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Environment driven Superconductor-Insulator phase transition in One-Dimensional Josephson-Junction Arrays

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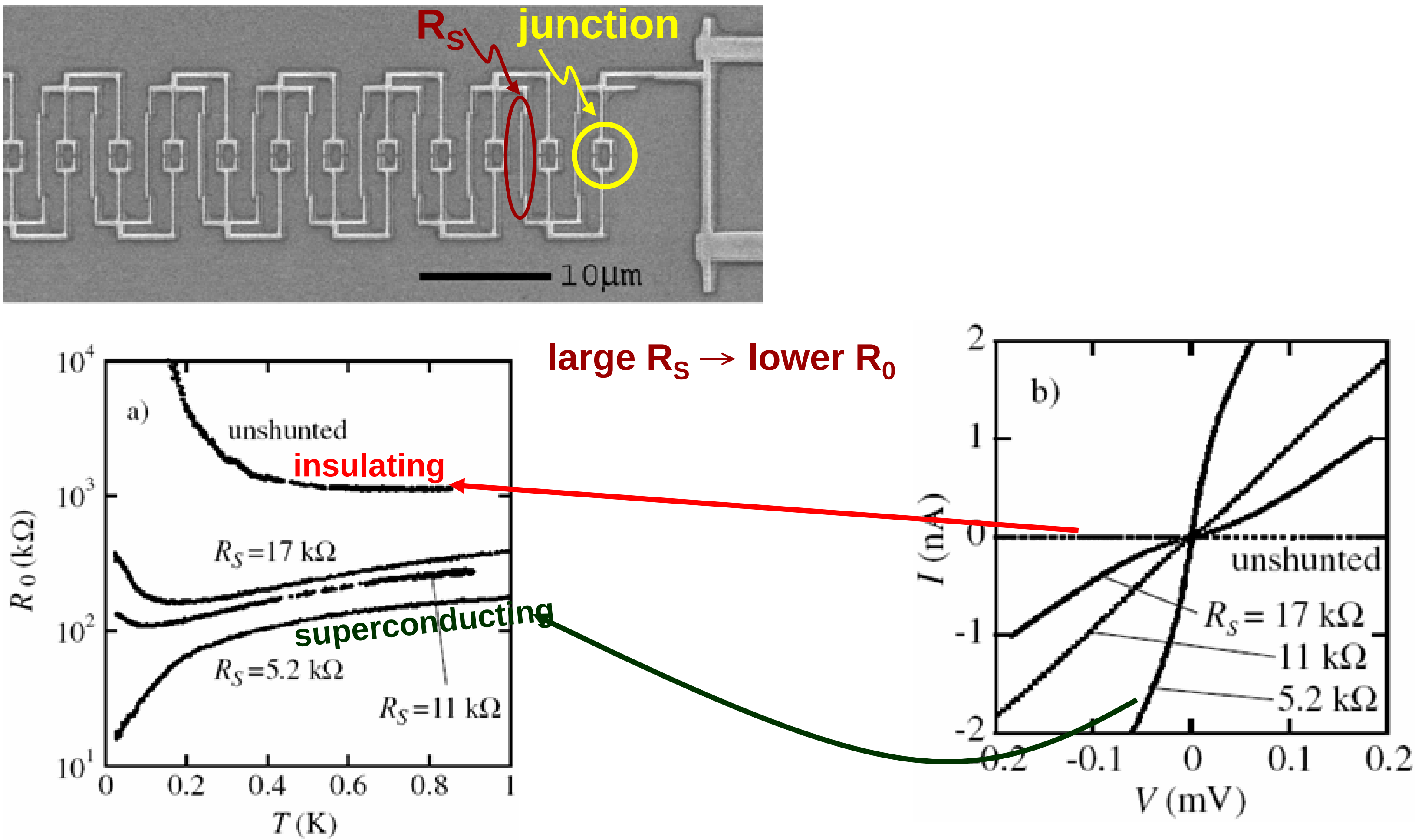
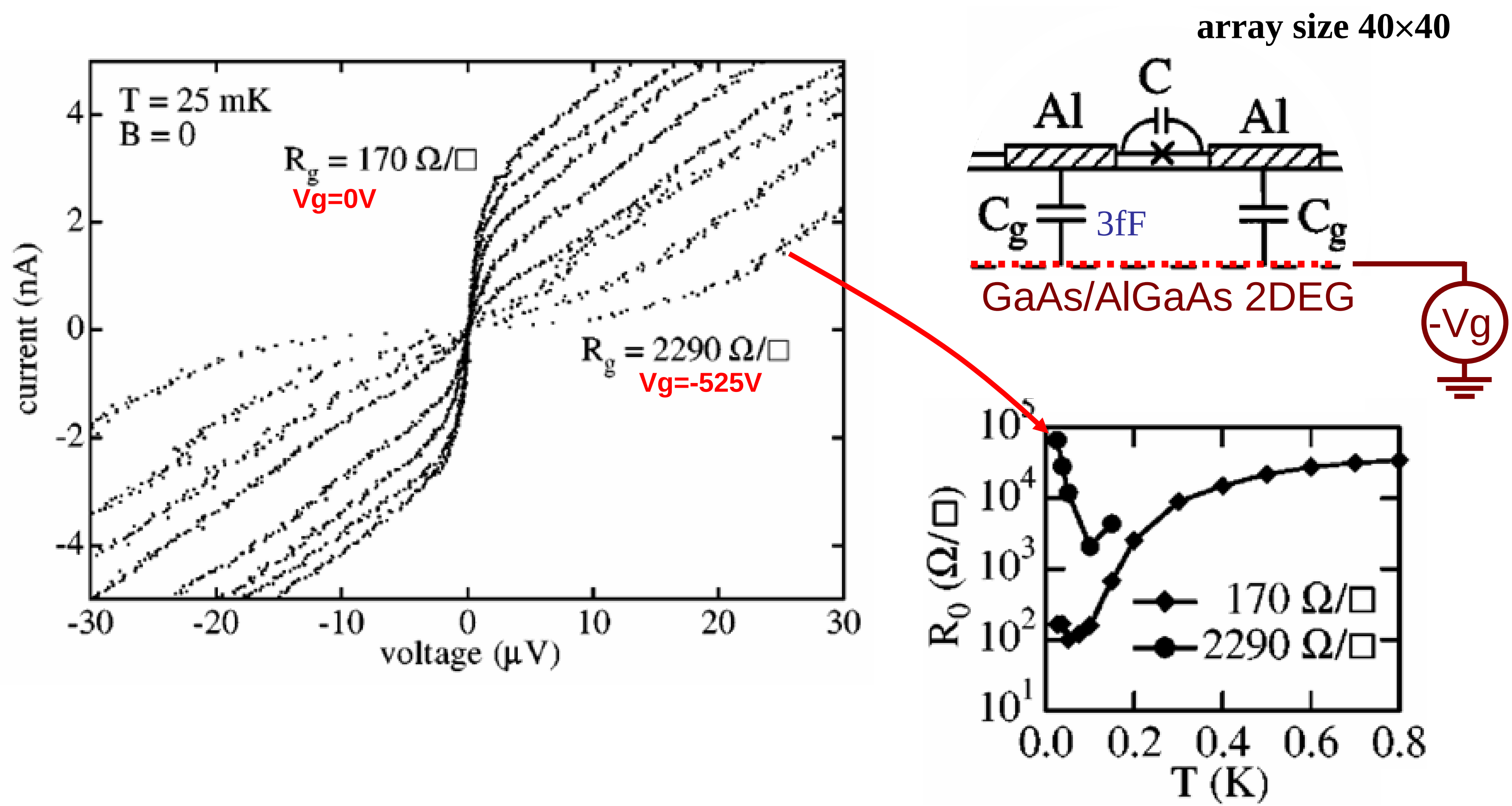
Quantum Phase Transition in One-Dimensional Arrays of Resistively Shunted Small Josephson Junctions

Hisao Miyazaki, Yamaguchi Takahide, Akinobu Kanda, and Youiti Ootuka, PRL, 89, 197001 (02)

