

Charge Amplification Nearing the Quantum Limit

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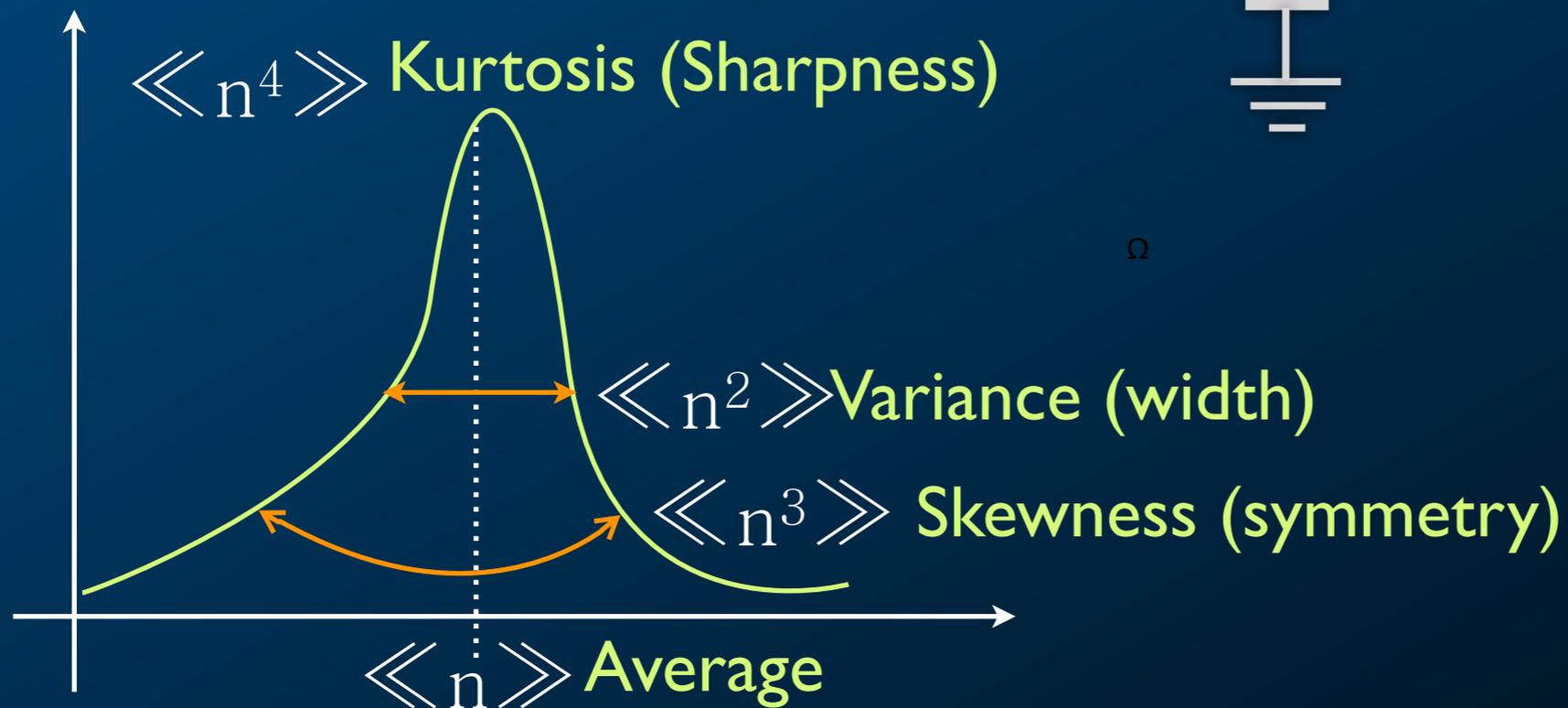


Established by Govt. of India in 2008

I-V measurements: time-averaged

Conventional transport

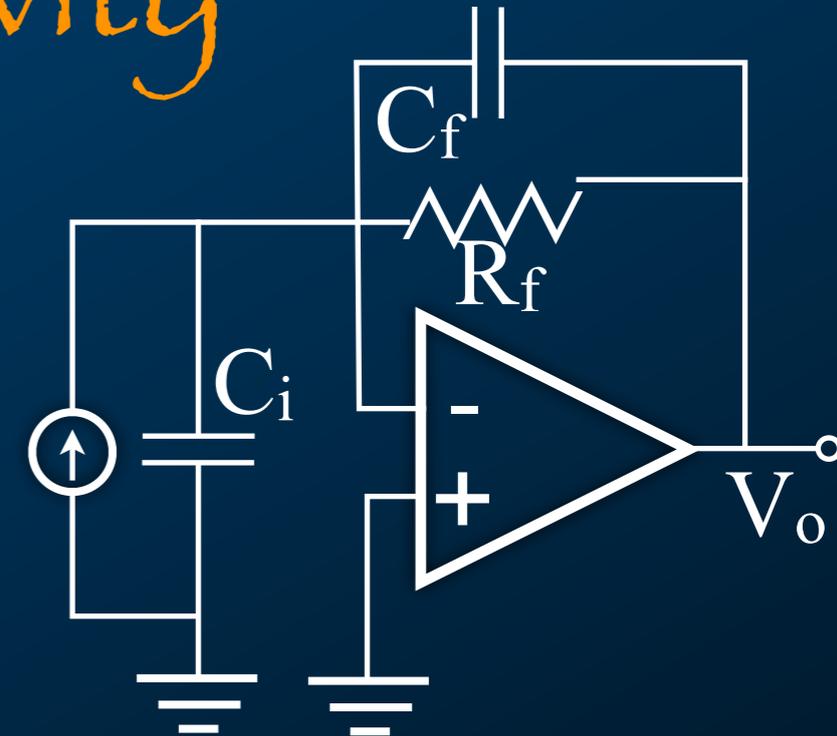
Average number of electrons transported.



