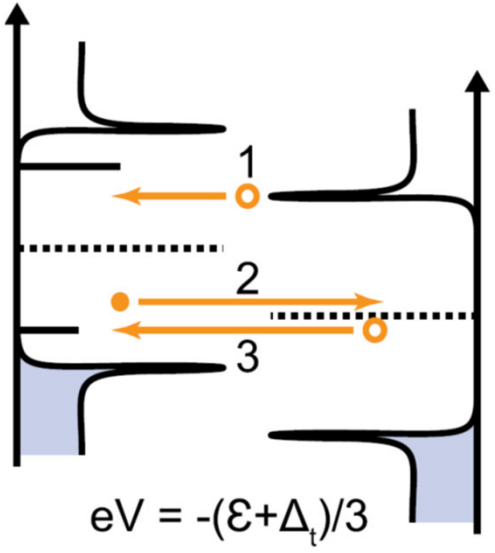
Freie Universität Berlin

- Voltage bias

Josephson regime

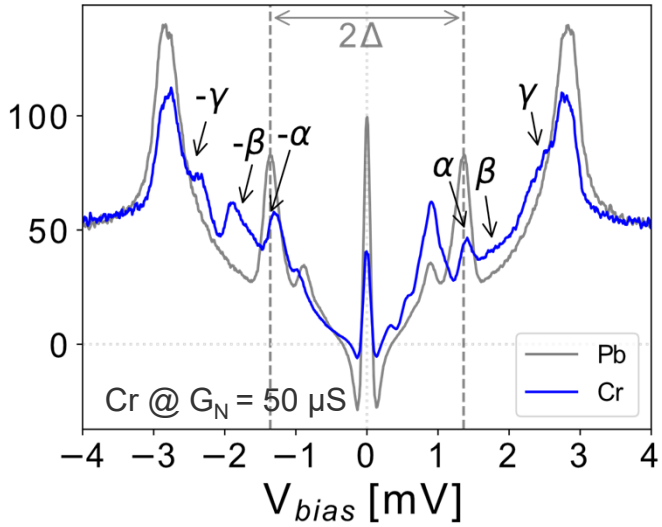
- Particle-hole asymmetric YSR excitations by Andreev reflections

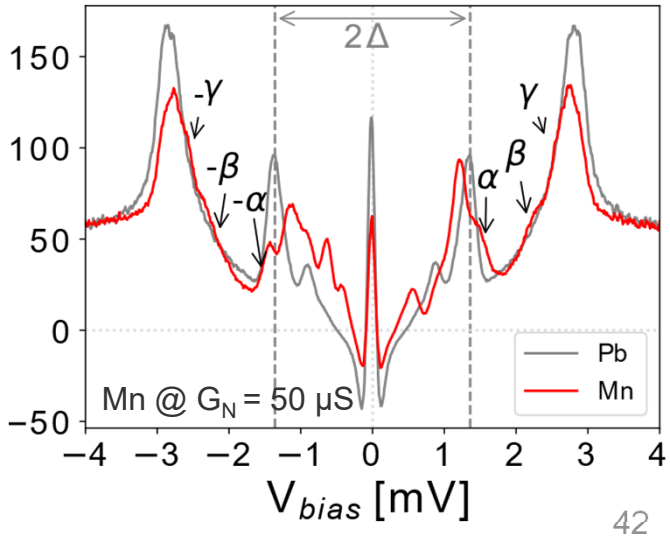




Josephson regime

- Particle-hole asymmetric dI/dV





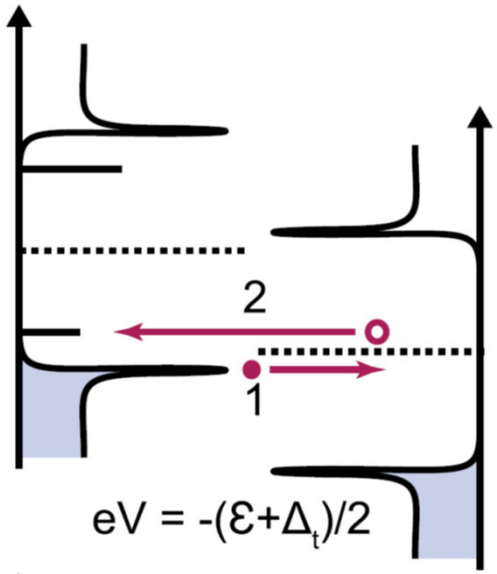
Excitation of YSR states by Andreev reflections