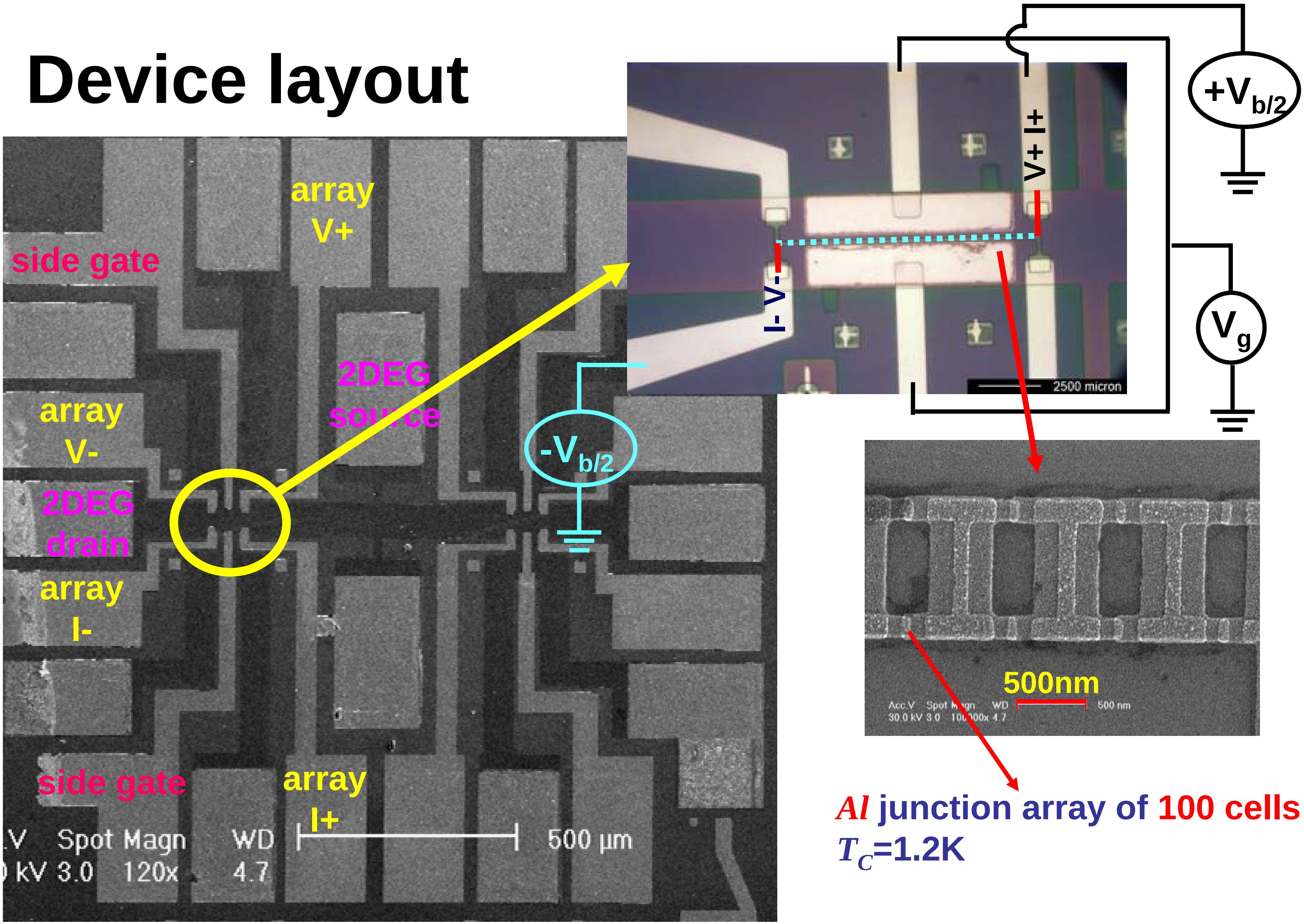


Dissipation-Driven Superconductor-Insulator Transition in a Two-Dimensional Josephson-Junction Array

A. J. Rimberg, T. R. Ho, ¸ C. Kurdak, and John Clarke, PRL 78, 2632 (97)



Device layout

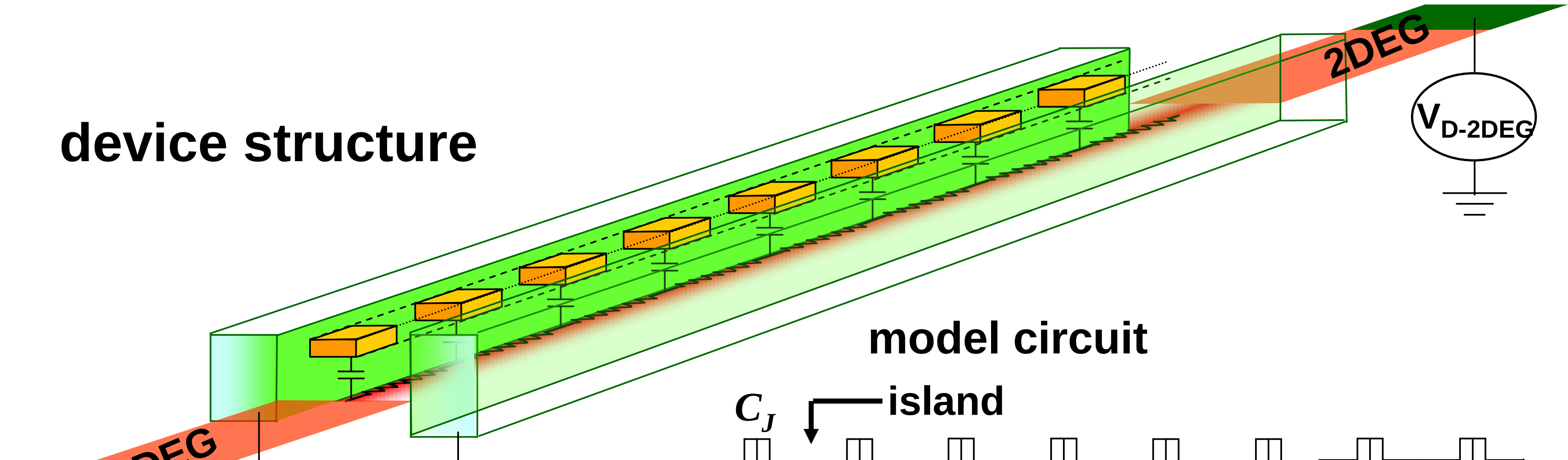


Al junction array of 100 cells

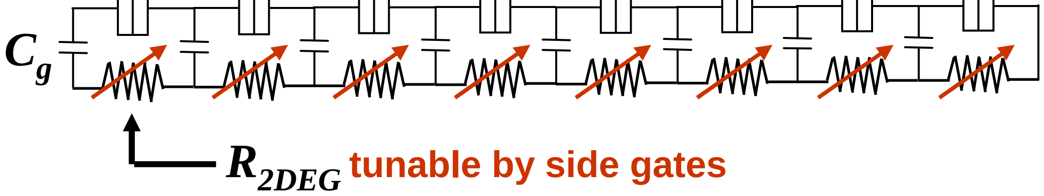
T_C=1.2K

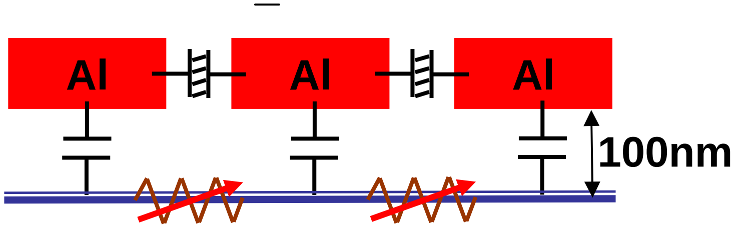
1D Josephson junction array with tunable environment

device structure

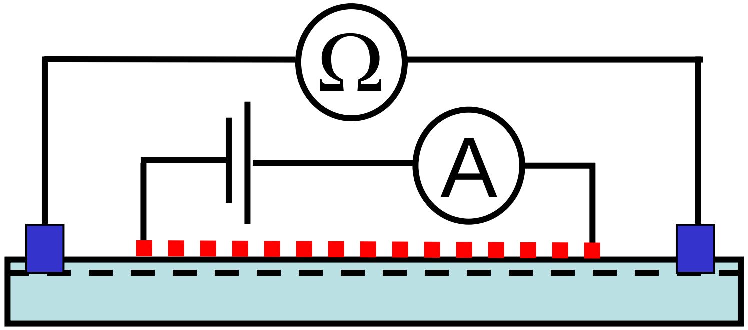


model circuit

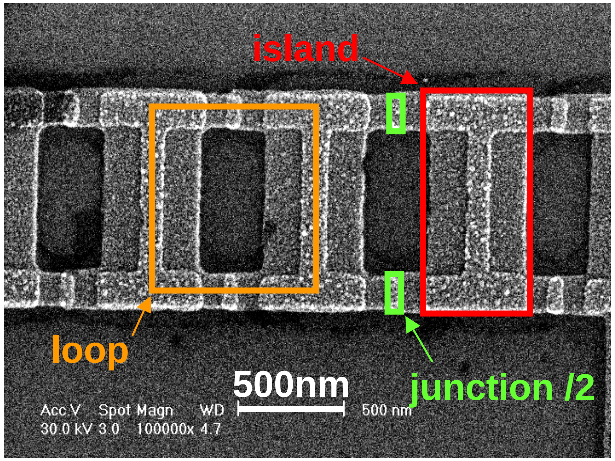


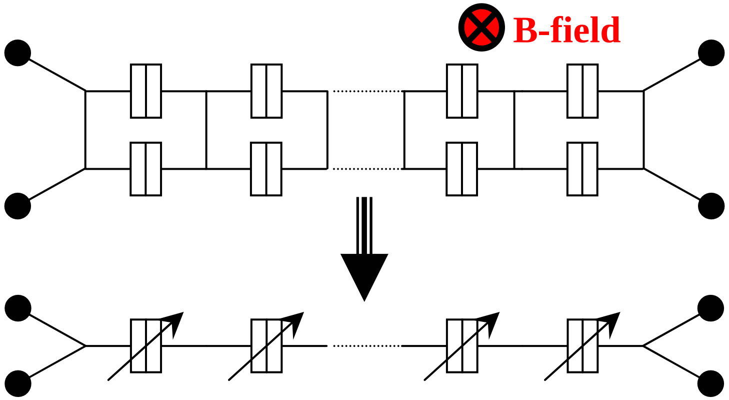


measurement circuit



1D-Josephson Junction Array with tunable coupling strength





Two relevant energy scales:

Charging energy
for single electrons

$$E_{CP} = \frac{4e^2}{2(2C)}$$

= 212 μeV **2C = 1.5fF with C_S=45fF/μm²**

Josephson coupling energy

$$E_J^0 = \frac{\Delta}{2}\frac{R_Q}{R_N}$$

= 96.3 μeV (A1) and 81.3 μeV (A2)

R_N (6.75kΩ for A1 and 8.0kΩ for A2), Δ=200μeV

modulated coupling energy

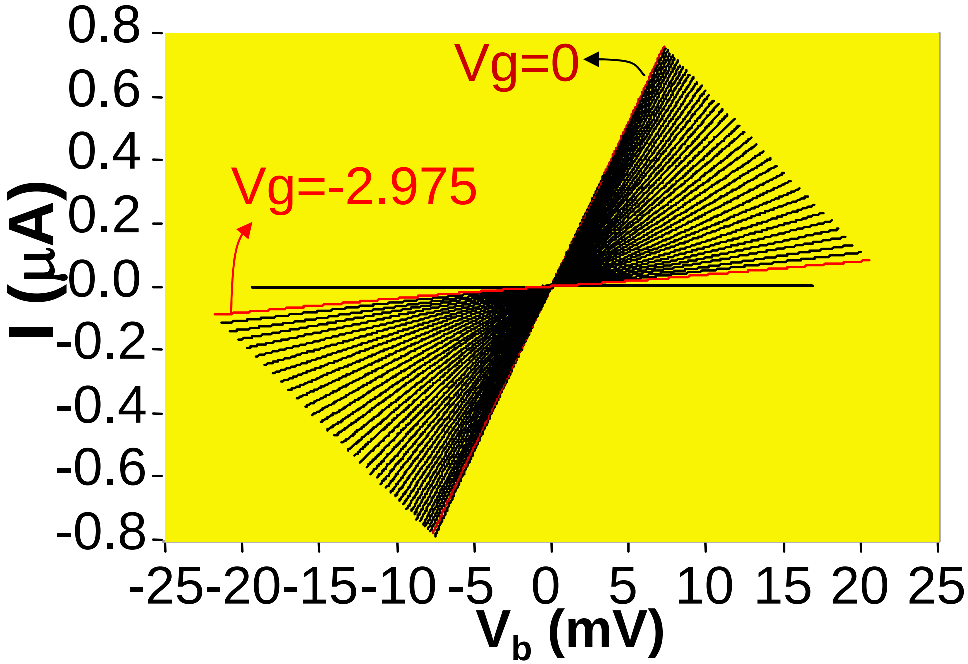
$$E_J = E_J^0 \cos(\pi f)$$

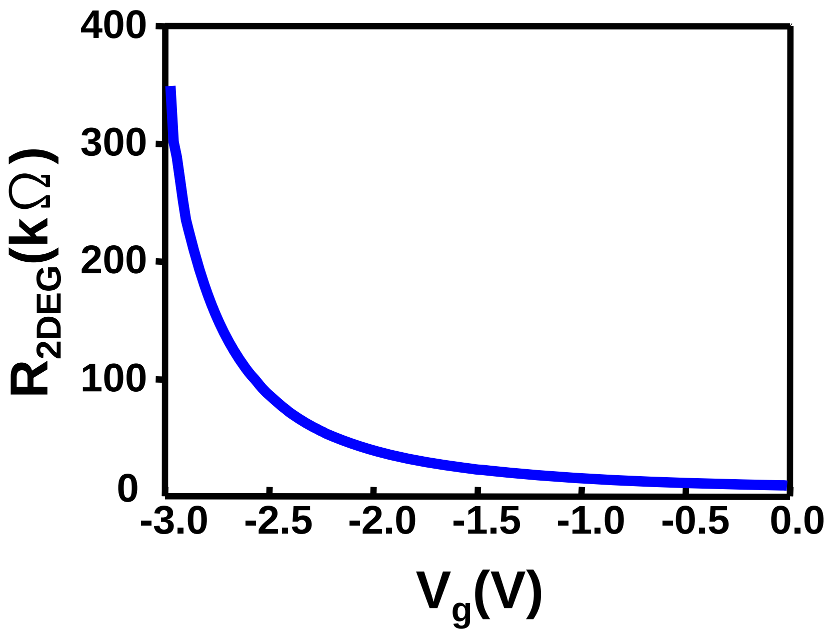
$$f = AB/\Phi_o$$

f = B/42.5Gs

$$\alpha \equiv R_Q/R_{2DEG}$$

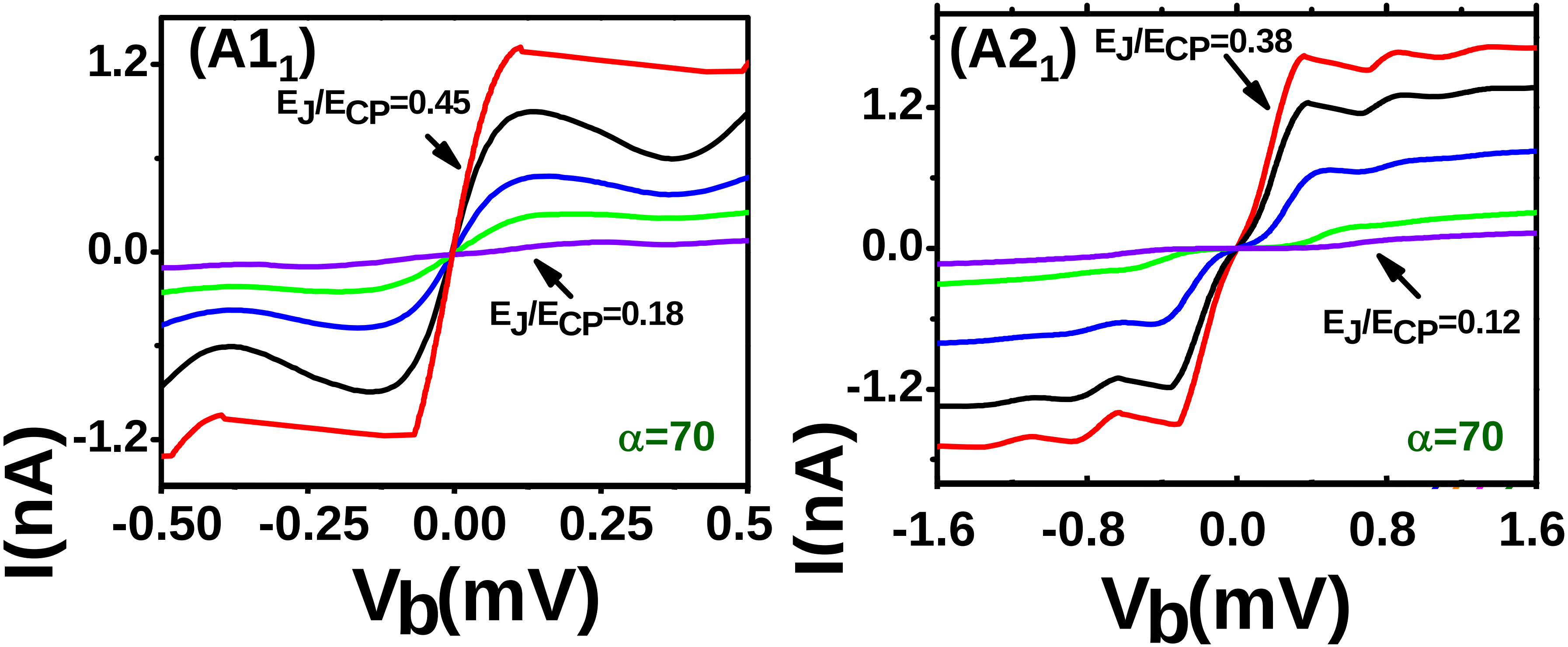
Characteristics of the 2 Dimensional Electron Gas layer