Higher cumulants carry information regarding the electron-electron correlations and other interactions

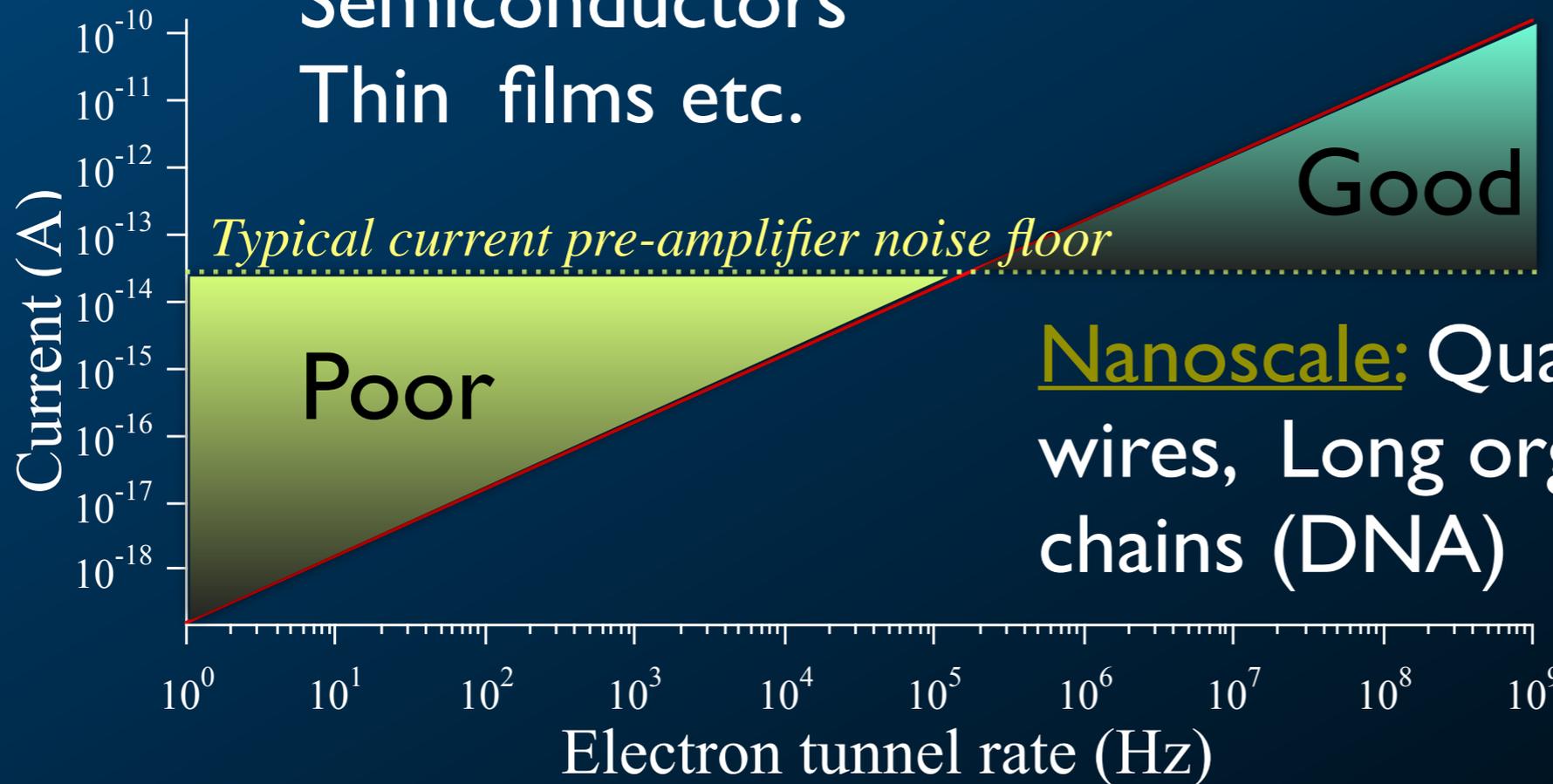
I-V measurements: sensitivity

Current levels are generally in the sub Pico Ampere to sub Femto Ampere range



Bulk:

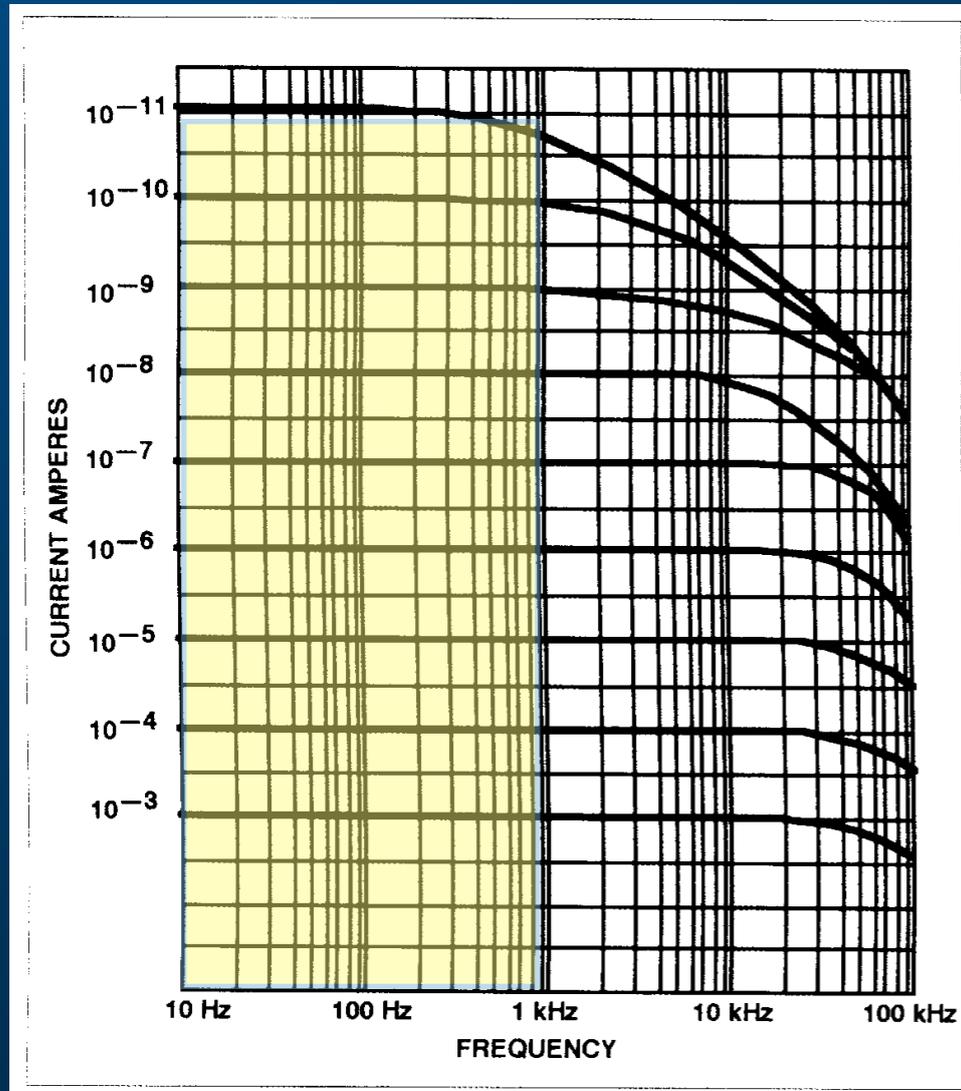
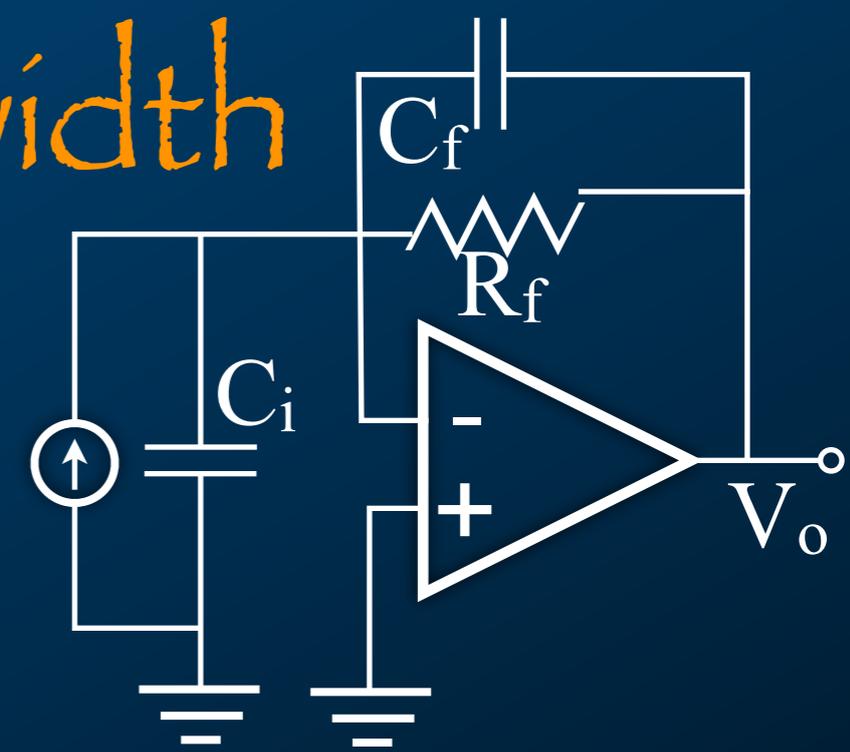
Semiconductors
Thin films etc.



Nanoscale: Quantum dots, Nano wires, Long organic conducting chains (DNA)

Not suitable for systems with low tunnel rate

I-V measurements: bandwidth limitations



NOISE PERFORMANCE, REFERRED TO INPUT ³

Sensitivity A/V	Limited BW Noise at Indicated Rise Time Setting ⁴		Min. Rise Time Full BW Noise ⁴ A rms	Spectral Noise Density A rms/√Hz
	A rms	Msec		
10 ⁻³	20 x 10 ⁻⁹	.1	50 x 10 ⁻⁹	75 x 10 ⁻¹²
10 ⁻⁴	2 x 10 ⁻⁹	.1	5 x 10 ⁻⁹	7.5 x 10 ⁻¹²
10 ⁻⁵	200 x 10 ⁻¹²	.1	500 x 10 ⁻¹²	1 x 10 ⁻¹²
10 ⁻⁶	30 x 10 ⁻¹²	.1	150 x 10 ⁻¹²	200 x 10 ⁻¹⁵
10 ⁻⁷	8 x 10 ⁻¹²	.1	40 x 10 ⁻¹²	60 x 10 ⁻¹⁵
10 ⁻⁸	700 X 10 ⁻¹⁵	1	15 x 10 ⁻¹²	15 x 10 ⁻¹⁵
10 ⁻⁹	60 x 10 ⁻¹⁵	1	3 x 10 ⁻¹²	5 x 10 ⁻¹⁵
10 ⁻¹⁰	4 x 10 ⁻¹⁵	10	600 x 10 ⁻¹⁵	2.5 x 10 ⁻¹⁵
10 ⁻¹¹	1 x 10 ⁻¹⁵	300	150 x 10 ⁻¹⁵	1.5 x 10 ⁻¹⁵