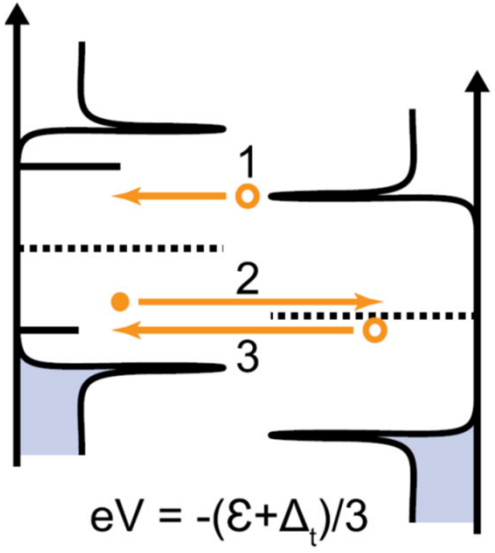
Freie Universität Berlin

Josephson regime

- Particle-hole asymmetric YSR excitations by Andreev reflections

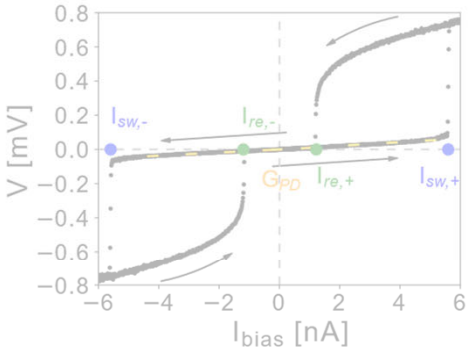
- Voltage bias



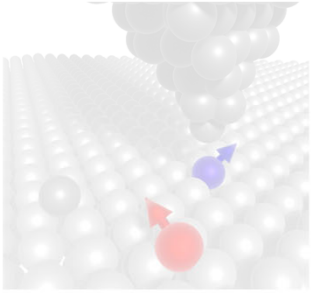


Influence of dissipative excitation of YSR states on diode effect?

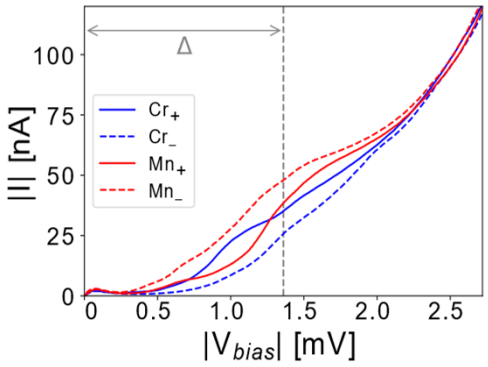
Outline



- Current-biased spectroscopy in a STM
- Switching and retrapping currents



- Magnetic adatoms on superconductors
- Asymmetry of retrapping currents
  - Diode behavior



- Origin of diode behavior

Particle-hole asymmetry of YSR states of Mn and Cr

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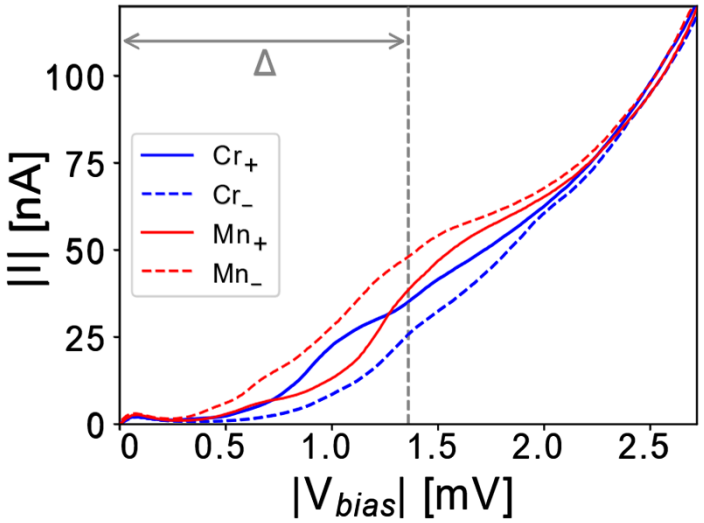
- Voltage bias