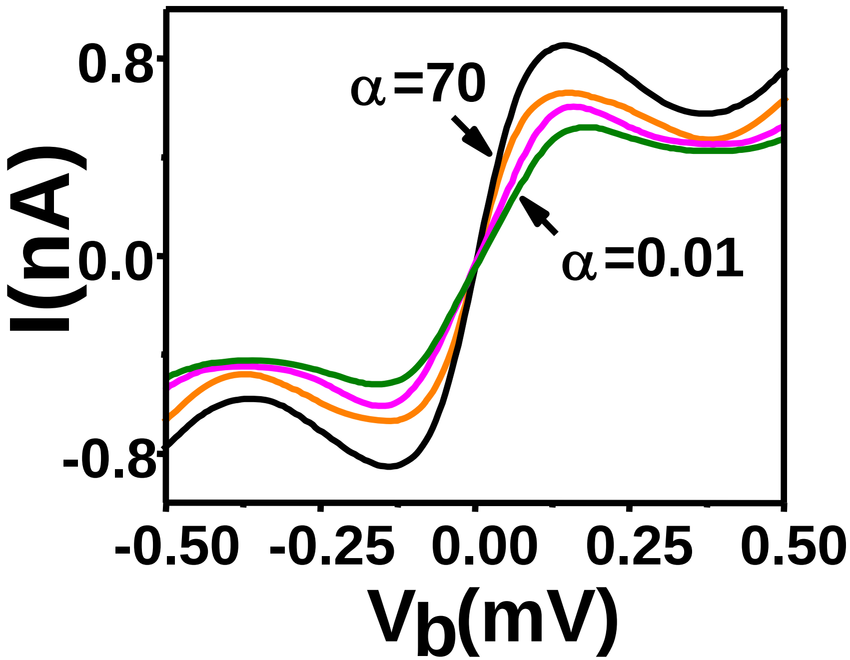
$$\alpha \equiv R_Q / R_{2DEG}$$

E_J/E_{CP} and α dependence of IV_b curves

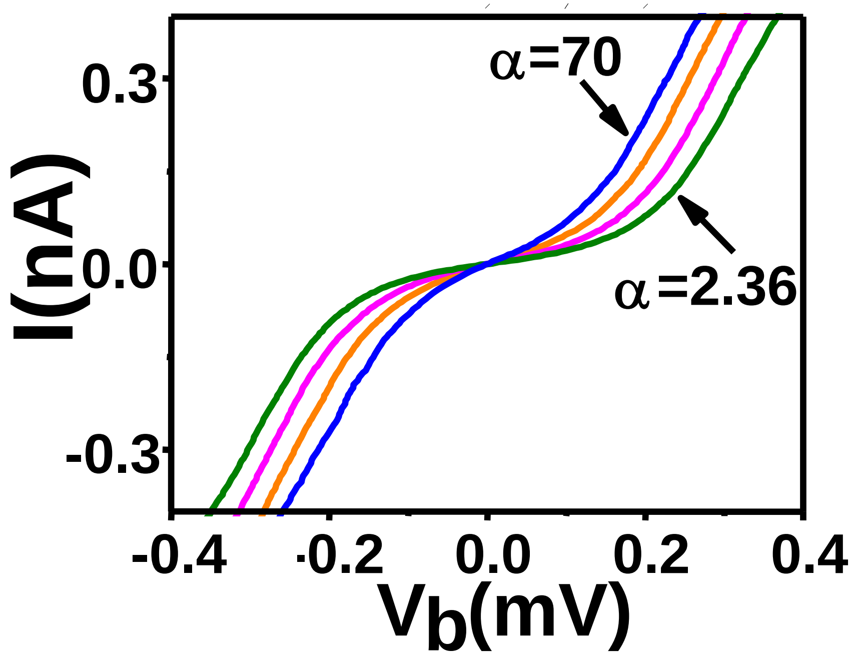


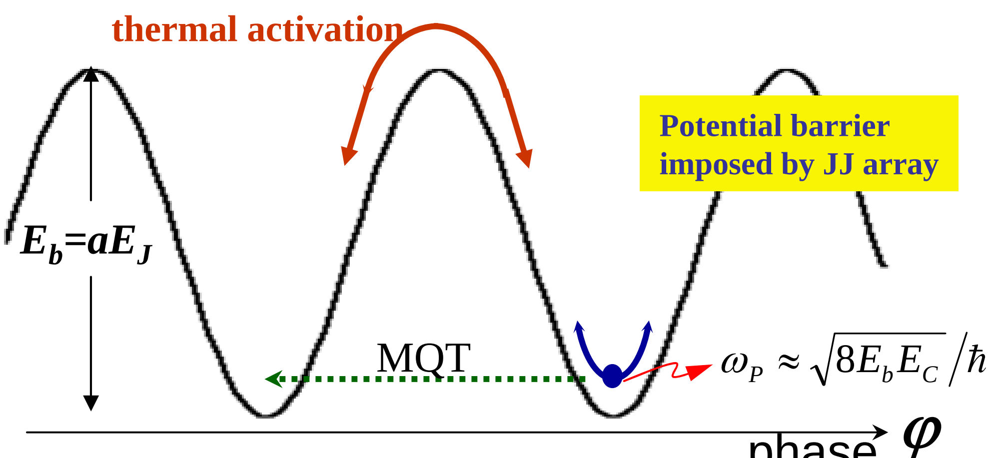
Effect of α in phase- and charge-order regimes