Bandwidth X Gain = Constant

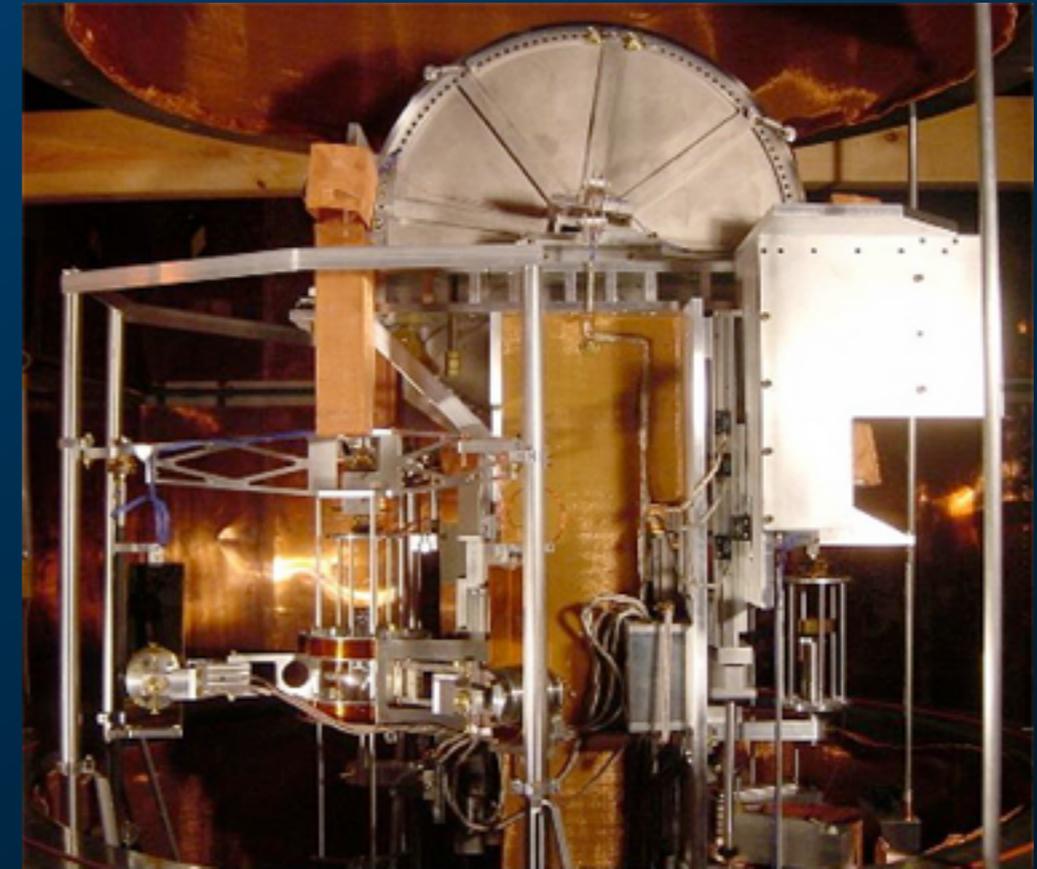
For nA/V Gain ~ 1 kHz, 3 ms events

Lower frequencies, $1/f$ contribution is significant

Ampere from Kilogram

Watt balance

“The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length”



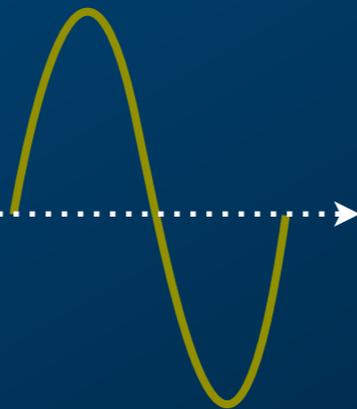
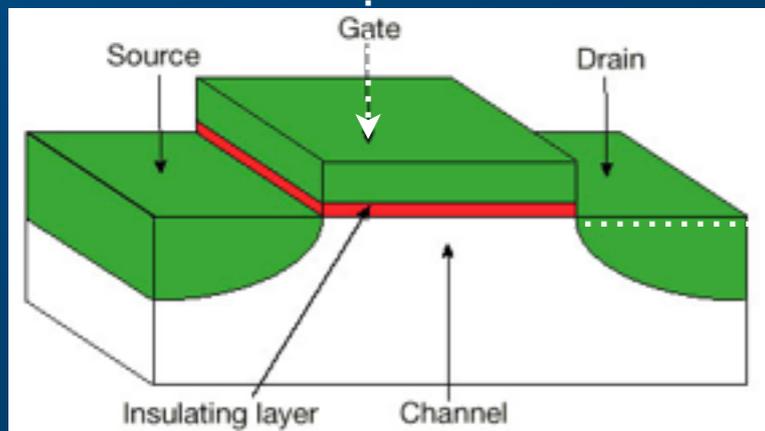
Ampere from
electron counting
 6.24×10^9 GHz

Kilogram in terms
of fundamental
constants

Bureau International des Poids et Mesures,
The international system of units (SI), 8th
Edition, 2006

Field effect transistors

$$V_g = \delta q / C_g$$



$$\delta q = 0.01 e / \text{Hz}^{1/2}$$

Cryogenic field-effect transistor with single electronic charge sensitivity

D. J. Mar and R. M. Westervelt

*Division of Applied Sciences and Department of Physics, Harvard University,
Cambridge, Massachusetts 02138*

