The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

International Atomic Energy Agency

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COLLEGE ON

PHYSICS OF NANO-DEVICES

10 - 21 July 2006

Introduction to the Physics of Semiconductor Quantum Dots
The physics of nano-electronics

Presented by:

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Introduction to the Physics of Semiconductor Quantum Dots

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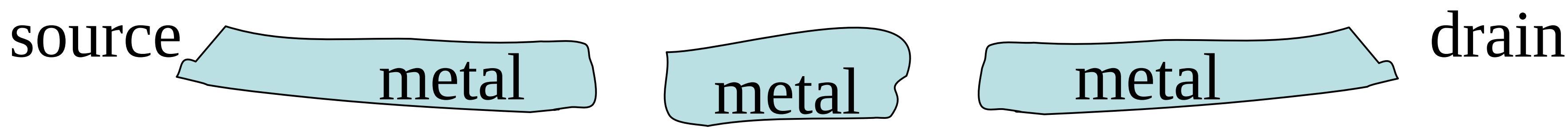
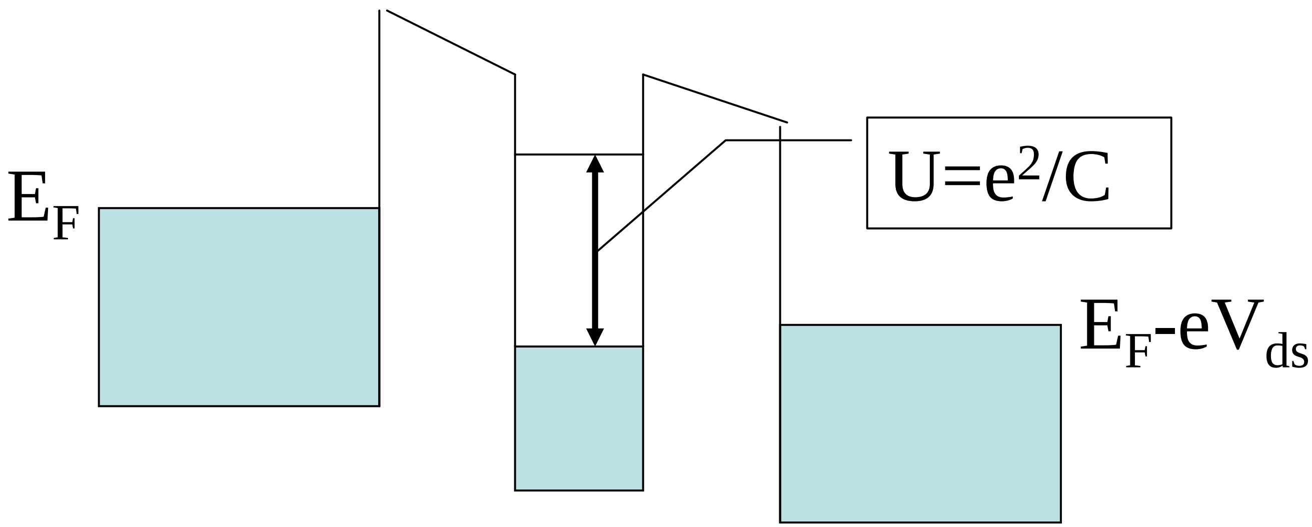
Outline: Measuring Energy Scales

- Coulomb blockade energy U (Metal Single Electron Transistor)
- Energy level spacing $\Delta\varepsilon$ (Semiconductor SET)
- Coupling to the leads Γ

Two Barriers with Small Island

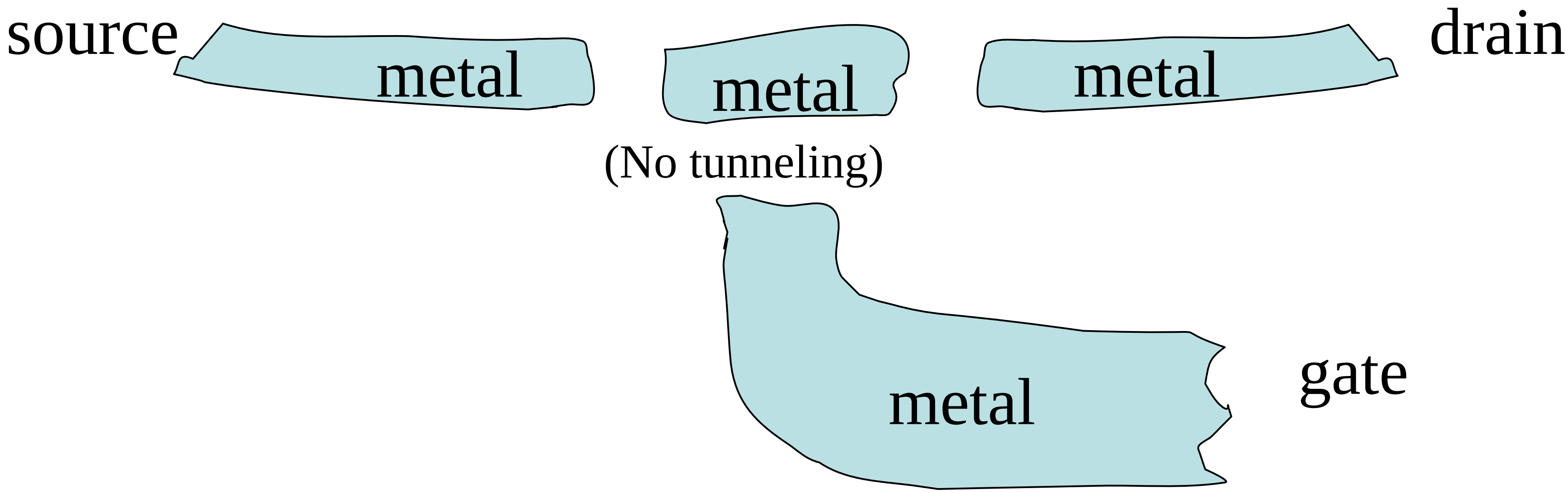


Small
Metal
Island



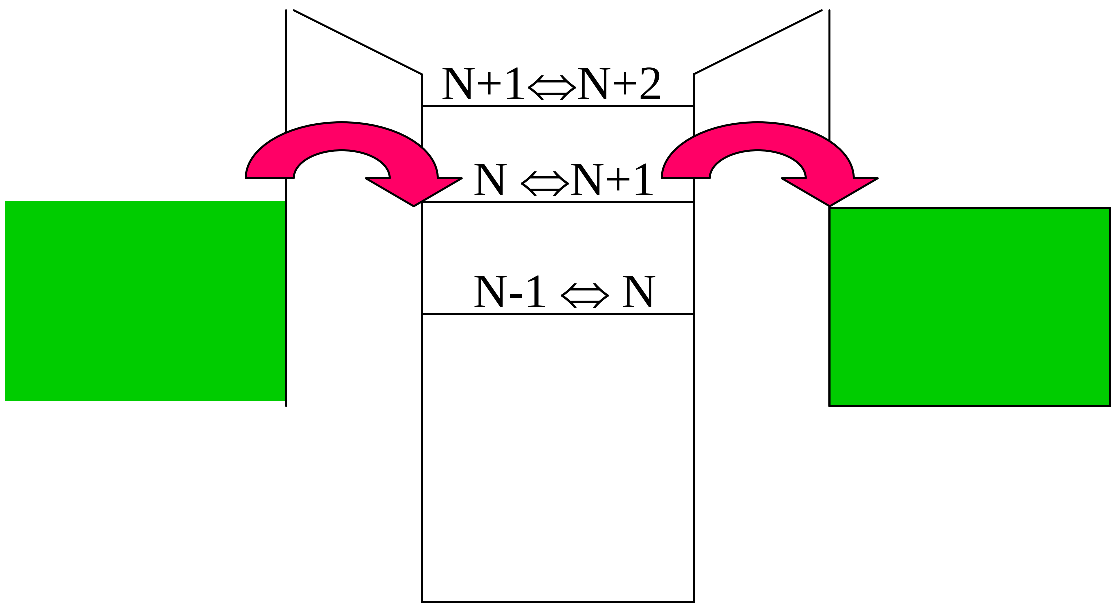
→ No current at zero temperature

Schematic of Metal SET



Sequential Charging

E_F

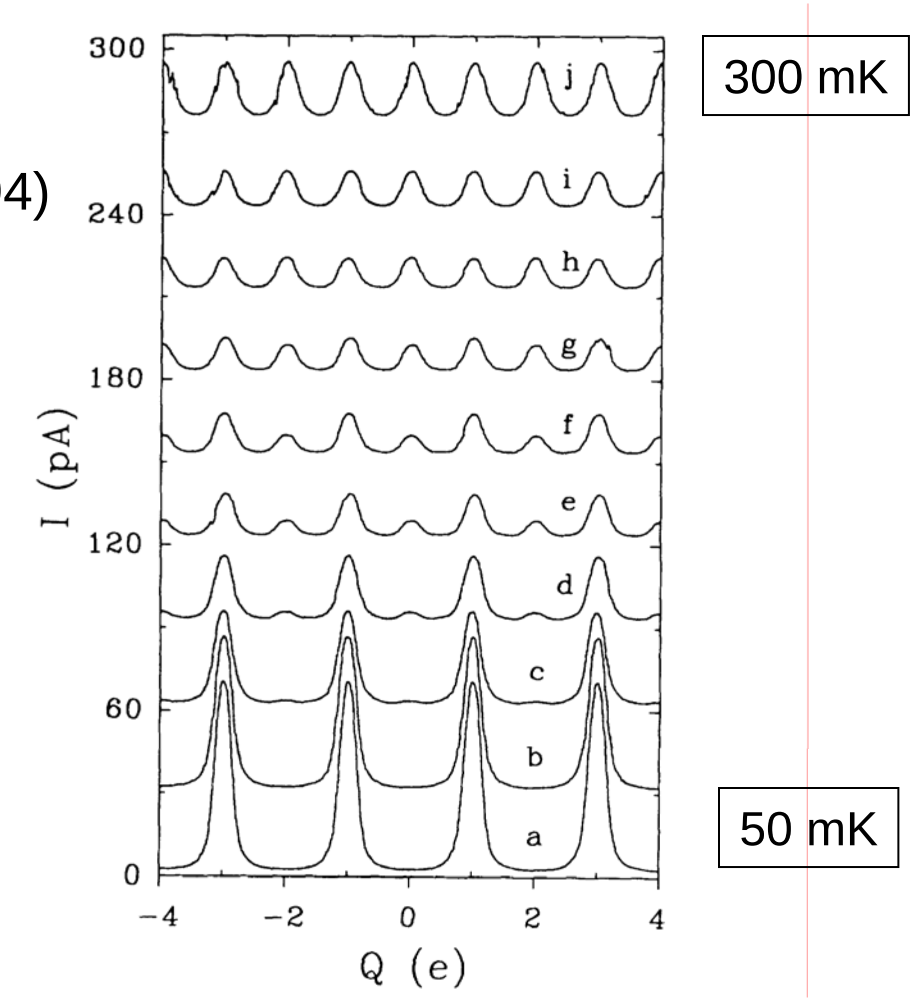


At low T and with very small V_{ds} get one sharp peak for each electron added.

Current vs. Gate Voltage

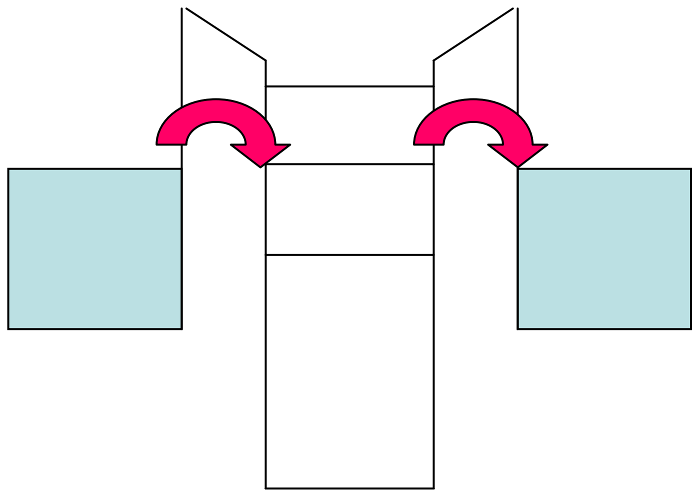
Aluminum SET
A. Amar et al. PRL **72**, 3234 (1994)

Note: Because of superconductivity, below T_C one gets a peak every time Cooper pair is added.



$Q = C_G V_G$

Condition for Charge Quantization

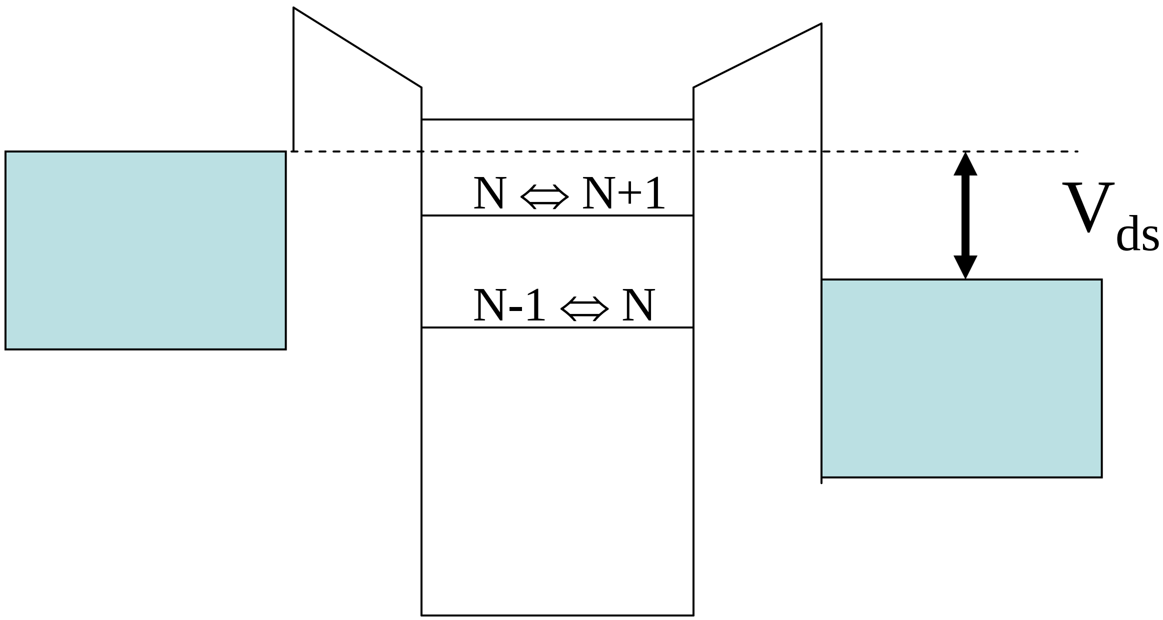


An extra electron stays on the island for time RC. This time must be long enough that the uncertainty in its energy is less than U.