phase order regime

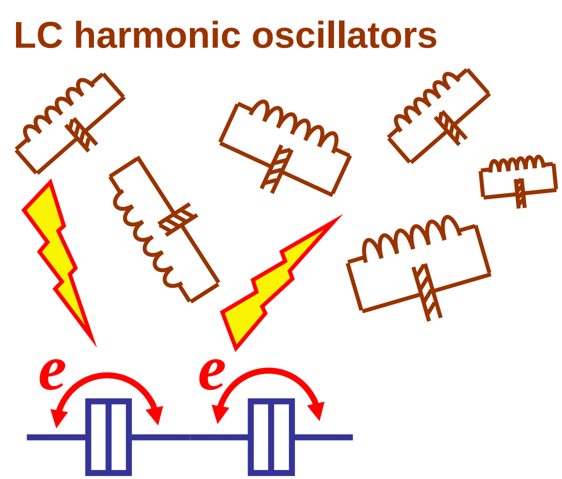


charge order regime



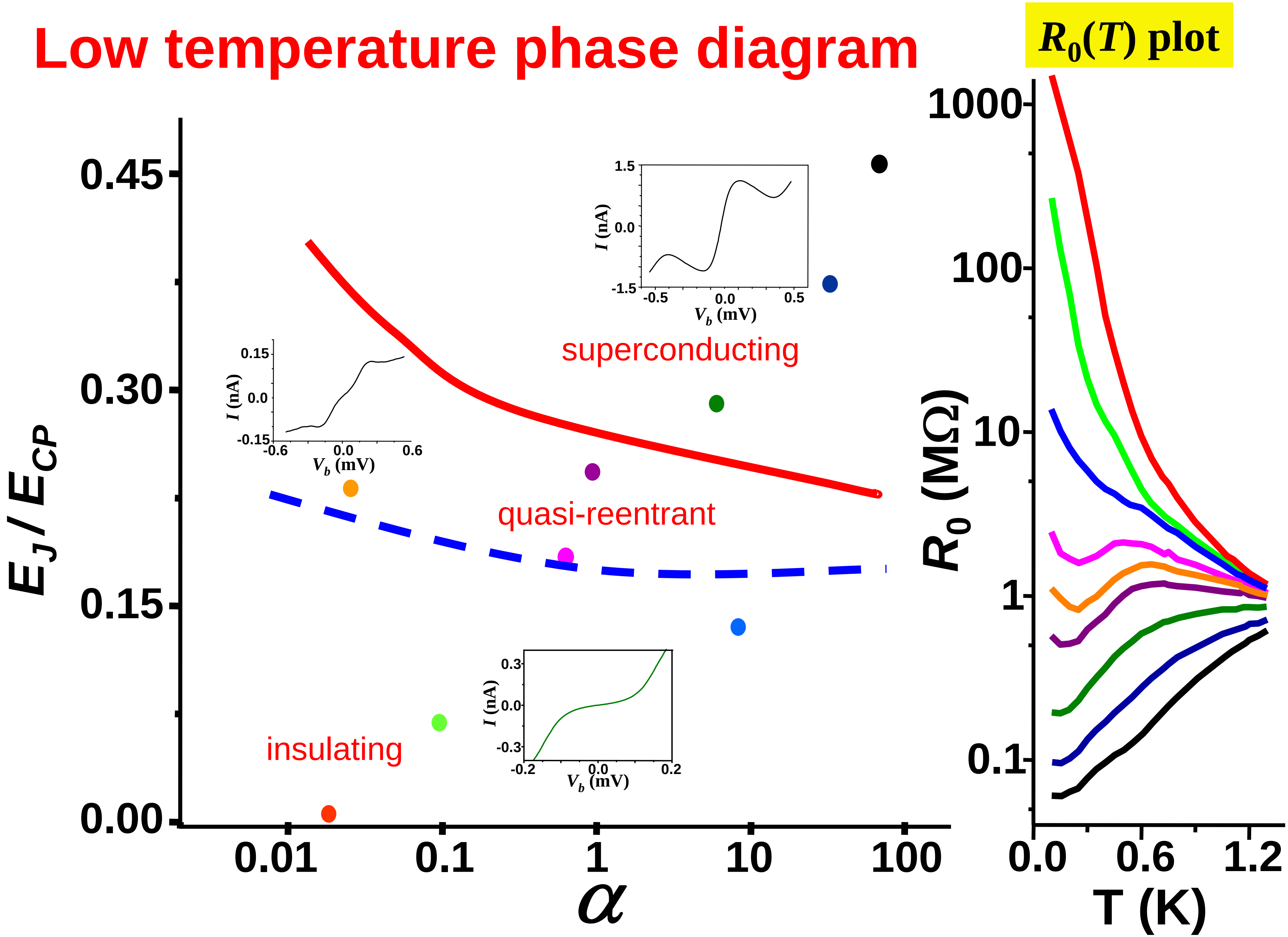


α =friction to phase motion

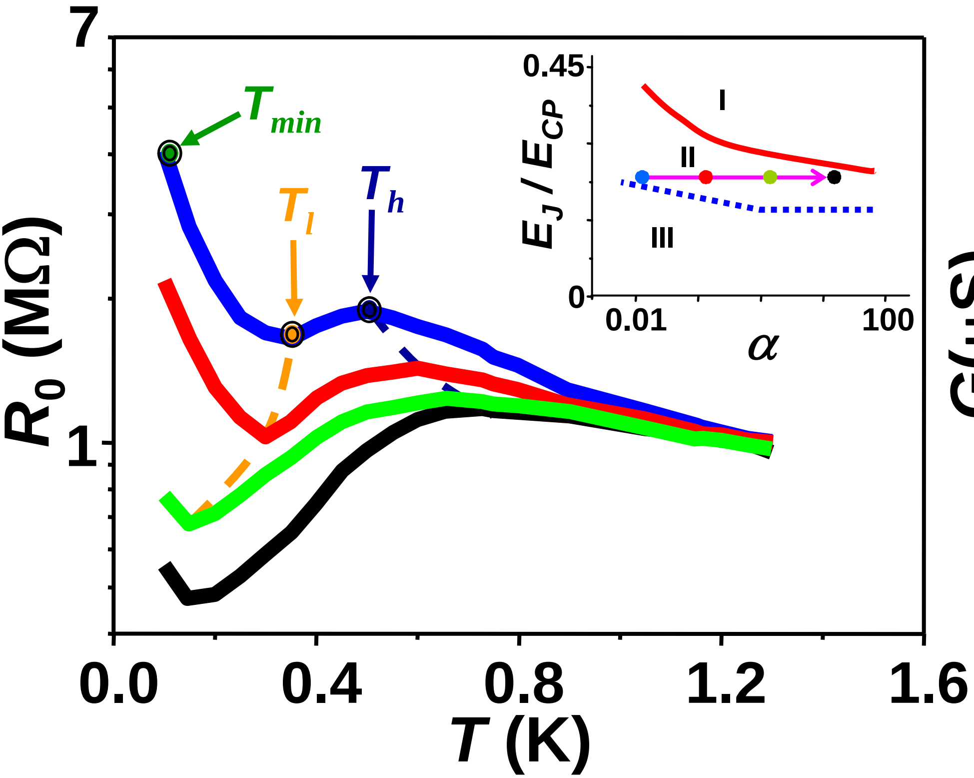


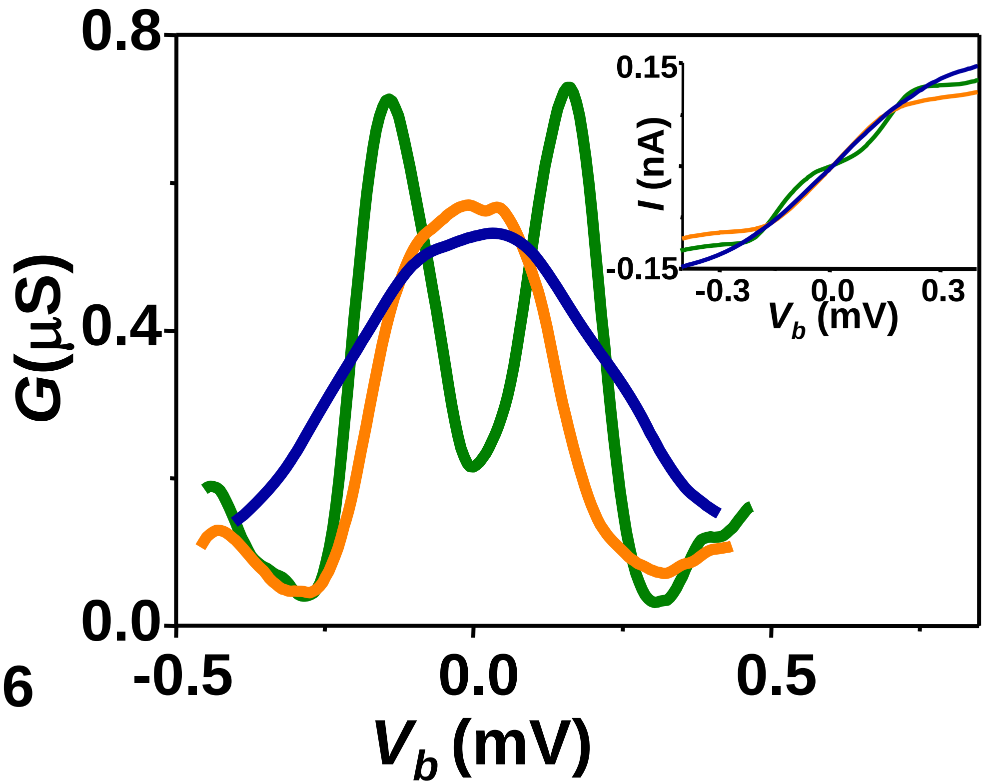
α = promote charge tunneling

Low temperature phase diagram



Effect of α on quasi-reentrance behavior





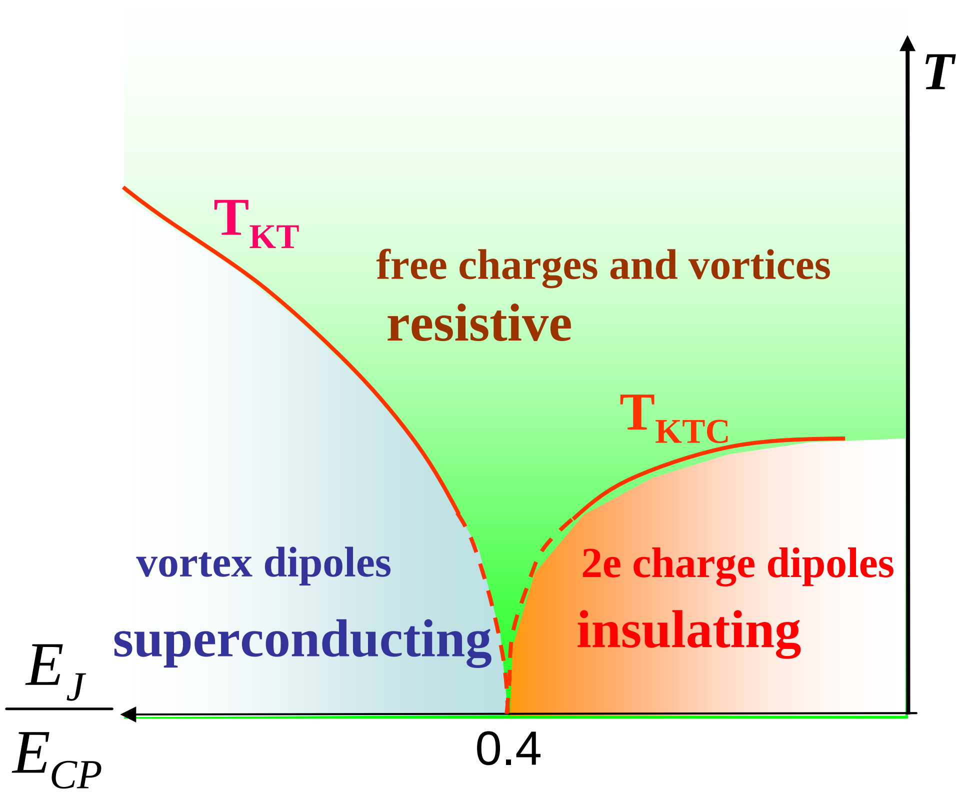
Phase diagram

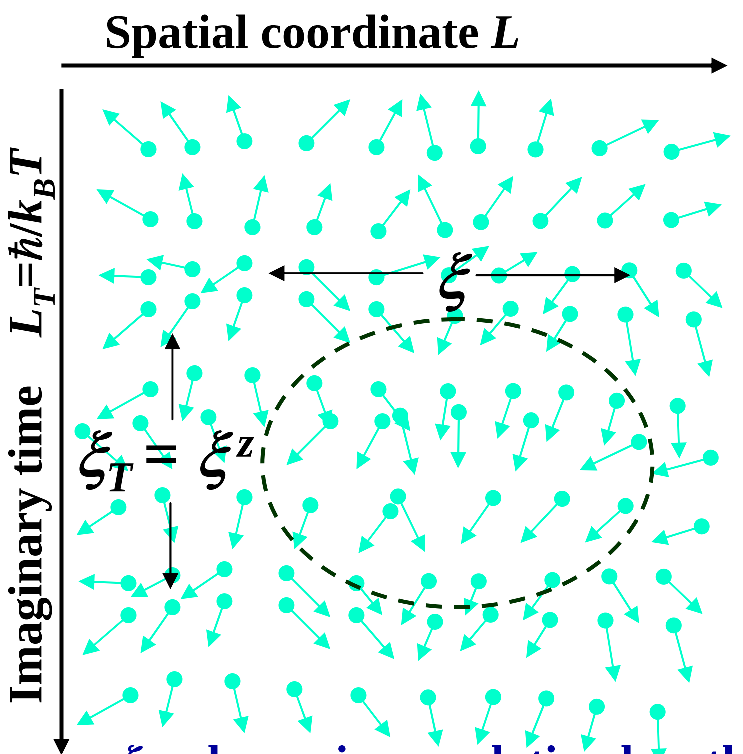
- **no electromagnetic environment**
- **varying temperature**