P. F. Hopkins

Materials Department, University of California, Santa Barbara, California 93106

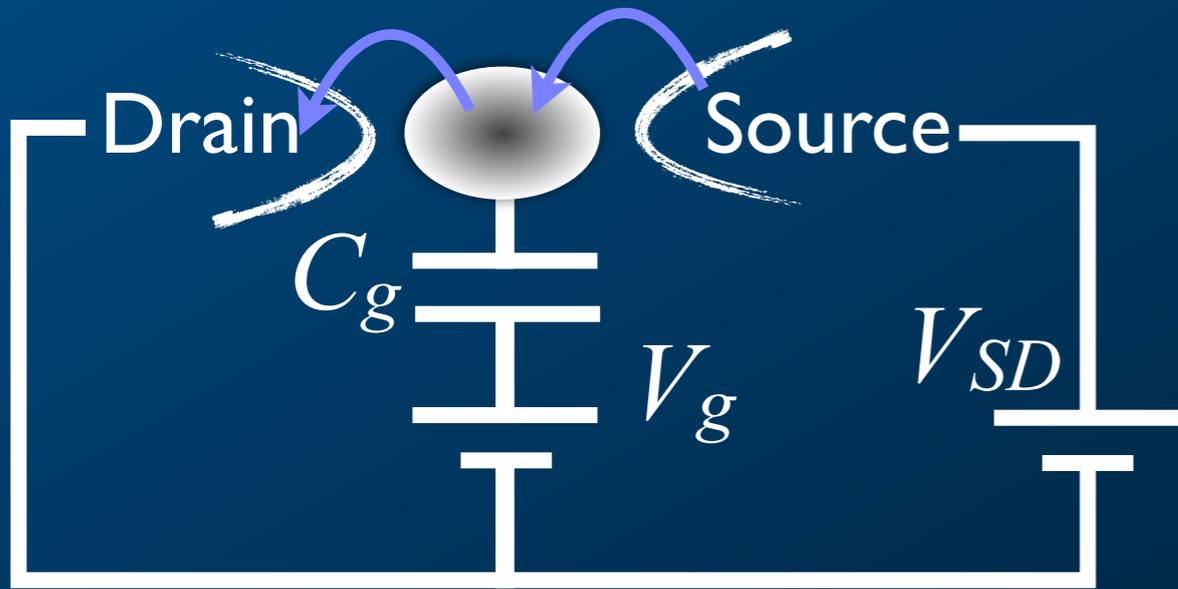
(Received 19 July 1993; accepted for publication 5 November 1993)

Best sensitivity of **one electron** in a band width of **100 Hz**

Mesoscopic cousin of FET is SET

Single electron transistor (SET)

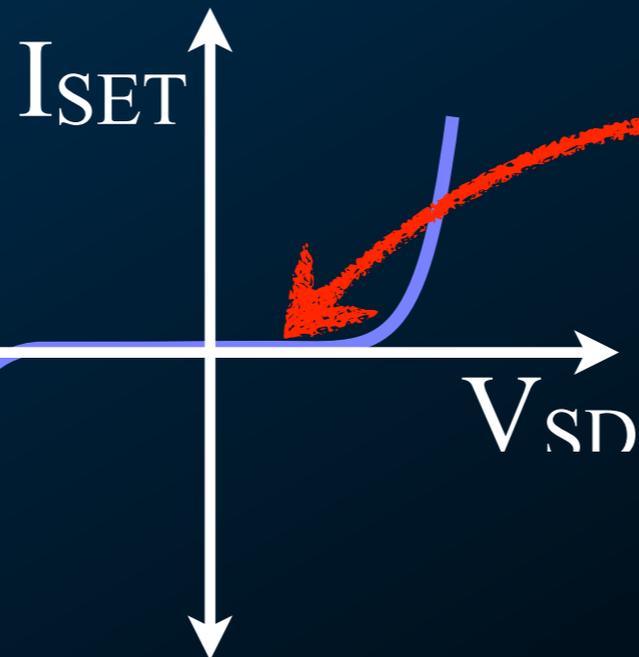
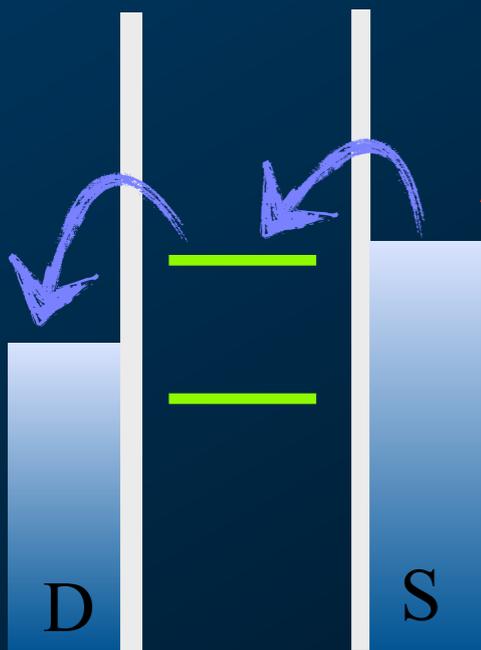
SET: Quantum dot with source and drain