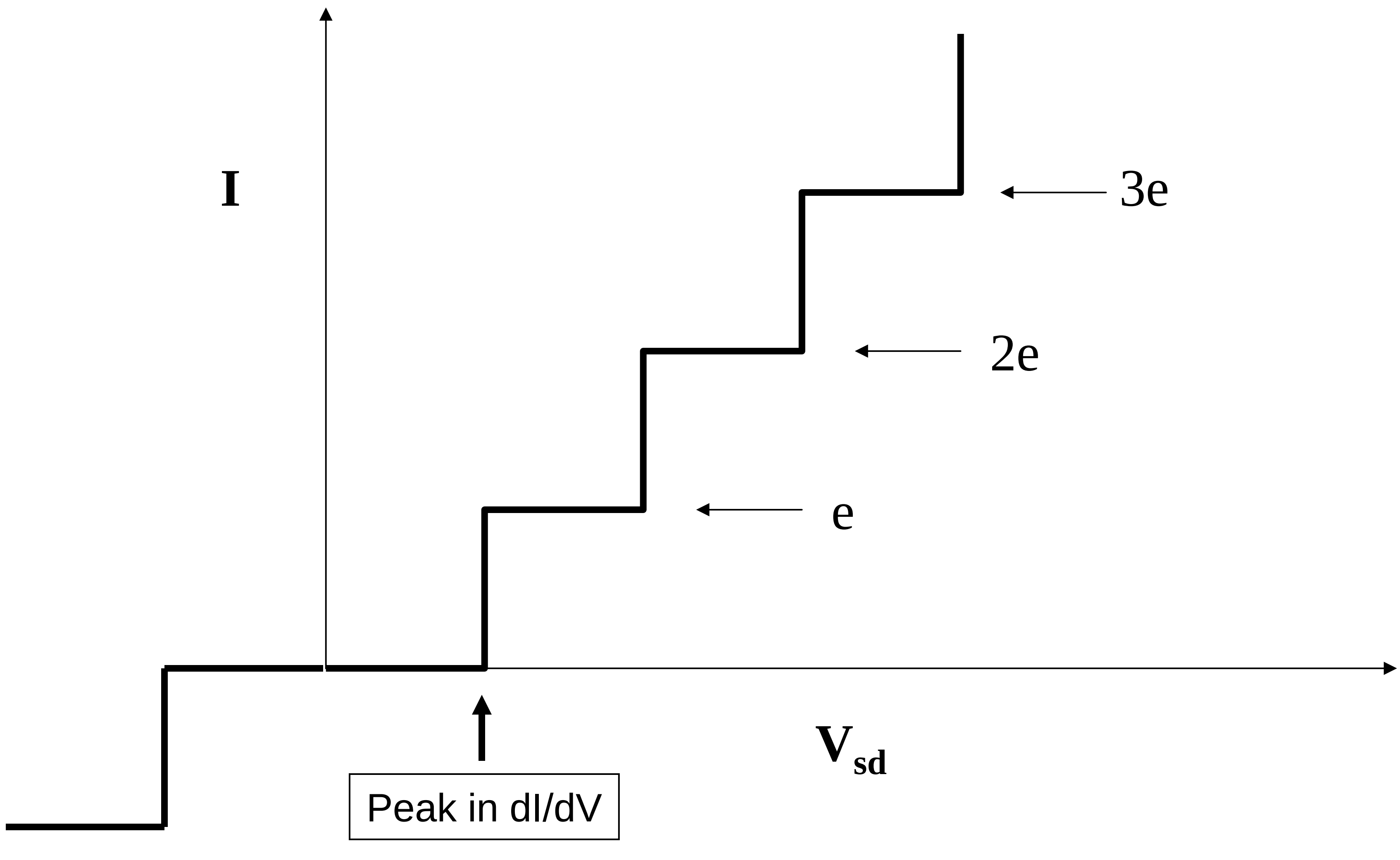
$U > h/RC$, but $U = e^2/C$

$R > h/e^2$ or $G < e^2/h$

Adding Charge by Source-Drain

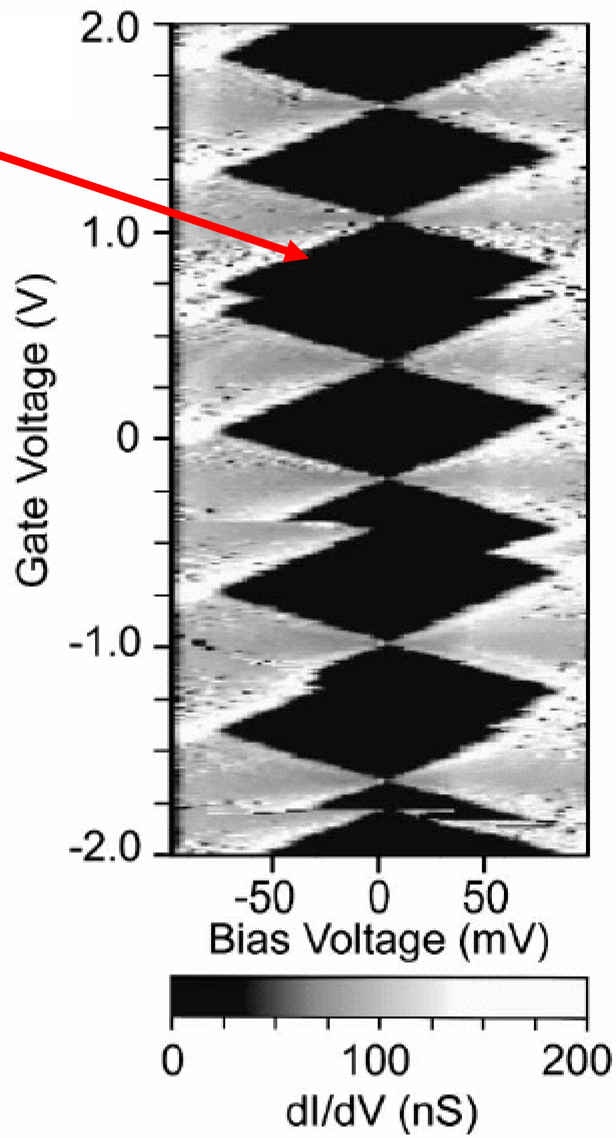


Coulomb Staircase



Coulomb Diamonds

First step in Coulomb staircase



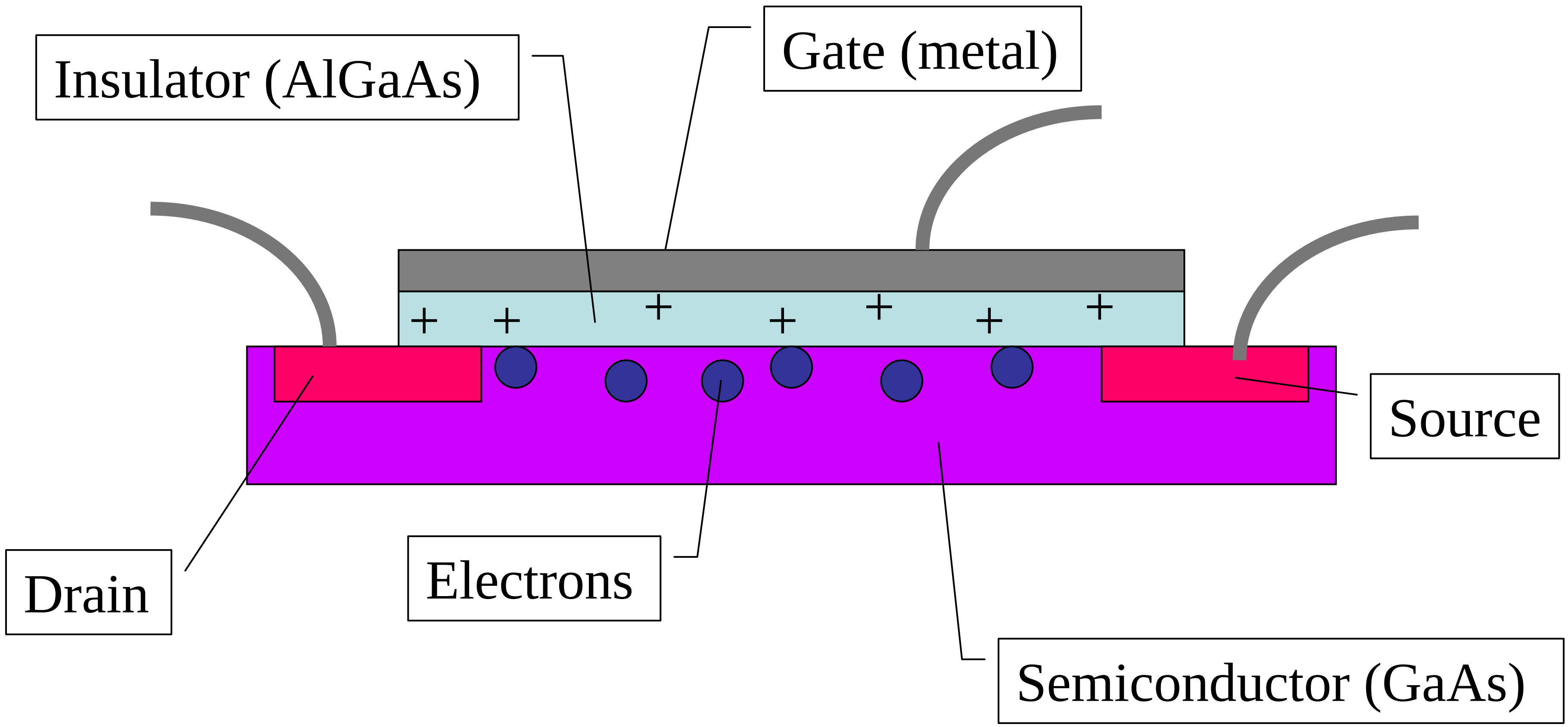
SET made with nano-particle, Bolotin et al. APL **84**, 3154 (2004)