$$L_{JJA} = \frac{1}{2}\sum_{ij} Q_i \left(\hat{C}^{-1}\right)_{ij} Q_j + \sum_{<i,j>} E_J \left[1 - \cos\left(\varphi_i - \varphi_j\right)\right]$$

charging energy — Josephson coupling energy

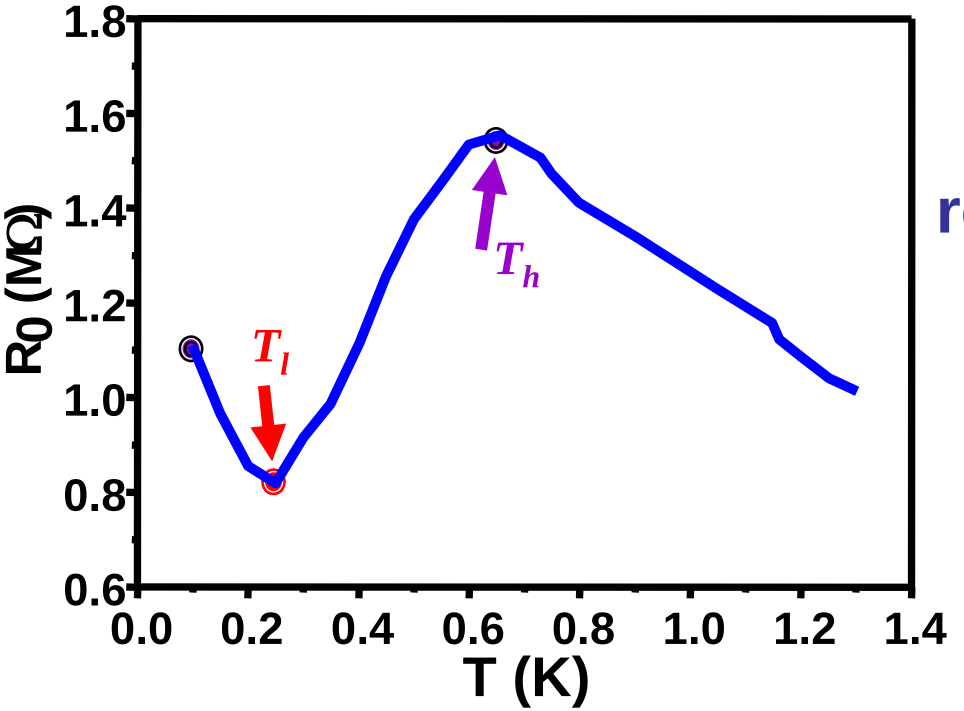
S. Chakravarty, G. L. Ingold, S. Kivelson, and A. Luther, Phys. Rev. Lett.**56**, 2303 (1986)





ξ_T : dynamic correlation length

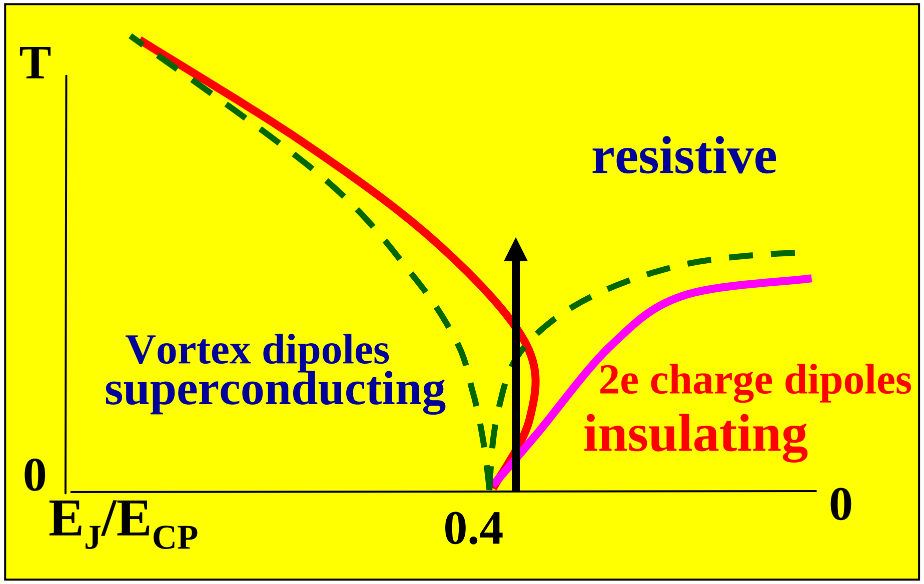
Quasi-reentrance behavior: no environment



renormalization and dissipation from junction R_J

Capacitance renormalization

$$C^* \rightarrow C + \delta C \qquad \delta C = \frac{3\pi h}{32\Delta R_J}$$



In the presence of an electromagnetic environment

$$L_{total} = \frac{1}{2}\sum_{ij} Q_i\left(\hat{C}^{-1}\right)_{ij} Q_j + \sum_{<i,j>} E_J\left[1-\cos\left(\varphi_i - \varphi_j\right)\right] + \frac{1}{2}\sum_n \left(m_n \dot{x}_n^2 - m_n\omega_n^2 x_n^2\right) - \sum_{in} F_{in}\left(Q_i, \varphi_i, x_n, \lambda_{in}\right)$$

1D Junction array — 2DEG — array-2DEG interaction

2DEG → harmonic oscillators

resonant frequencies $\omega_n = 2\pi n k_B T$ Matsubara frequencies

λ_{in} = the coupling strength ↔ **superconducting island *i*** / **environment oscillator *n***

In phase order regime: (E_J > 0.2 E_{CP})

Ohmic environment →

$$\sum_n \frac{\pi\lambda_{in}^2}{2m_n}\delta\left(\omega - \omega_n\right) = R_{2DEG}^{-1}$$

Superconducting - insulating boundary $\langle E_J \cos\varphi_{ij}\rangle = 0$

$$1 - E_J\int_0^{\frac{1}{k_B T}} d\tau \exp\left[-2k_B T\sum_n \frac{E_{CP}}{\sqrt{1+\alpha E_{CP}/2\pi\omega_n}}\frac{1-\cos\left(\omega_n\tau\right)}{\omega_n^2}\right]$$

>0 → superconductor

<0 → insulator

$$1 - E_J \int_0^{\frac{1}{k_B T}} d\tau \exp\left[-2k_B T \sum_n \frac{E_{CP}}{\sqrt{1+\alpha E_{CP}/2\pi\omega_n}} \frac{1-\cos(\omega_n \tau)}{\omega_n^2} \right]$$