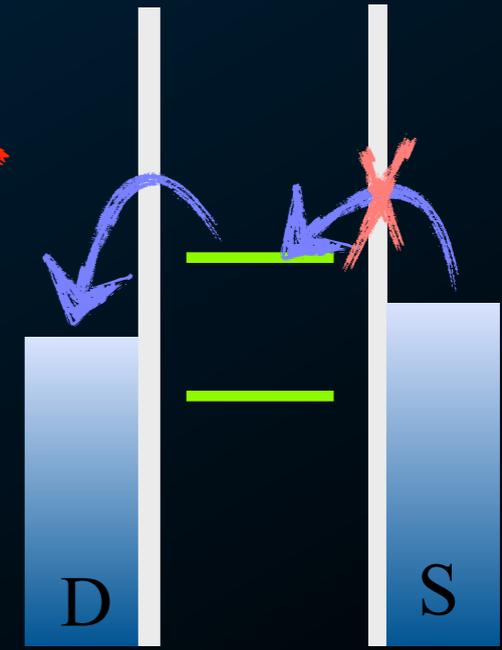
Charging energy, $E_C = e^2/2C_\Sigma$

One electron at a time

Transport

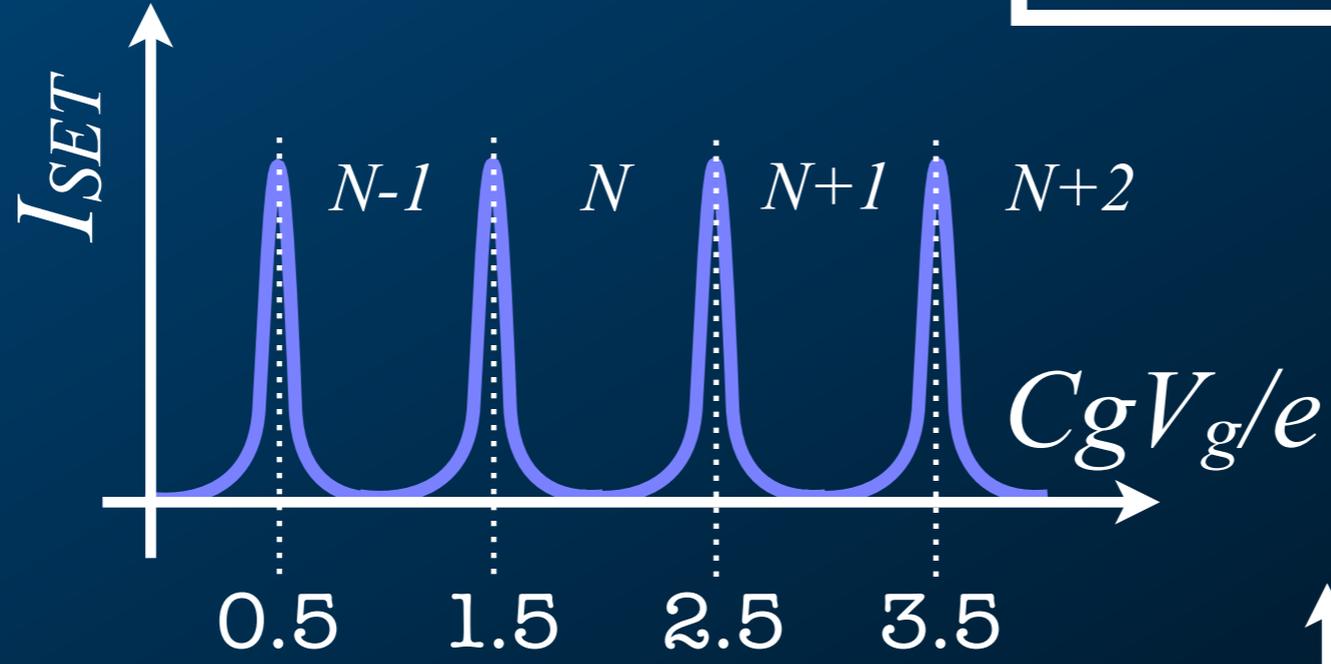
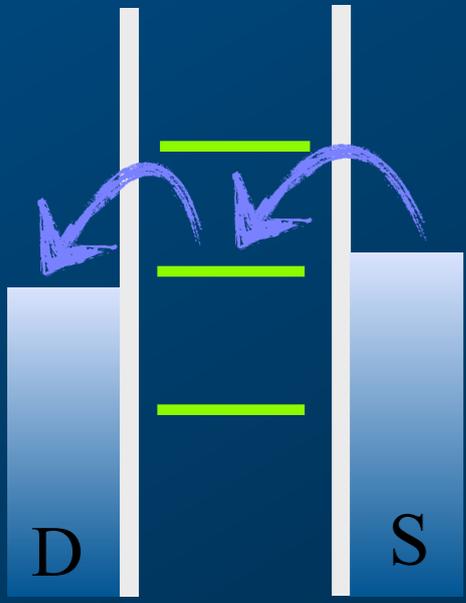
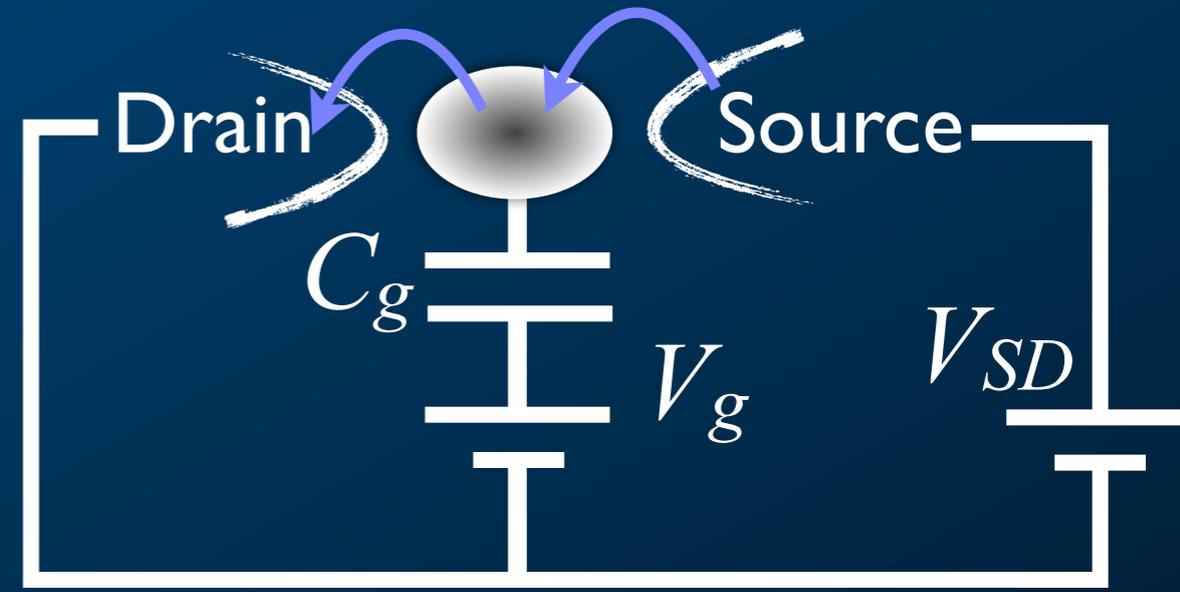