Josephson regime

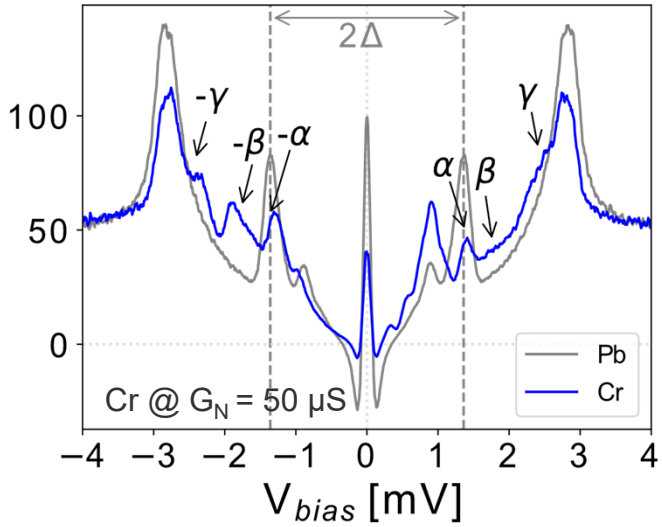
- Particle-hole asymmetric YSR excitations by Andreev reflections

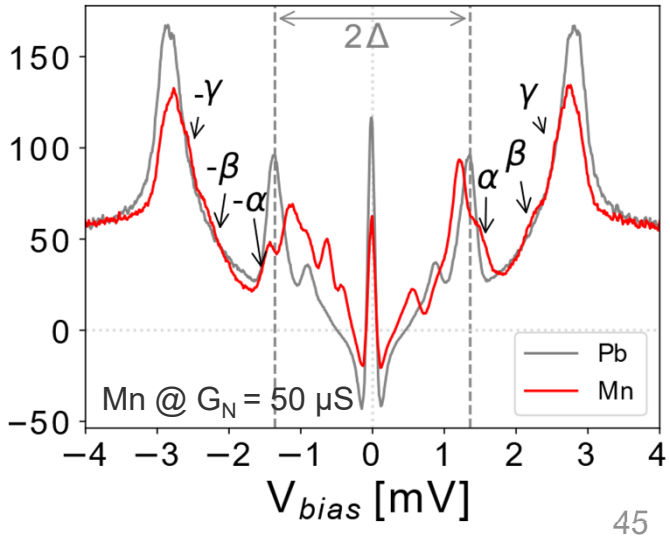


- Asymmetric I-V signal due to quasi-particle current
- Extracted for simulations