Slopes of diamonds give capacitance ratios

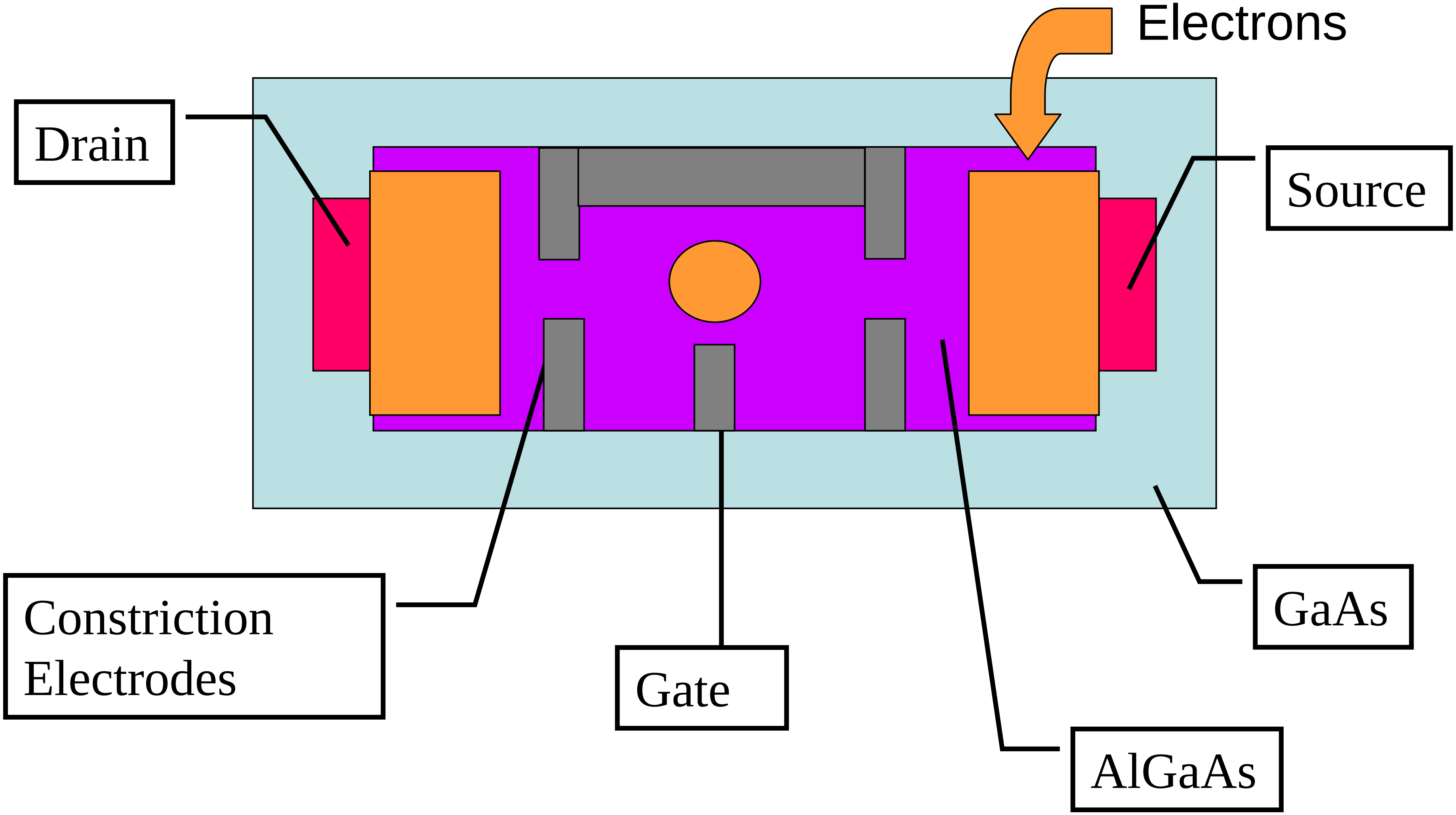
Note: switching from nearby charges

Making Semiconductor SETs

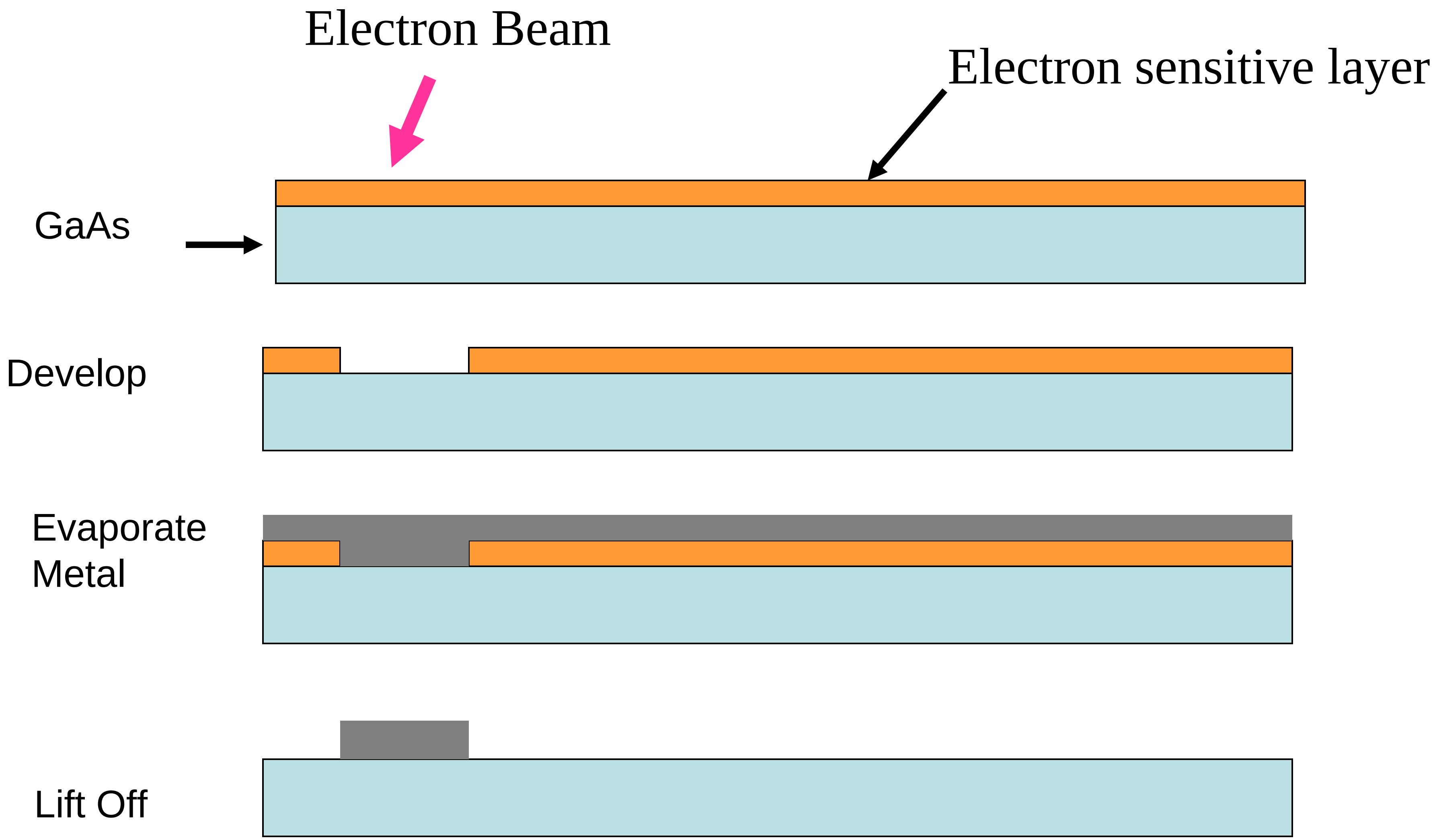
GaAs Field Effect Transistor



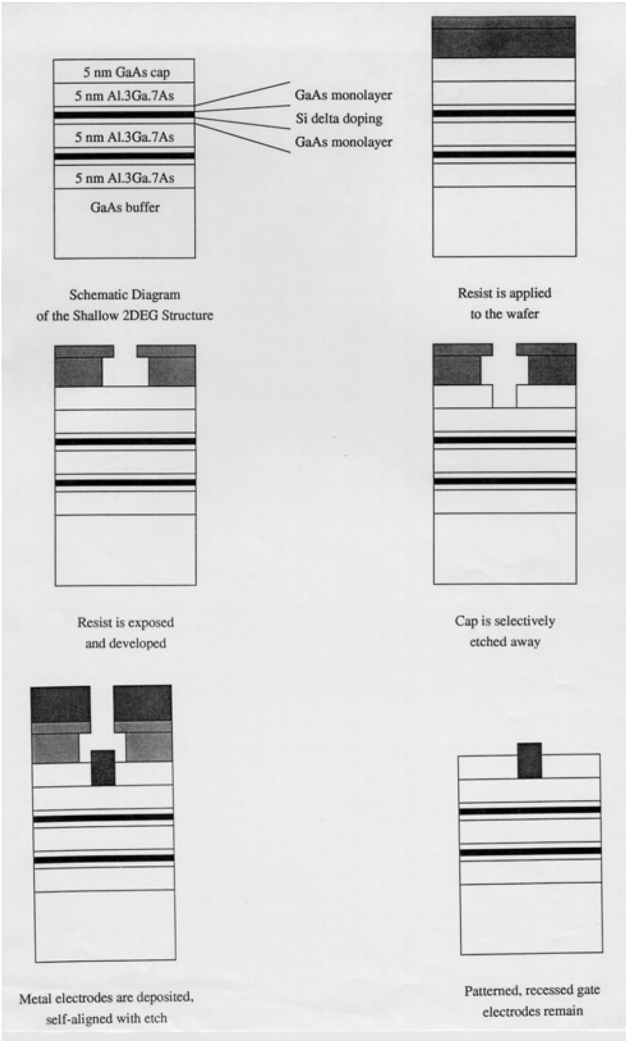
Schematic GaAs SET



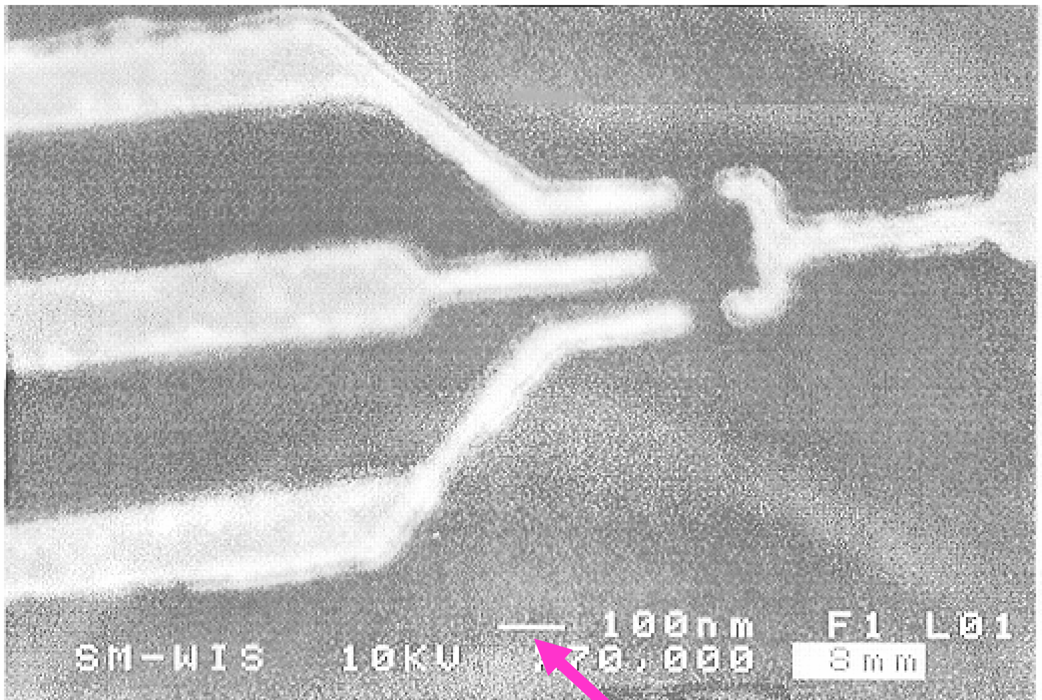
Electron Beam Lithography



Actual Process

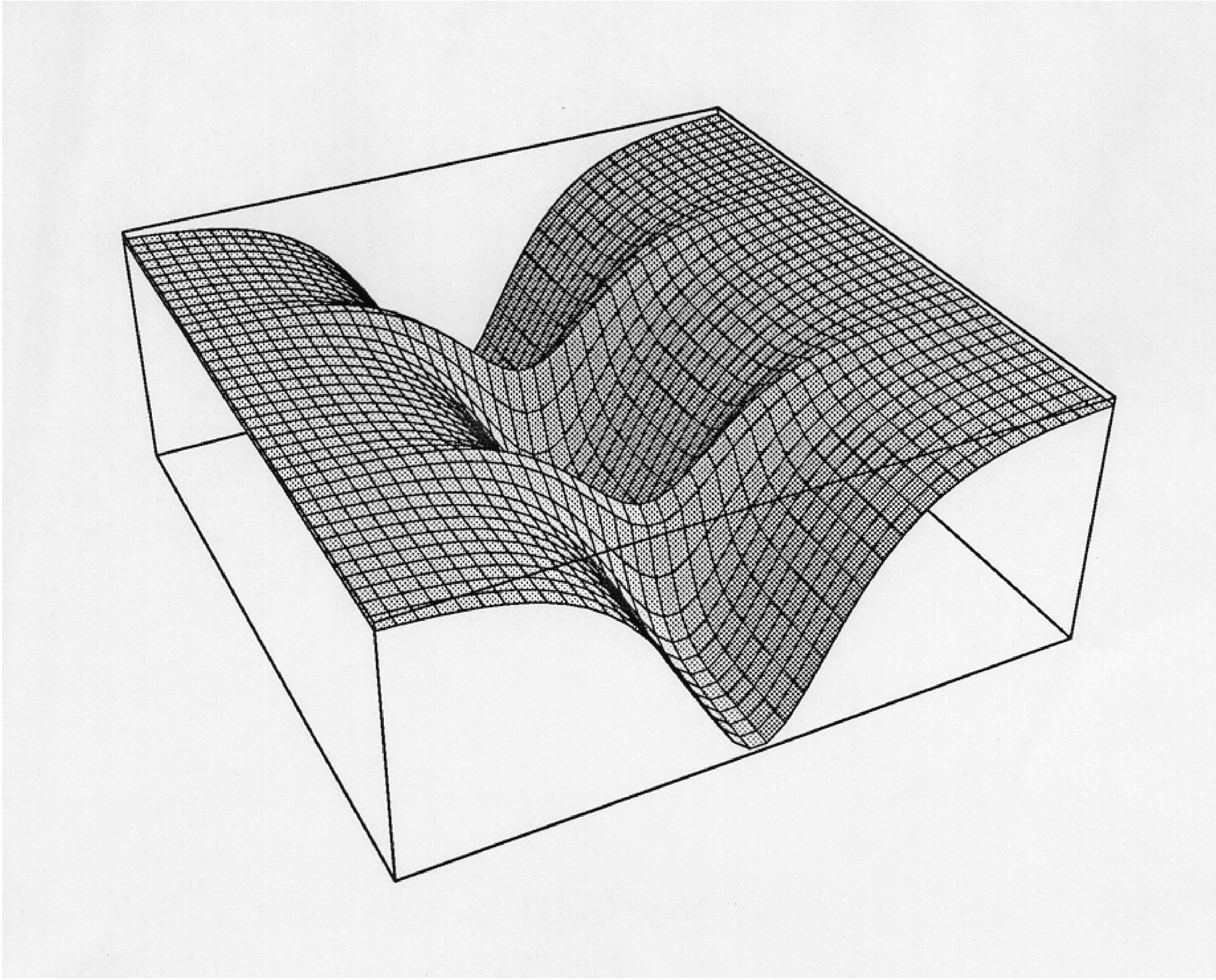


GaAs SET

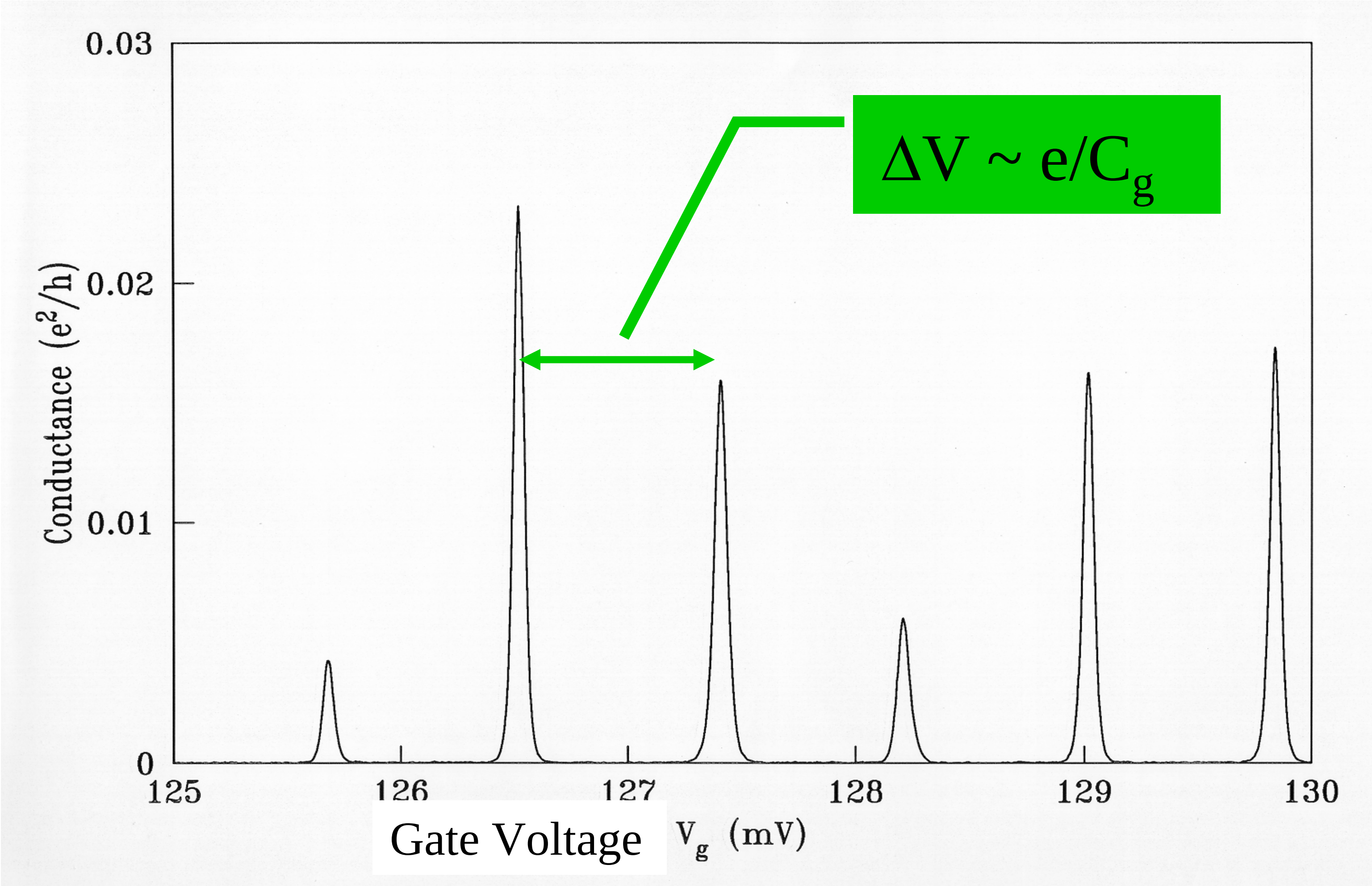


100nm = 1000Å

Schematic Potential in SET

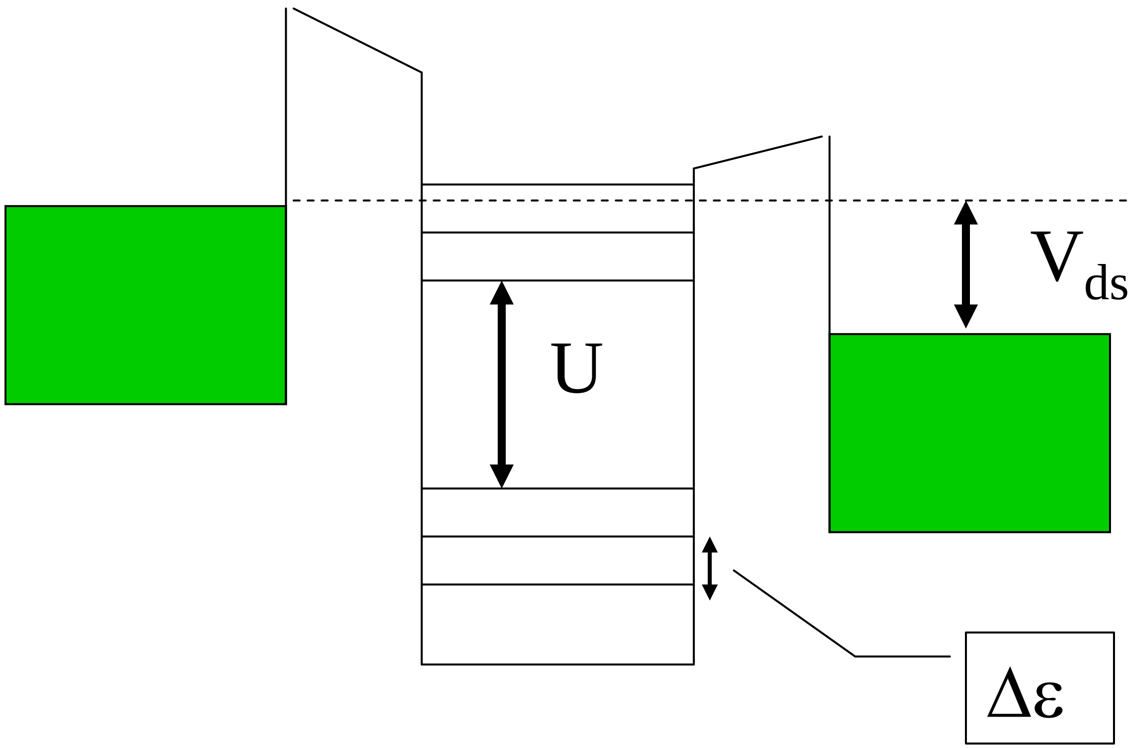


Coulomb Charging Peaks



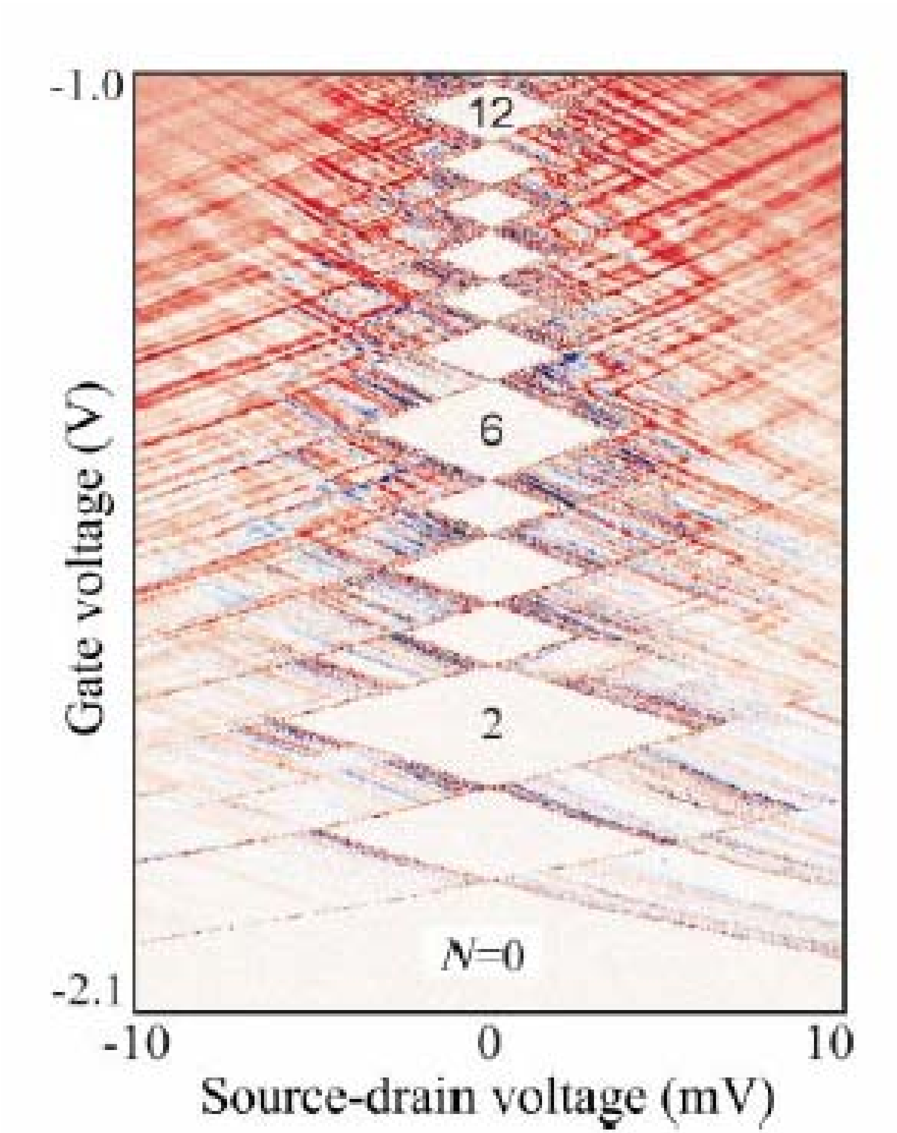
Note: Variation of peak height and spacing reflects individual levels.

Quantized Energy Levels



There is a peak in dI/dV_{sd} for every energy level. Although these have been detected in metal SET's it is hard because density of states is so large.

Excited State Spectroscopy



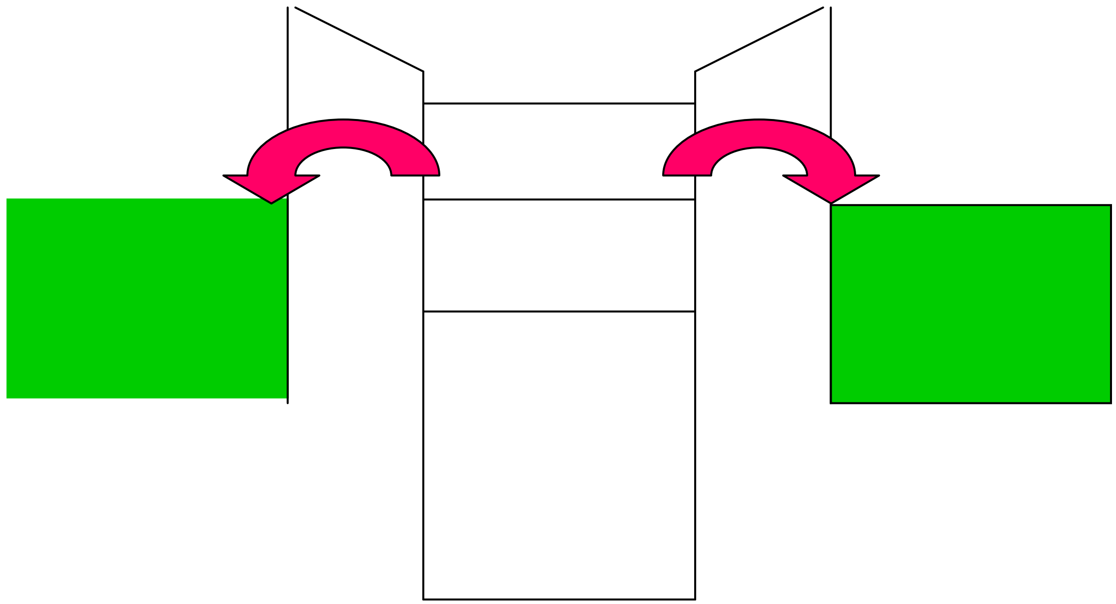