Coulomb blockade



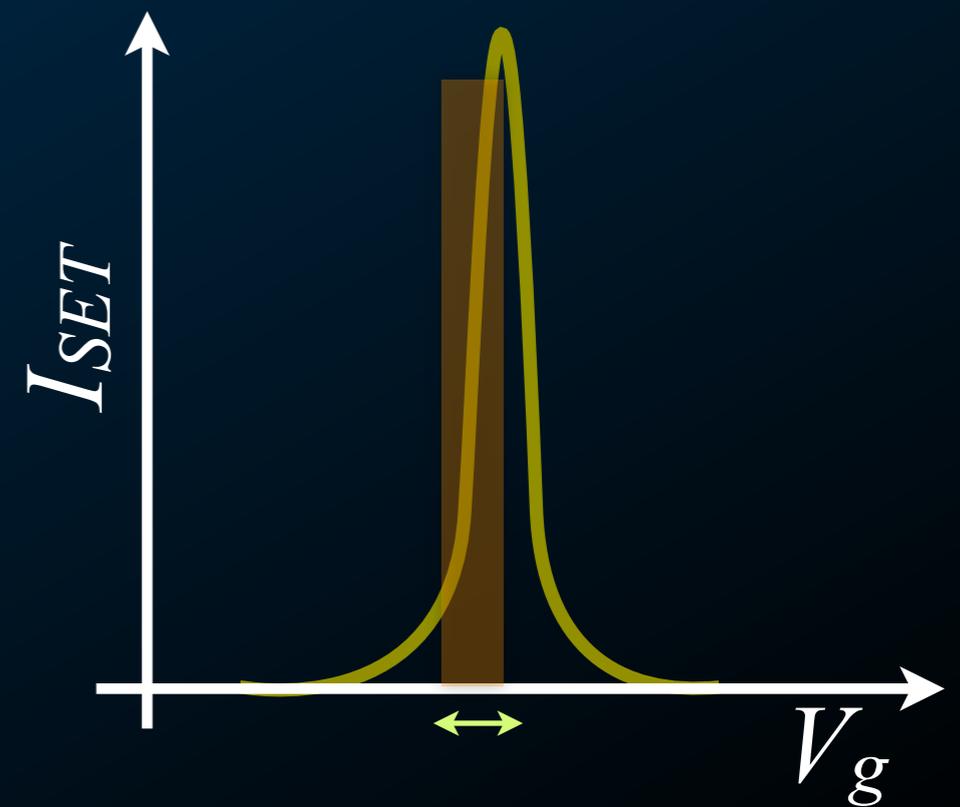
SET charge amplifier

Coulomb blockade oscillations

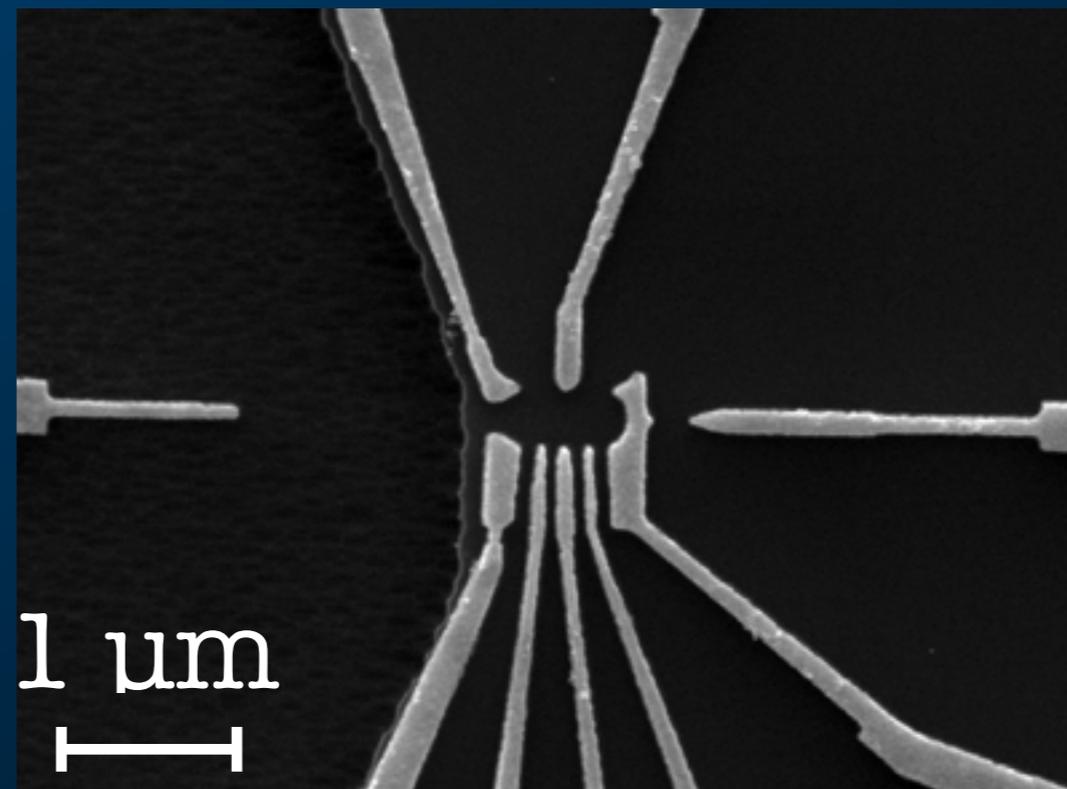
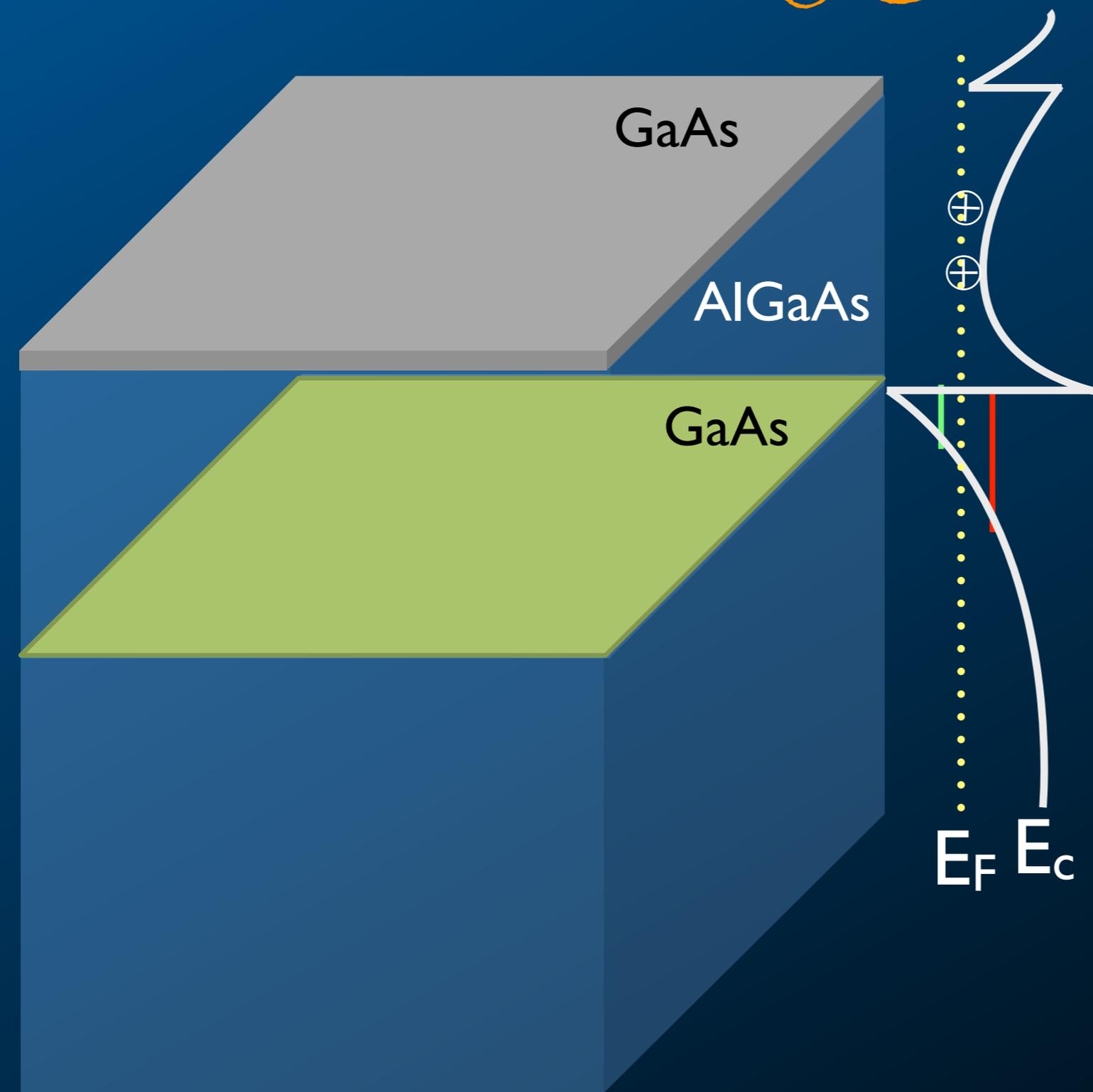