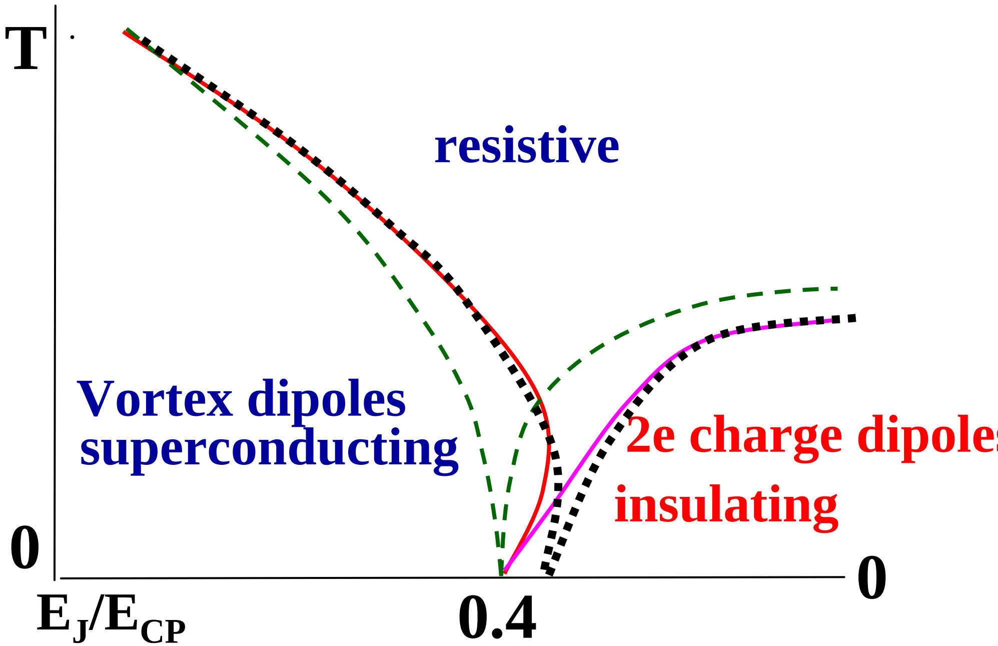
>0 → superconductor

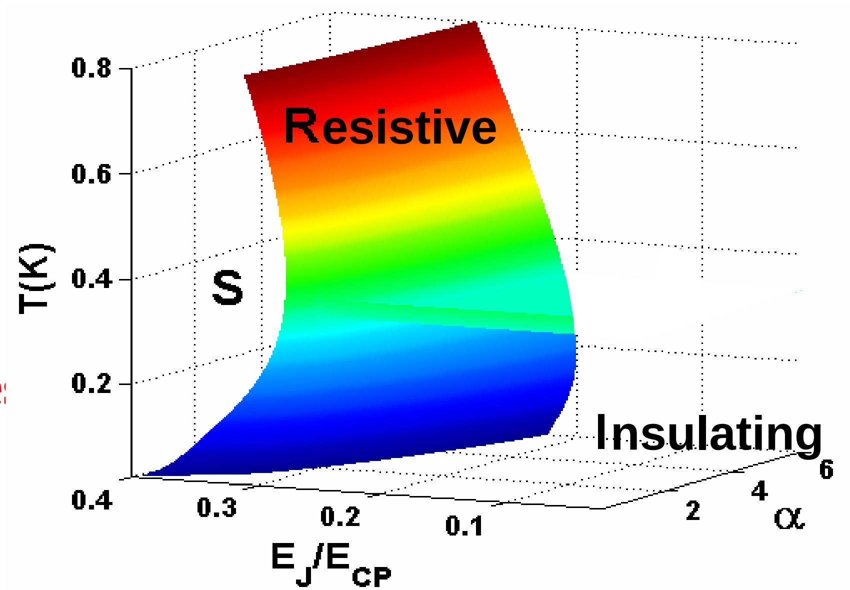
<0 → insulator

Presence of E_{CP} ⟵ phase-charge duality

$\alpha \neq 0$ suppresses phase fluctuations → promotes Cooper pair tunneling

→ an effective reduction of E_{CP} by a factor of $\sqrt{1+\alpha E_{CP}/2\pi\omega_n}$

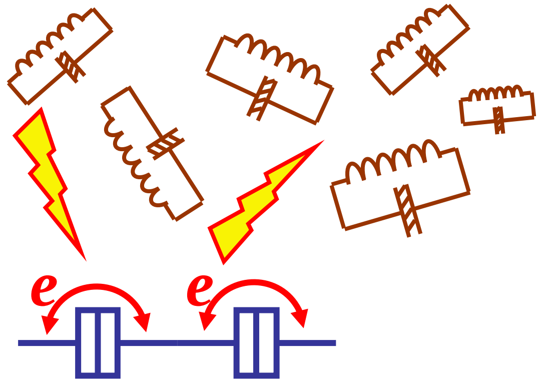


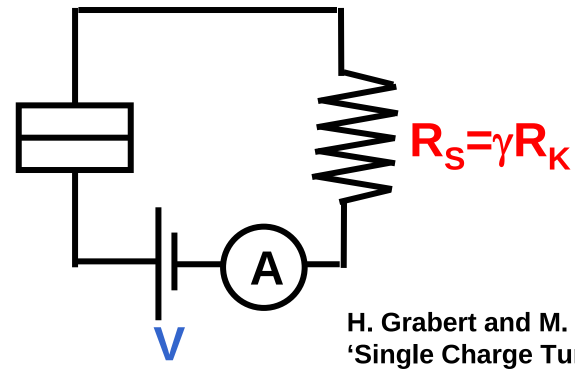


Phase boundary in charge order regime $(E_J << E_{CP})$

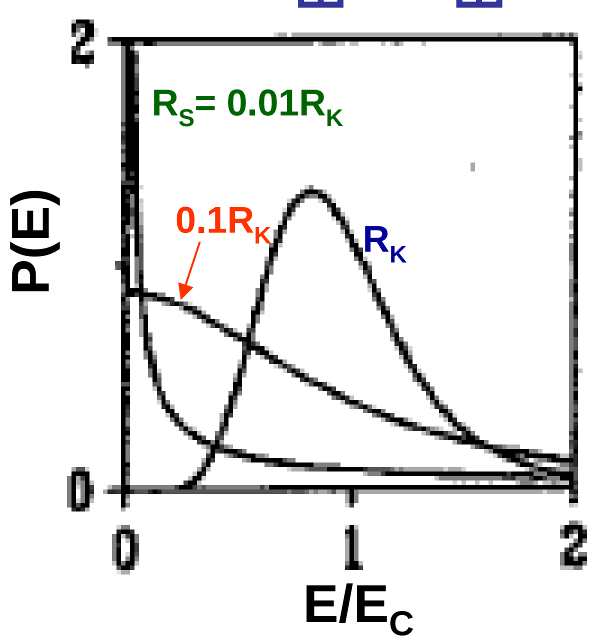
Cooper pair tunneling rate: $\Gamma(E) = \frac{\pi}{2\hbar} E_J^2 P(E)$

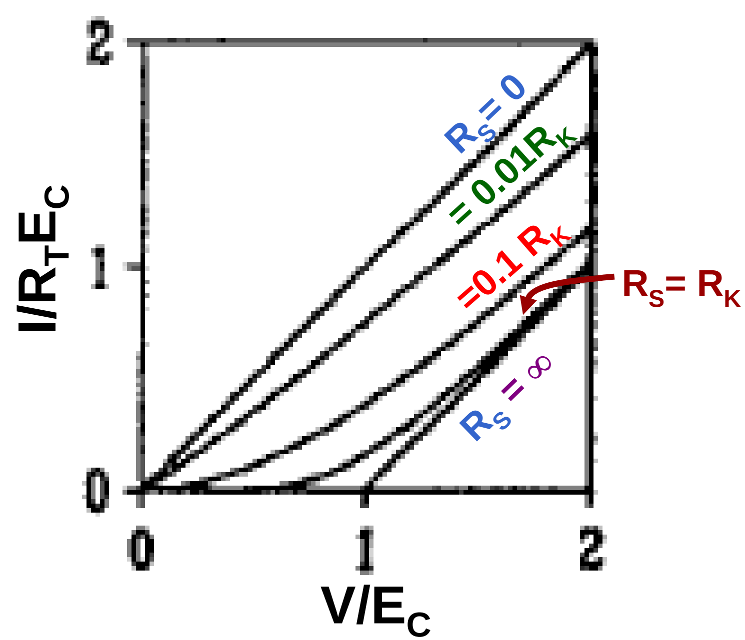
P(E) ---- Probability for the tunneling electron to exchange energy E with the environment.