dI/dV_{sd} has peak when level crosses E_F

Very small dot ⇒ peaks no longer periodic along V_{sd} = 0

Electron interactions are more complicated than just U and involve exchange.

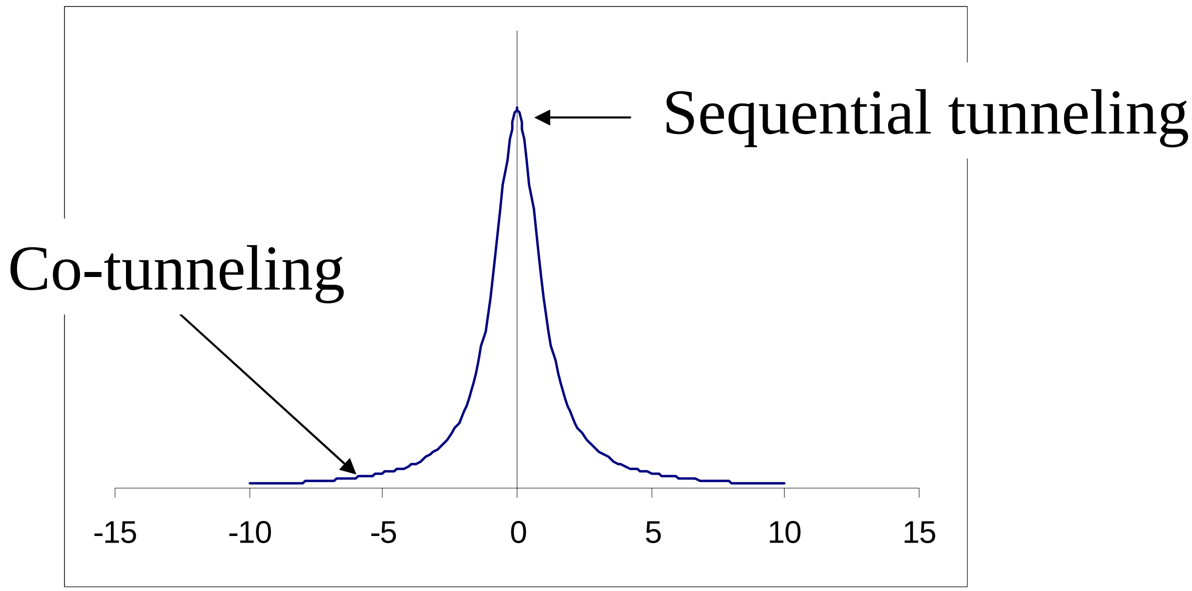
Kouwenhoven et al
Science **278**, 1788, 1997

Lifetime Broadening



Probability of electron remaining in a level on the dot decays as exp(-t/τ), so the level broadens into a Lorentzian with energy width $\Gamma = h/\tau$

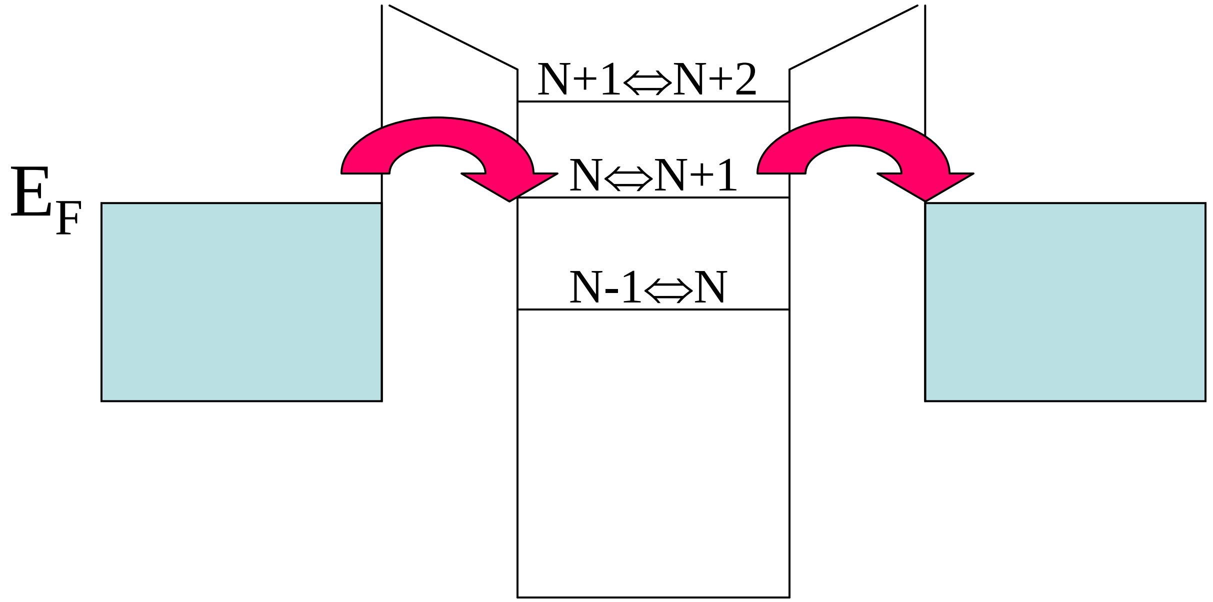
Lorentzian Line Shape of Peaks vs Gate Voltage



$2\mu/\Gamma$

The chemical potential μ is proportional to the gate voltage. The full width at half maximum is Γ. $\tau = h\Gamma^{-1}$ is the time for the electron to tunnel off.

Temperature



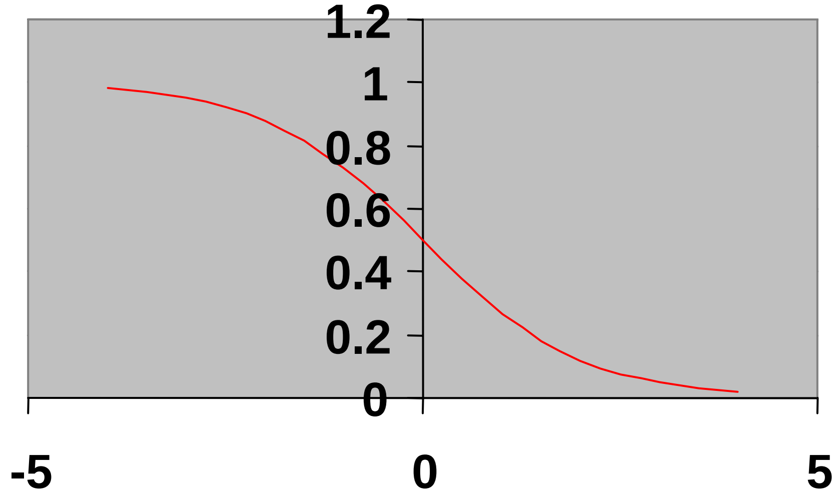
$$I \sim \int T(E)[f(E)-f(E-eV_{sd})]dE \qquad f(E) = \frac{1}{\exp[(E-E_F)/kT] + 1}$$

For resonant tunneling near zero bias, i.e. $eV_{sd} < kT$, if Γ is very small, $T(E) = \delta(E)$, $I = eV_{sd}\, df/dE$