Josephson regime

- Particle-hole asymmetric dI/dV

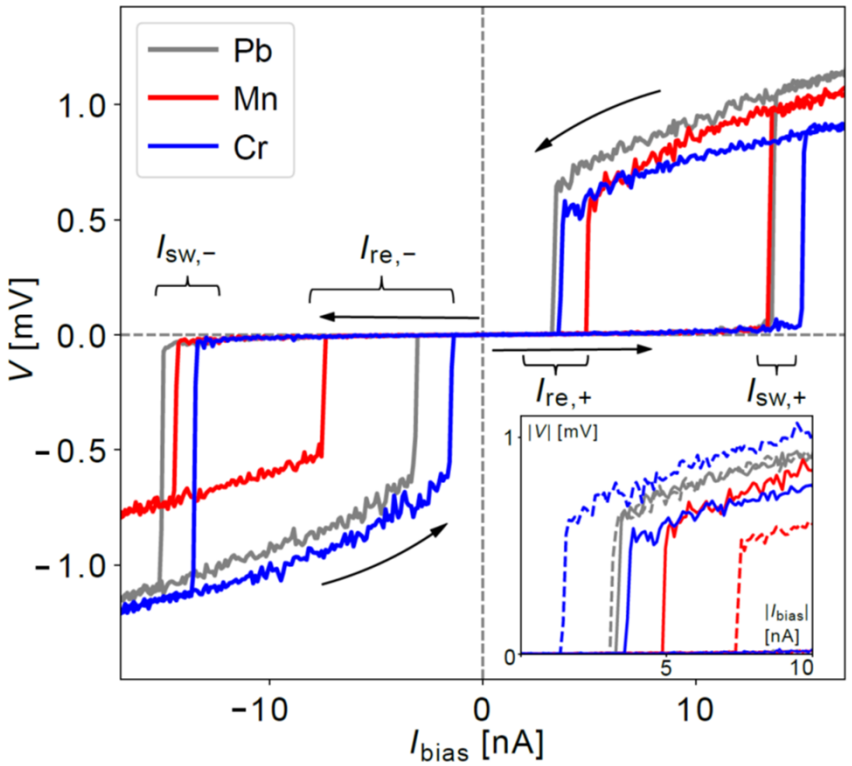




Simulations of V-I curves

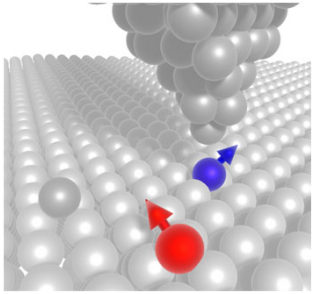
- Numerical simulations
- frequency-dependent damping
- Johnson-Nyquist noise

- Extended RCSJ model with asymmetric quasi-particle current (in contrast to ohmic resistance)

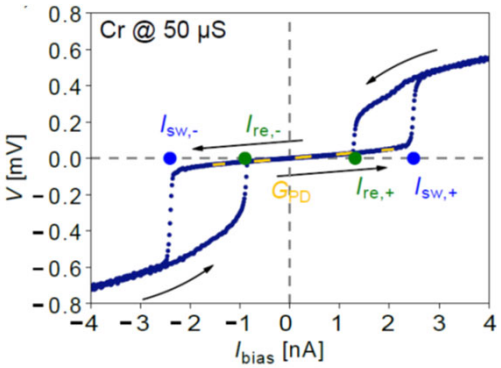


- Asymmetric retrapping currents reproduced
- Diode behavior due to broken e-h symmetry by YSR states

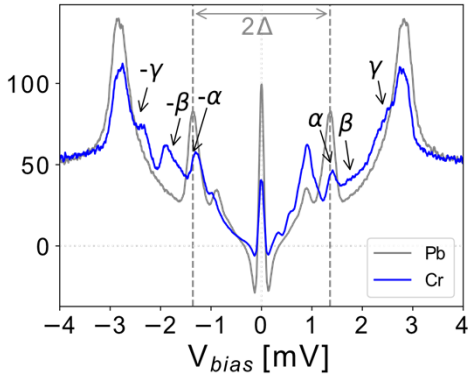
Conclusions



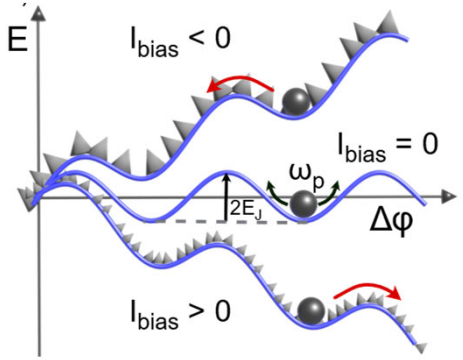
- Atomic-scale Josephson junctions



- Diode behavior when magnetic atoms are included
- Diode behavior in retrapping current (in contrast to earlier experiments)



- Diode behavior due to asymmetric damping
- Extended RCSJ model captures diode behavior



M. Trahms, L. Melischek, J.F. Steiner, B. Mahendru, I. Tamir, N. Bogdanoff, O. Peters. G. Reecht. C. B. Winkelmann, F. von Oppen, K.J. Franke, Nature 615, 628 (2023)

Related theory: J.F. Steiner, L. Melischek, M. Trahms, K.J.Franke, F. von Oppen, Phys. Rev. Lett. 130, 177002 (2023)

Thank you!

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Katharina Biel, Verena Caspari, Florian Faaber, Melvin Grumser, Margarete Huisinga, Christian Lotze, **Bharti Mahendru**, Vibhuti Rai, Lisa Rütten, Junyoung Sim, Rika Simon, **Martina Trahms,** Werner van Weerdenburg, Paul Wiechers

Larissa Melischek, Jacob Steiner, Felix von Oppen