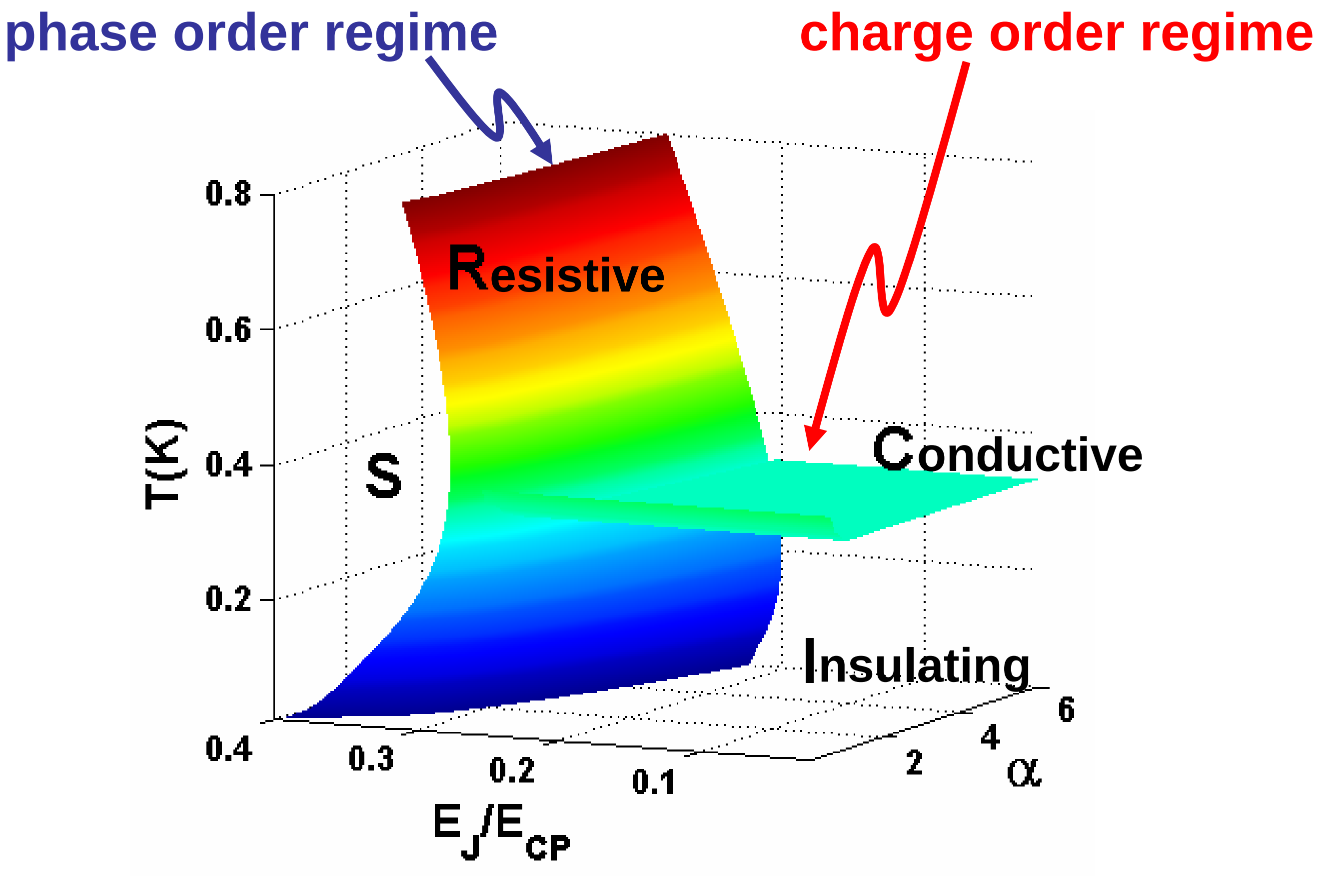


H. Grabert and M. H. Devoret, 'Single Charge Tunneling', (Plenum Press, New York, 1992)

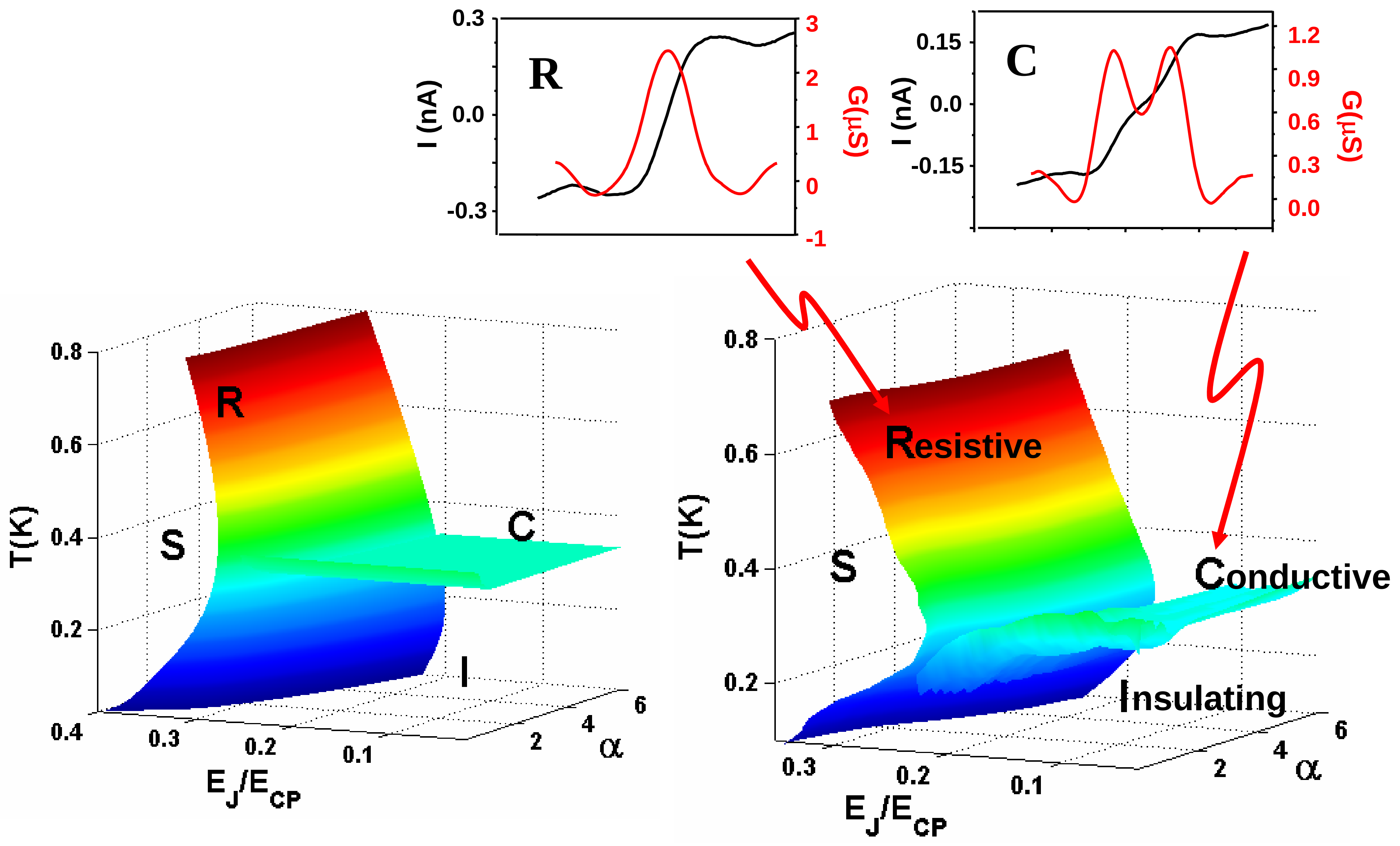




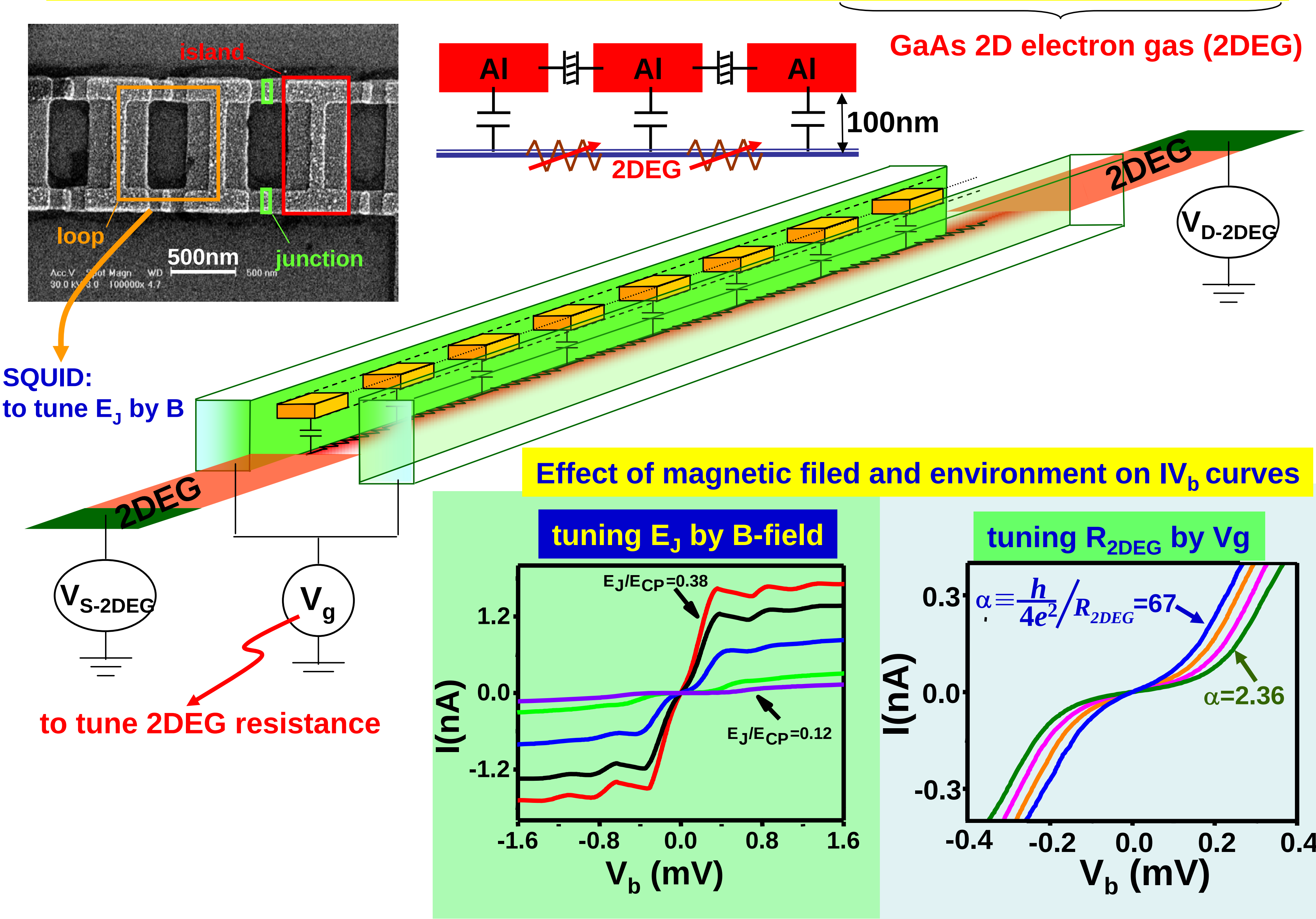
Calculated phase diagram for both



Comparison between theoretical and experimental phase diagram



1D Josephson junction arrays with a tunable environment



Phase diagrams

Finite temperature phase diagram