Thermal Broadening

Fermi-Dirac
Distribution

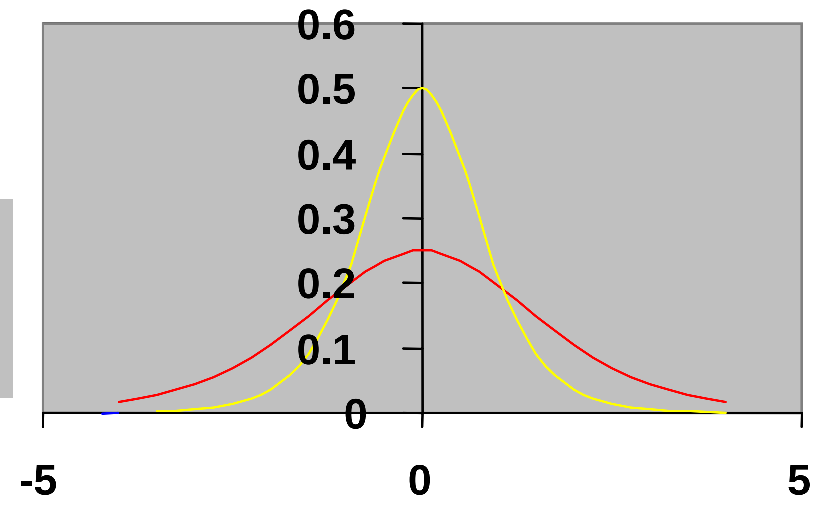
f(E)



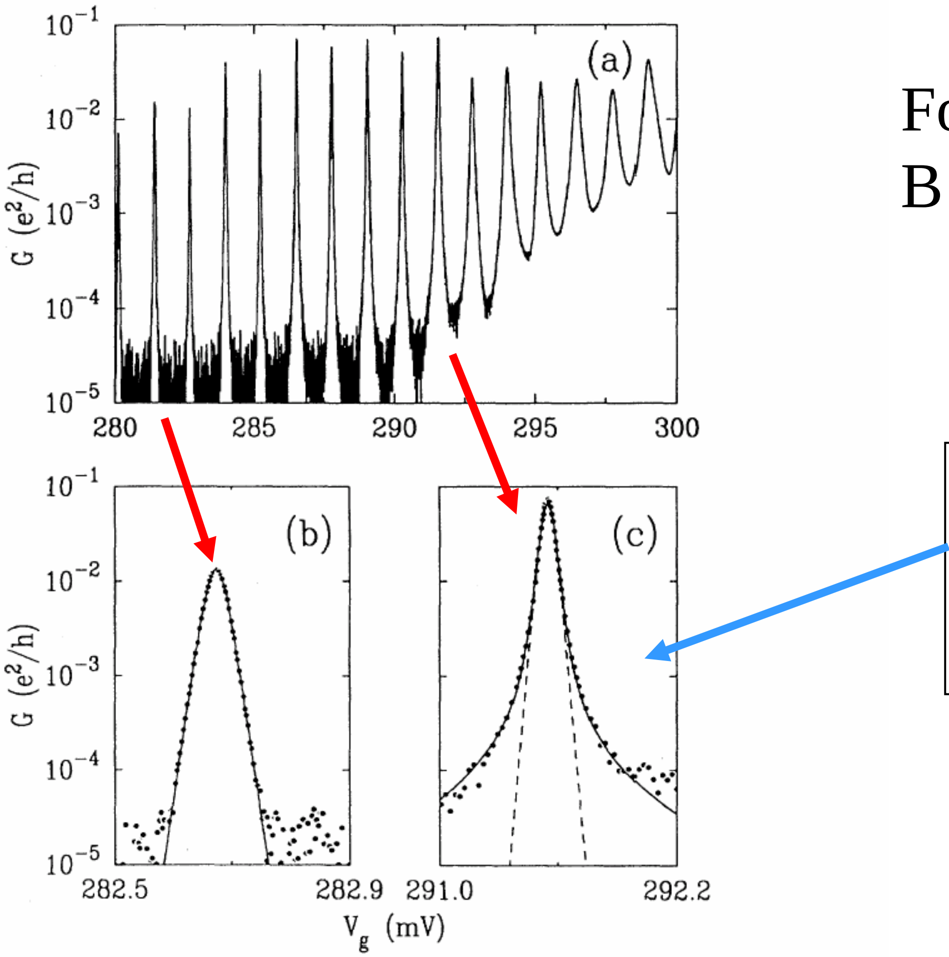
df/dE

Thermal broadening
gives width = 3.5kT
Height ~ 1/T

kT = 0.5
kT =1



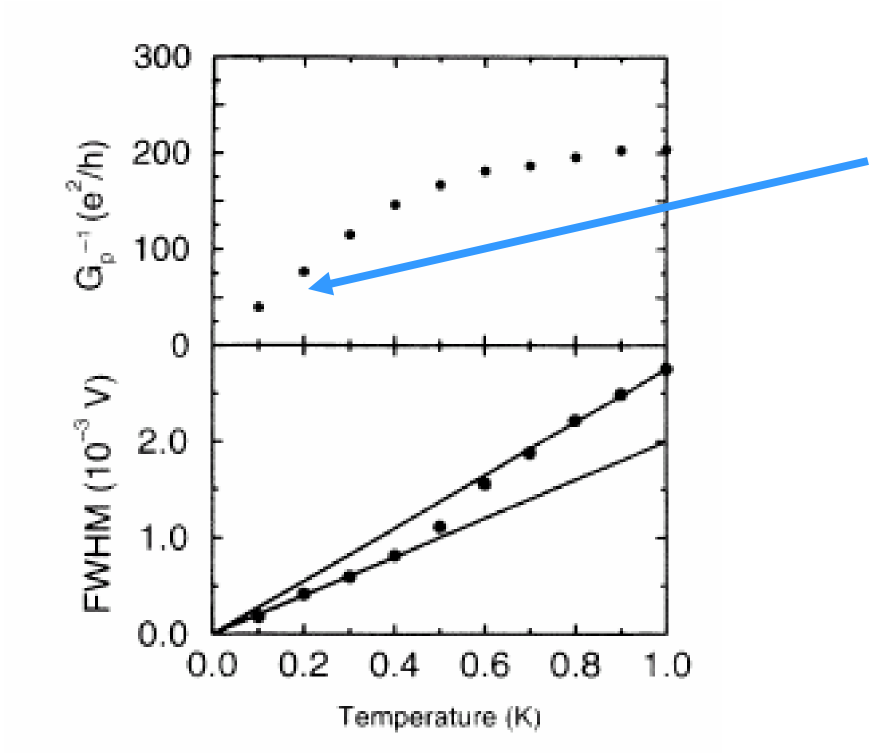
Thermal and Intrinsic Broadening



Foxman et al. Phys. Rev B 47, 10020 (1992)

Dashed line from Fermi alone, solid includes Lorentzian

Absolute Thermometer



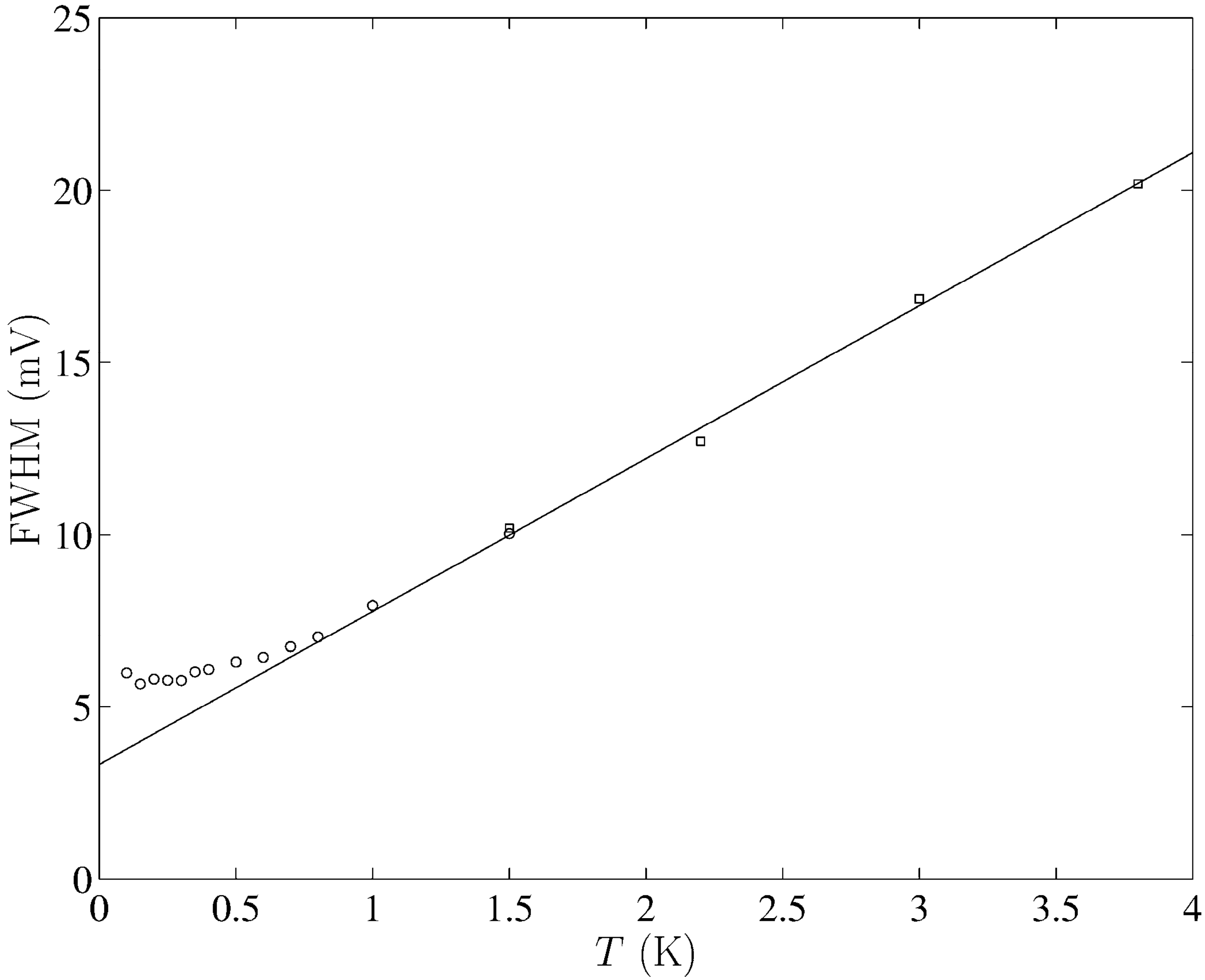
$1/G_p \sim T$

Full width at half max. ~ T

When kT > $\Delta\varepsilon$ the peak conductance becomes constant and the width changes slope slightly.

For thermometer application see Pekola et al. PRL **73**, 2903 (1994)

Determining Γ from peak width

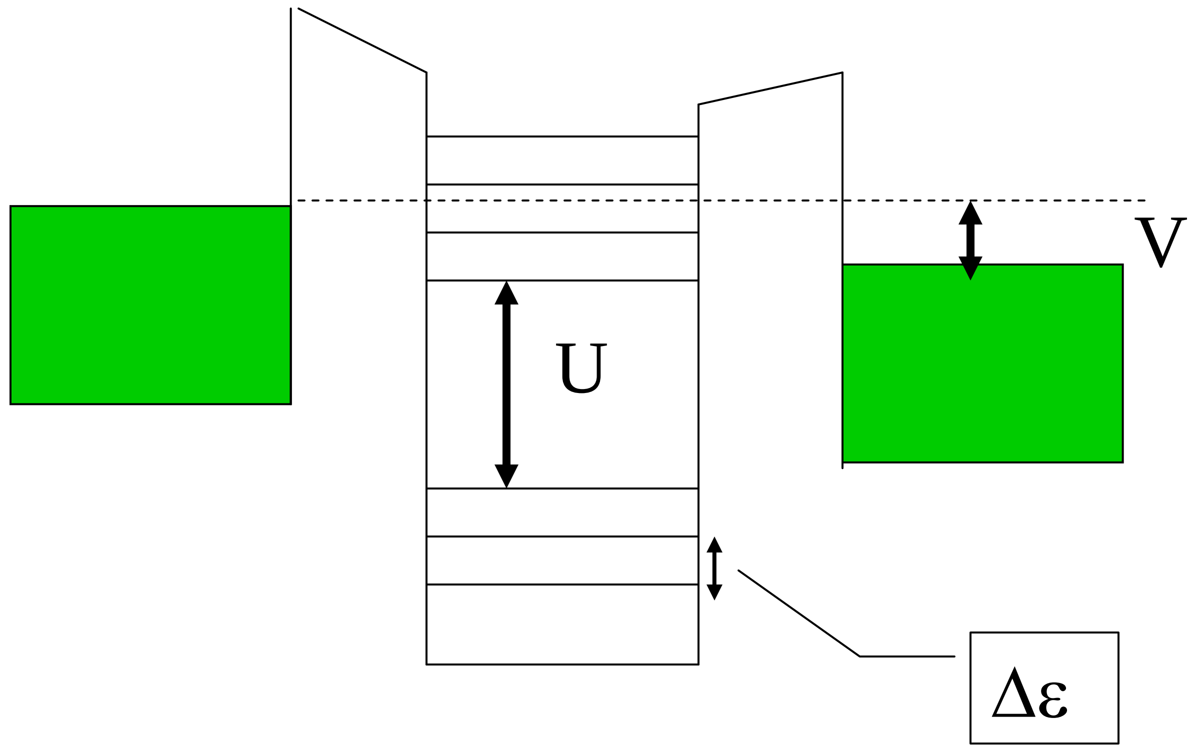


Slope gives conversion of voltage to energy.

T =0 intercept gives Γ

Note: in this case Γ/h~50GHz

Condition for Charge Quantization is Condition for Level Separation

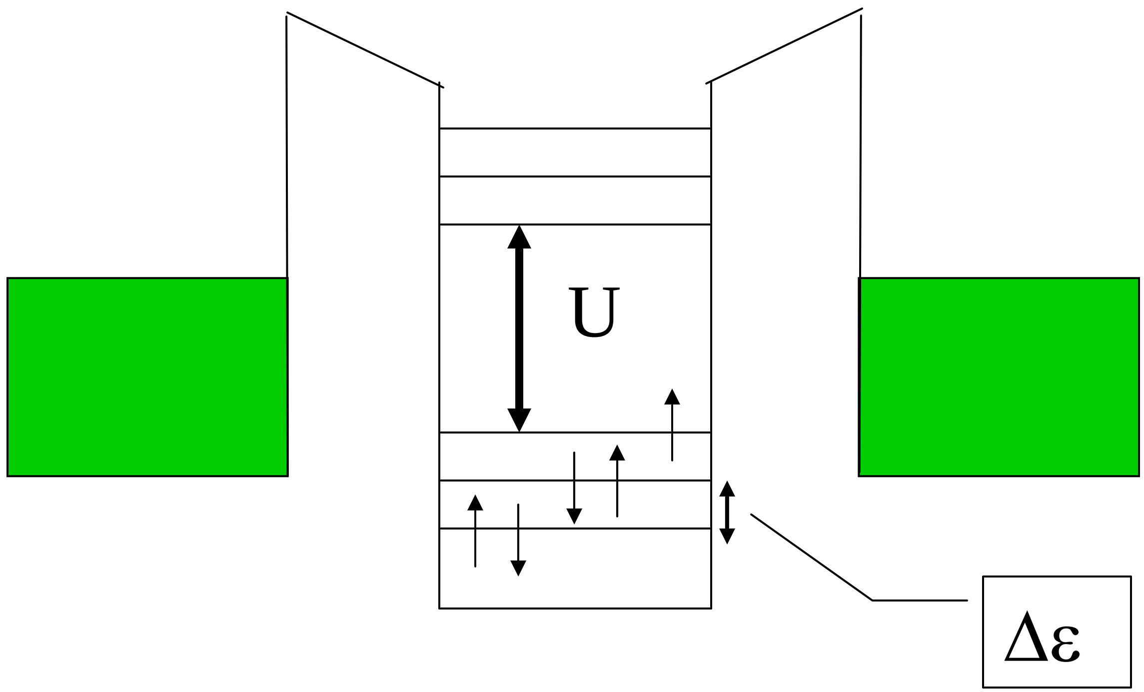


Above Coulomb gap, the current is $I = Ne/\tau$, $\tau = h\Gamma^{-1}$ and $N = eV/\Delta\varepsilon$

$$G = I/V = (e^2/h)(\Gamma / \Delta\varepsilon)$$

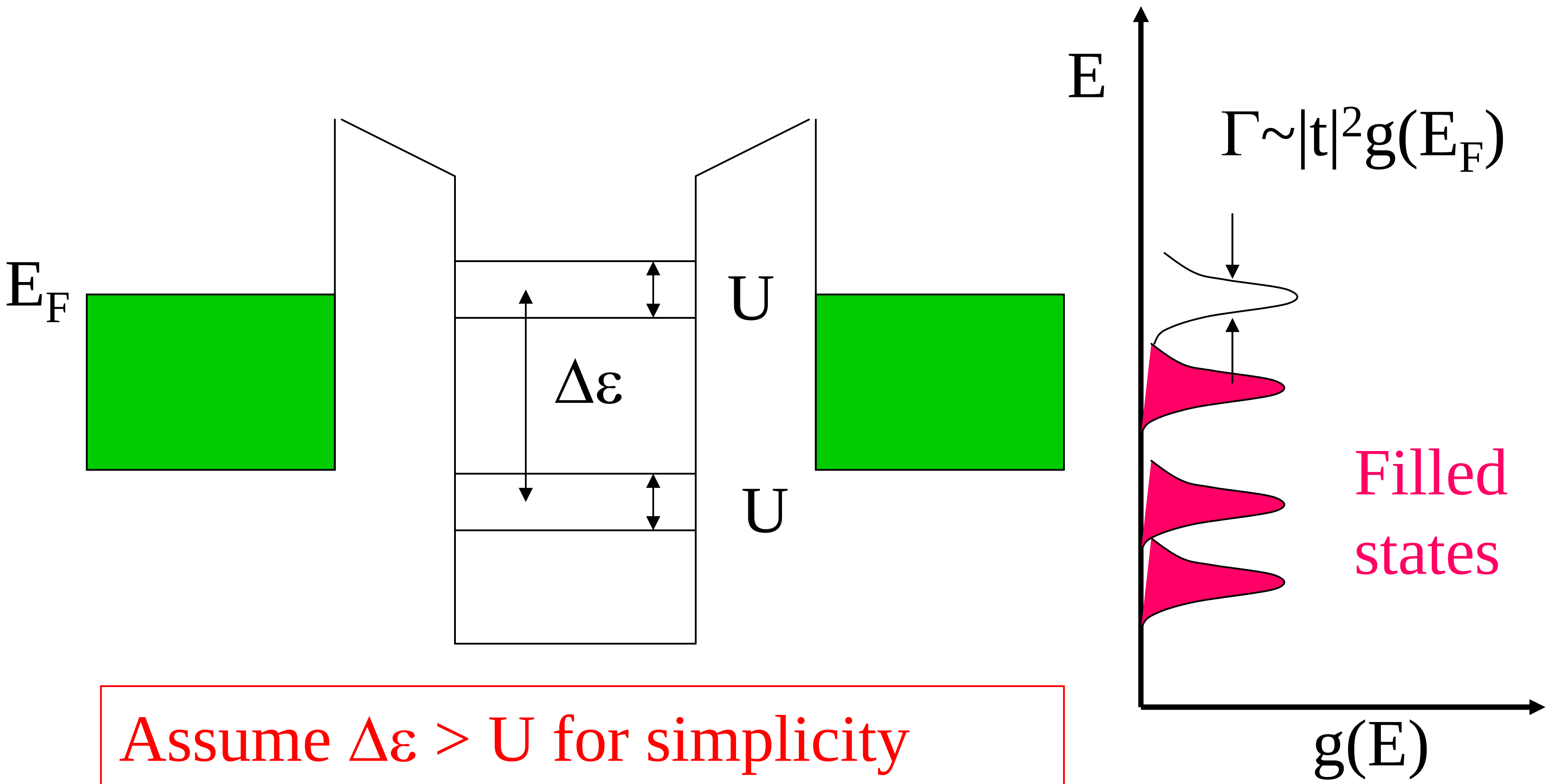
$$G < e^2/h \Rightarrow \Gamma > \Delta\varepsilon$$

Constant Interaction Model



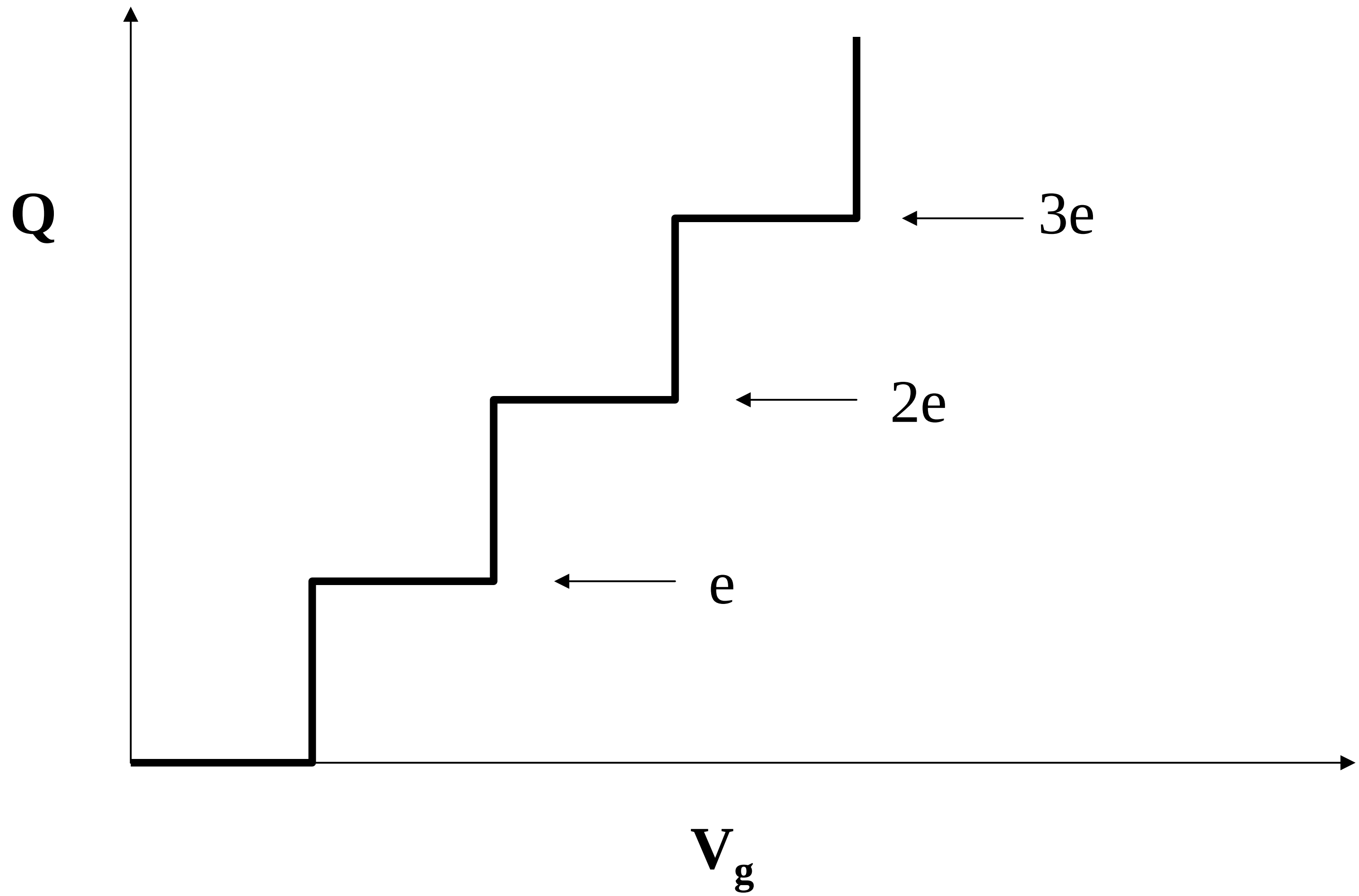
Ignore interactions among electrons on artificial atom.
States fill two at a time.
Actually more complicated, but it is a useful starting point.

Energy Scales in SET

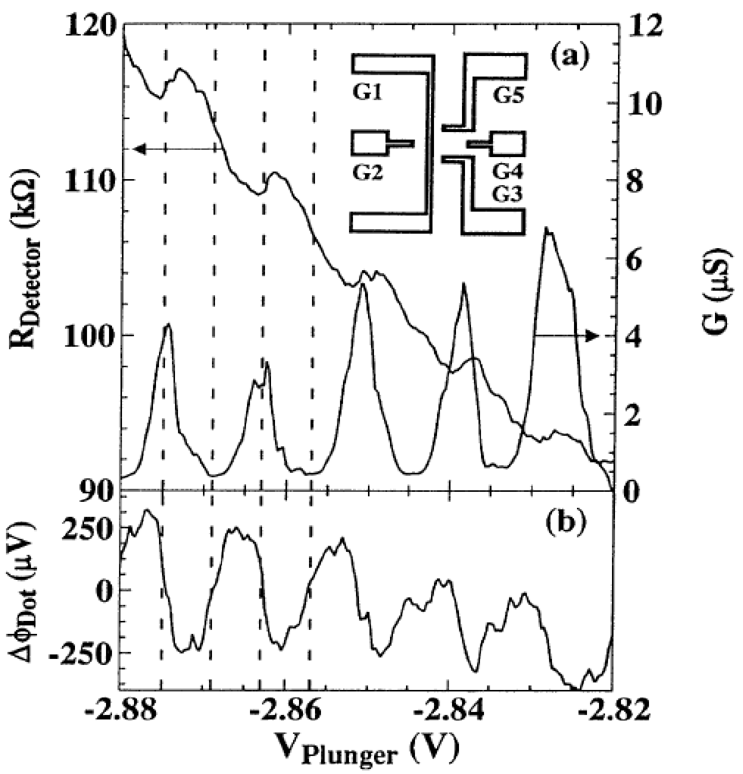


Assume Δε > U for simplicity
t is the hopping matrix element
between dot and leads

Charge Quantization

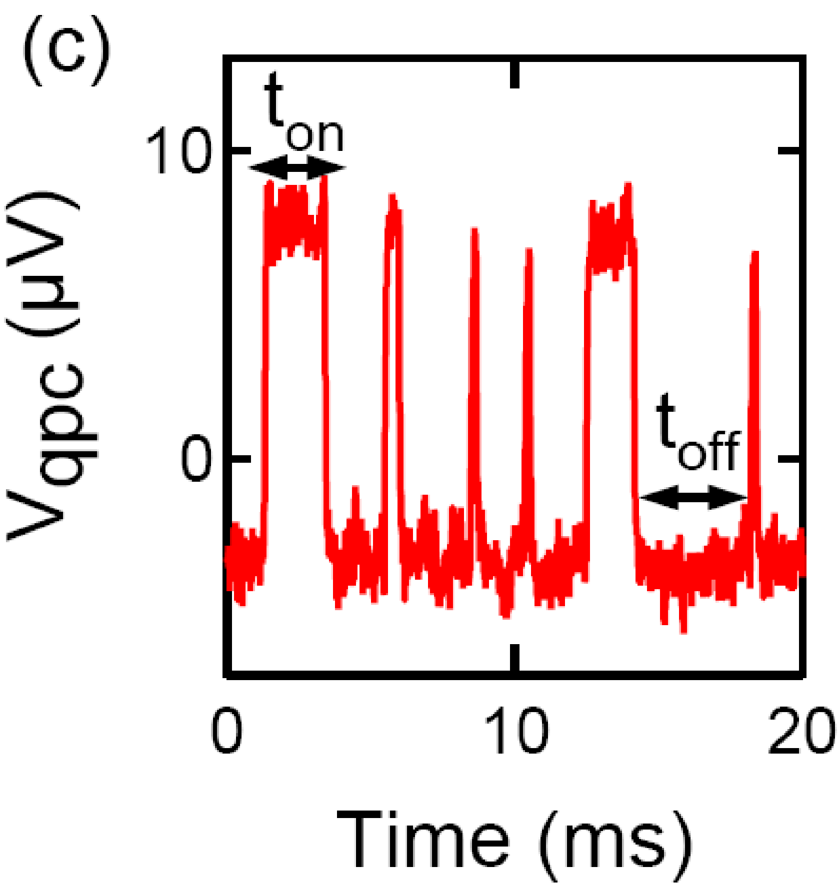


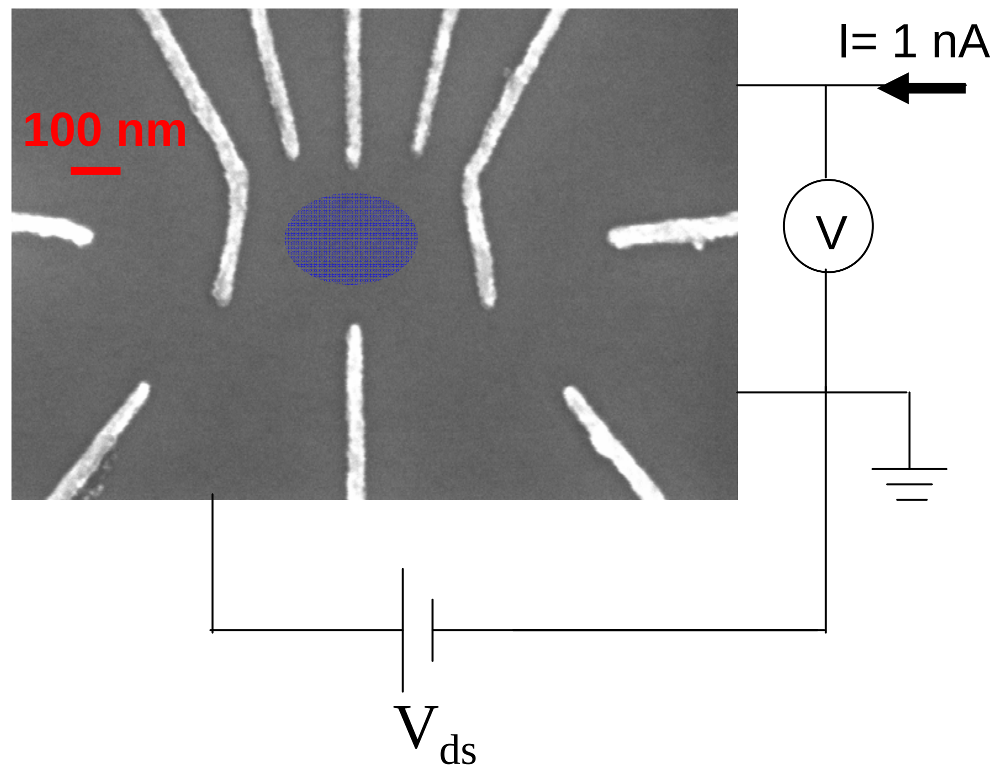
Measuring Charge



Field et al PRL **70** 1311 (1993)

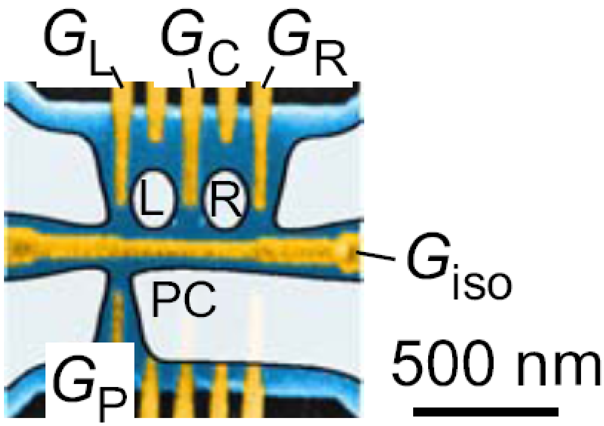
Measuring Very Small Γ



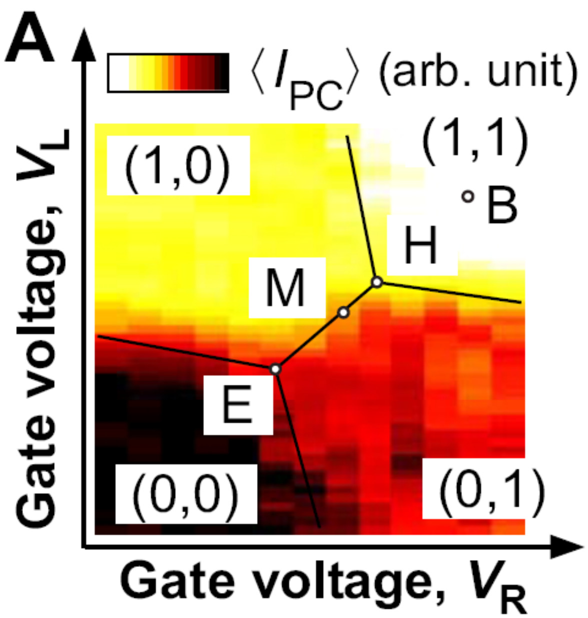


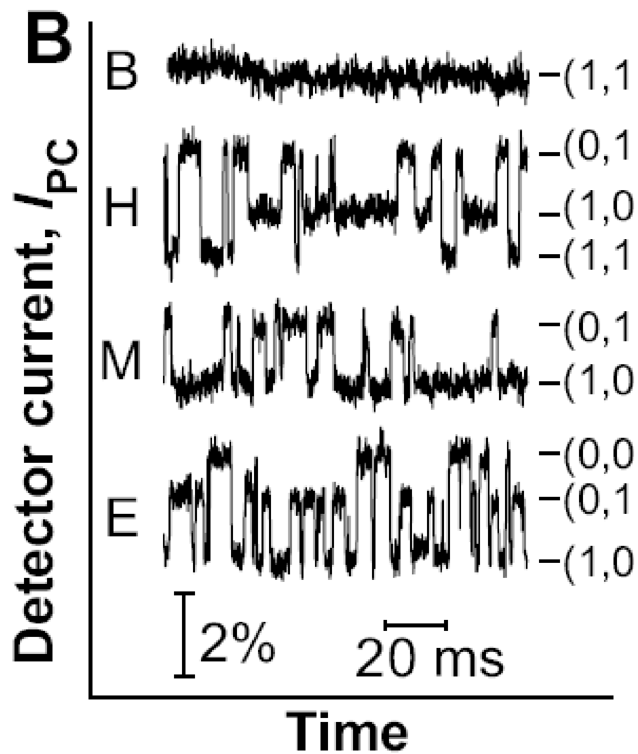
Γ/h can be measured from 10-1000 Hz, compared to 10-50 GHz from peak shapes

Measuring Electron Statistics

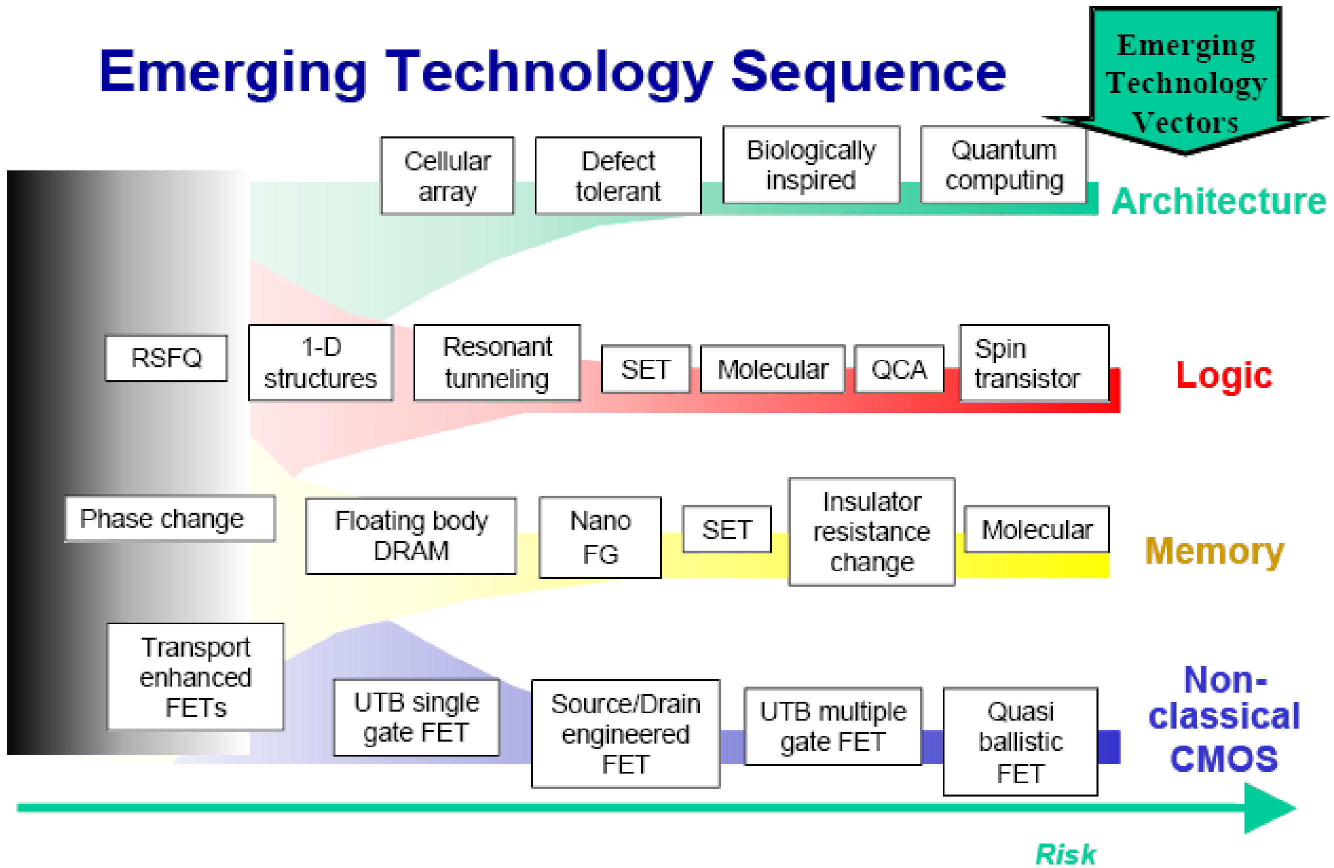


Fujisawa et al Science 312, 1634 (2006)

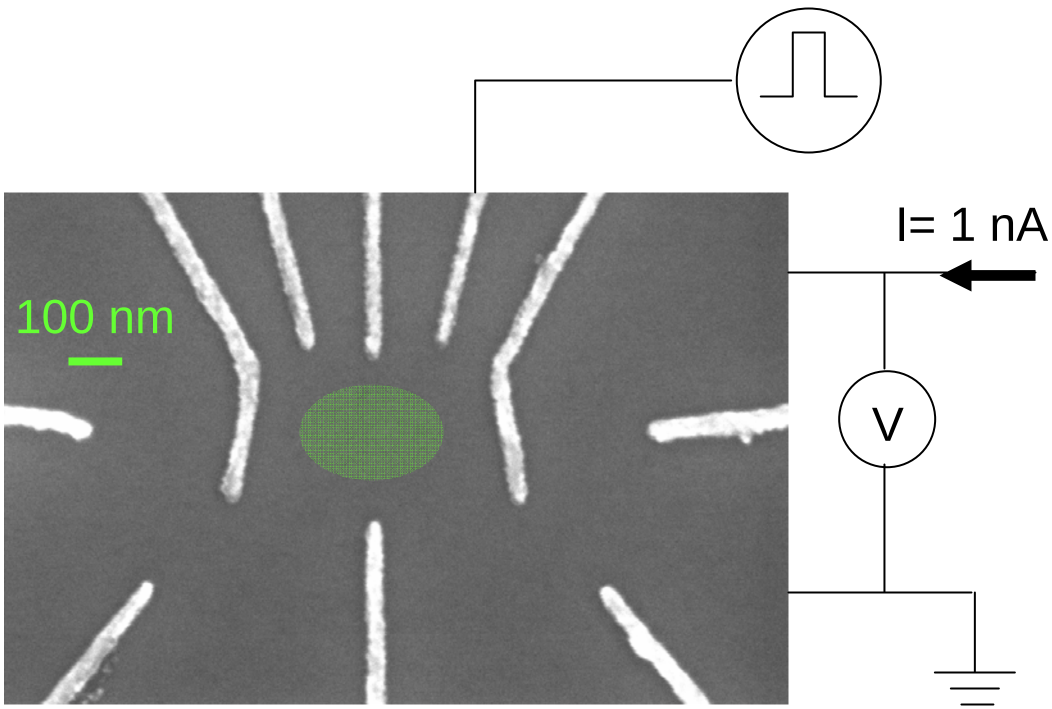




International Semiconductor Roadmap 2003



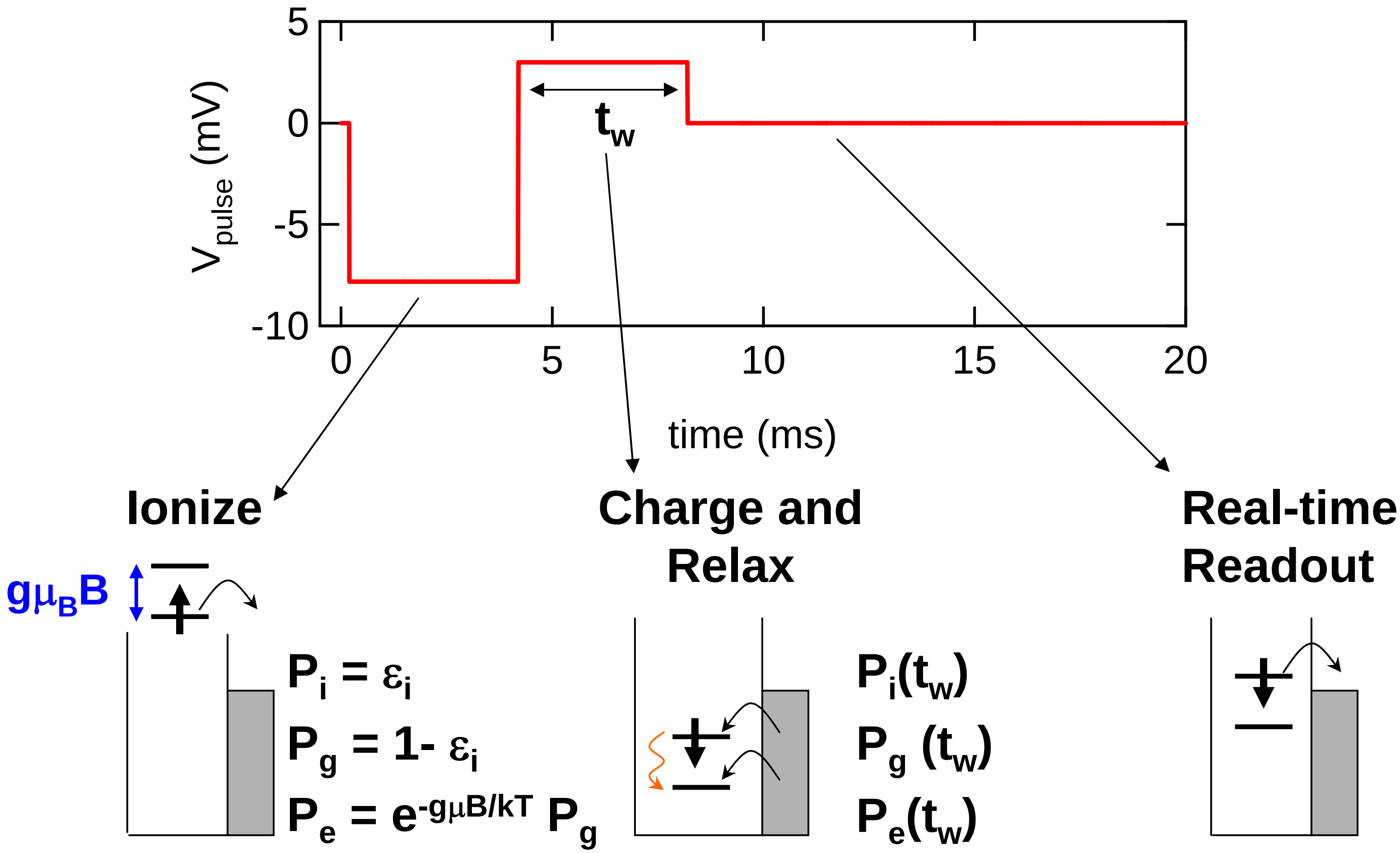
Measuring Spin Orbit Relaxation of Single Spin



1. Load one electron
2. Adjust chemical potential so only the higher energy spin state can be ionized

Pulse Sequence

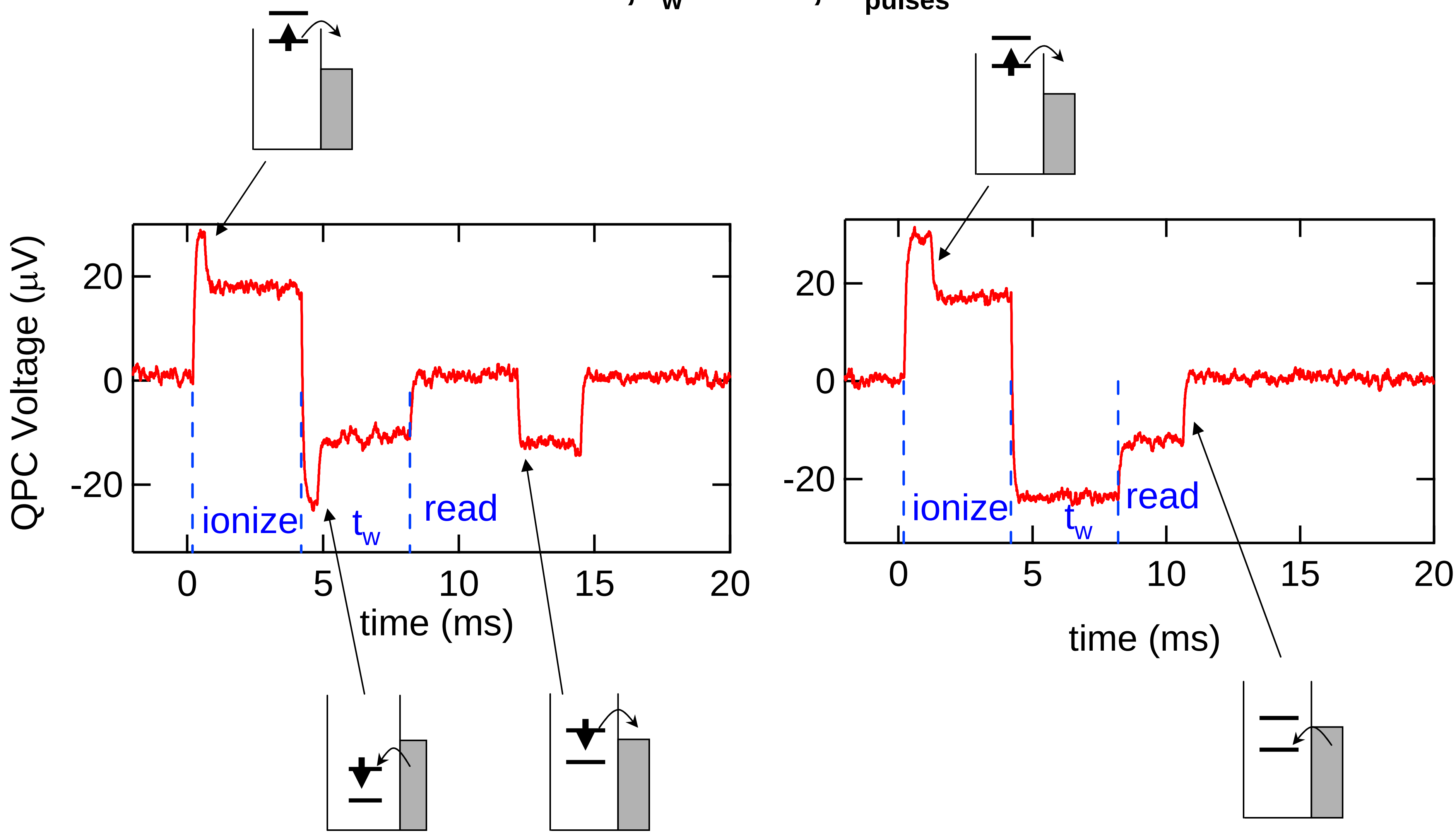
Fujisawa, *et al.*, Physical B **298**, 573 (2001)
Hanson, *et al.*, PRL **91**, 196802 (2003)
Elzerman, *et al.*, Nature **430**, 431 (2004)



$P_e(t_w)$ gives $W \equiv 1/T_1$

Real-Time Readout

B= 2.5 T, t_w= 4 ms, N_{pulses}= 14300

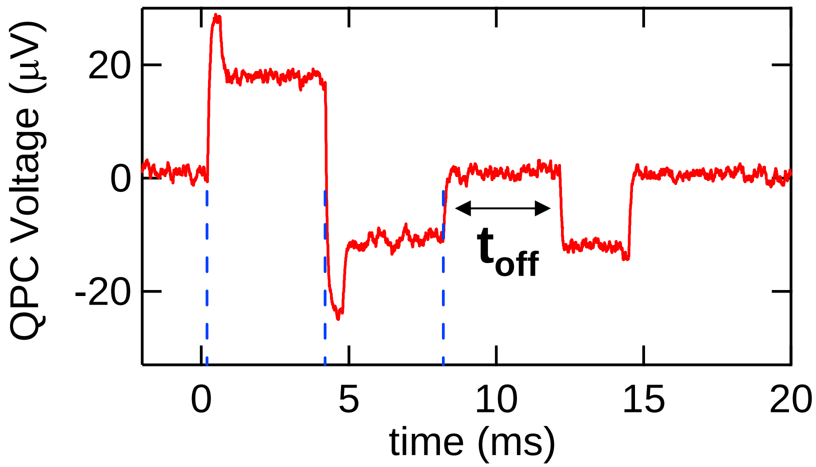


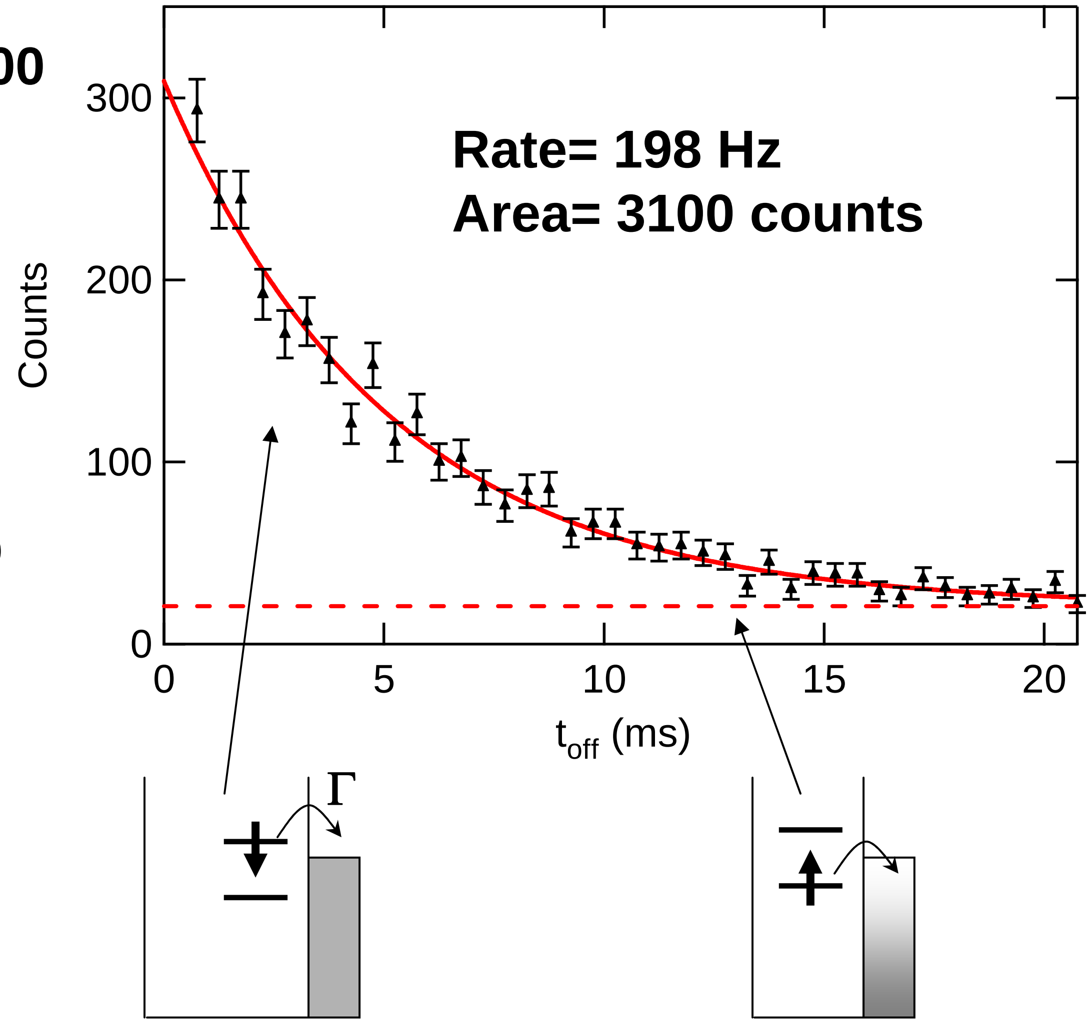
Electron tunnels from excited state

Electron tunnels into empty dot

Measuring $P_e(t_w)$

B= 2.5 T, t_w= 4 ms, N_{pulses}= 14300





Electron tunnels from excited state

Thermally activated tunneling from ground state

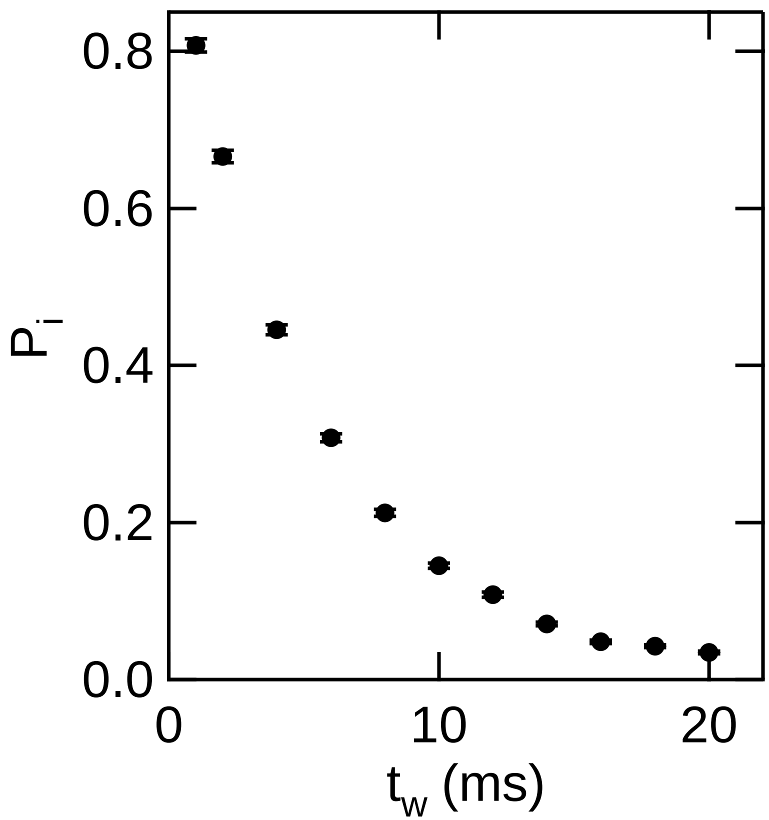
For $\Gamma \gg W$:

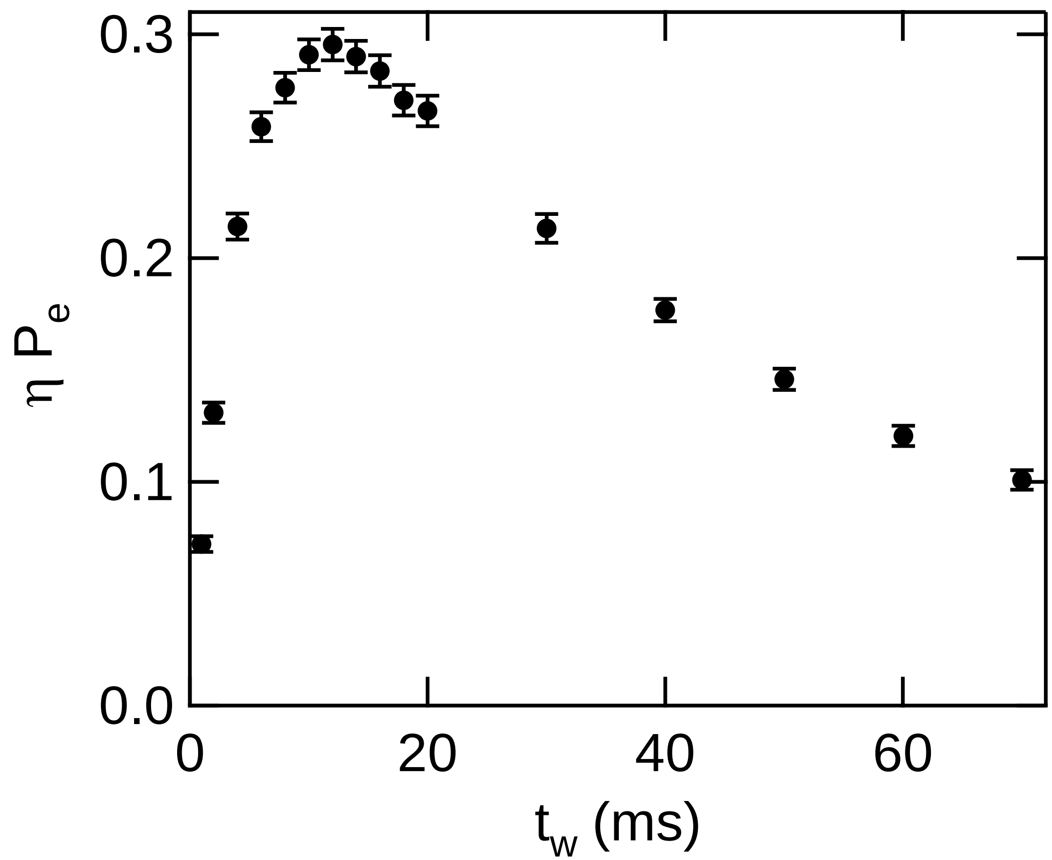
Rate = Γ
Area = $N_e(t_w)$

$P_e(t_w) = N_e(t_w) / N_{pulses}$

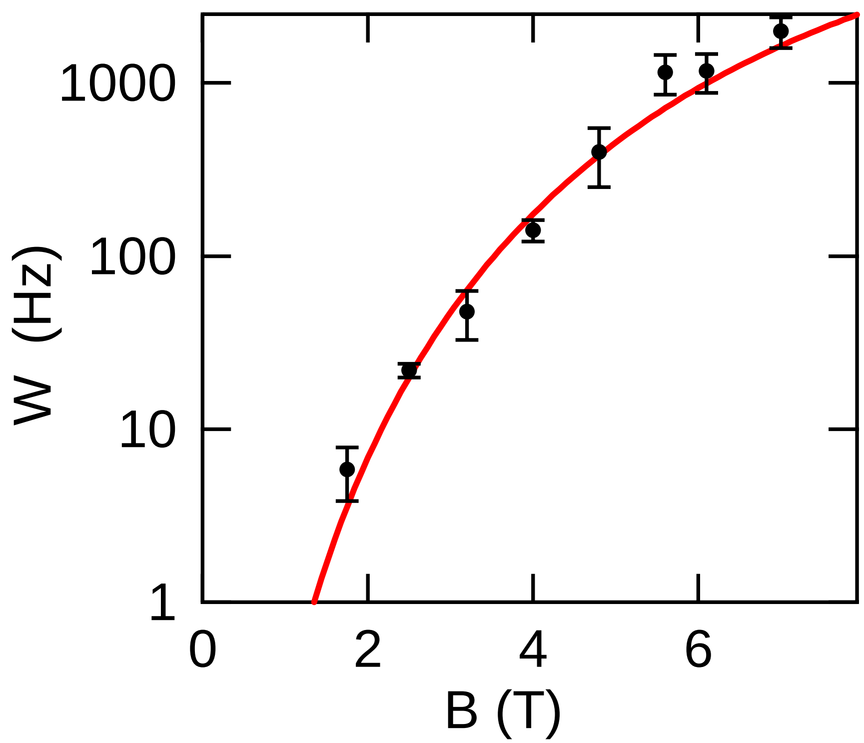
$P_i(t_w)$ and $P_e(t_w)$

B= 2.5 T





Theory vs Experiment



Theory:
Golovach, *et al.*
PRL, **93** 016601
(2004)