One electron induced charge

I_{SET} varies sharply with the electrostatic environment

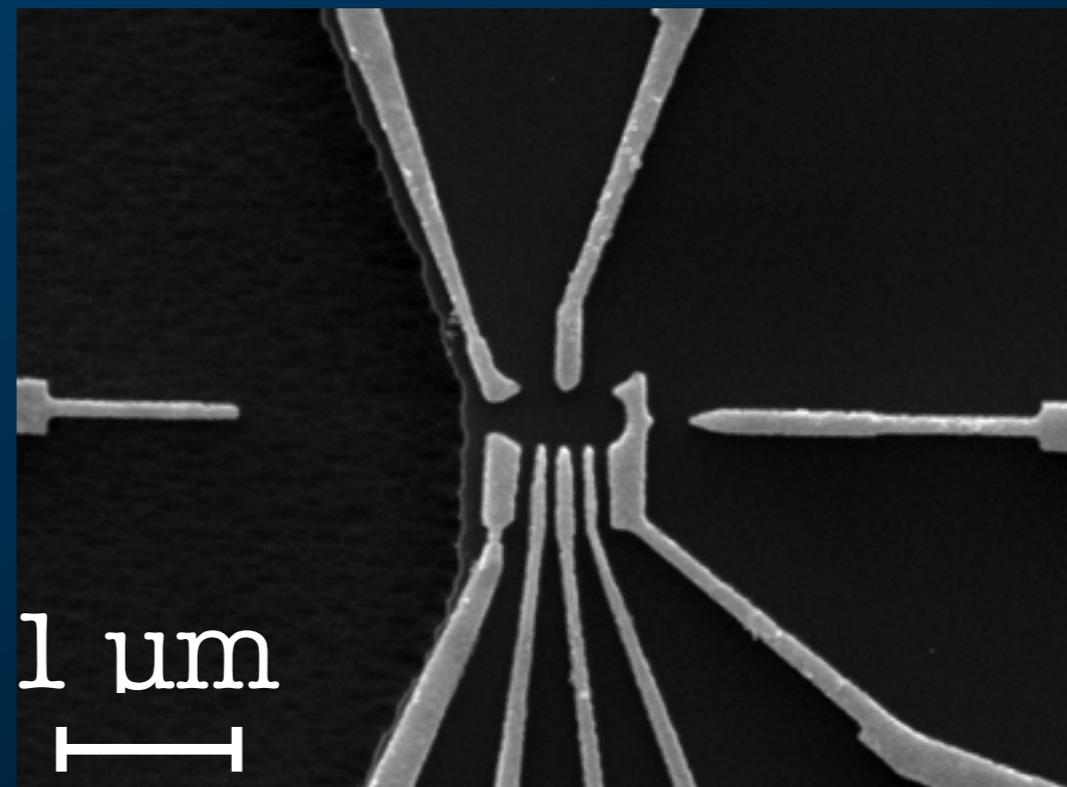
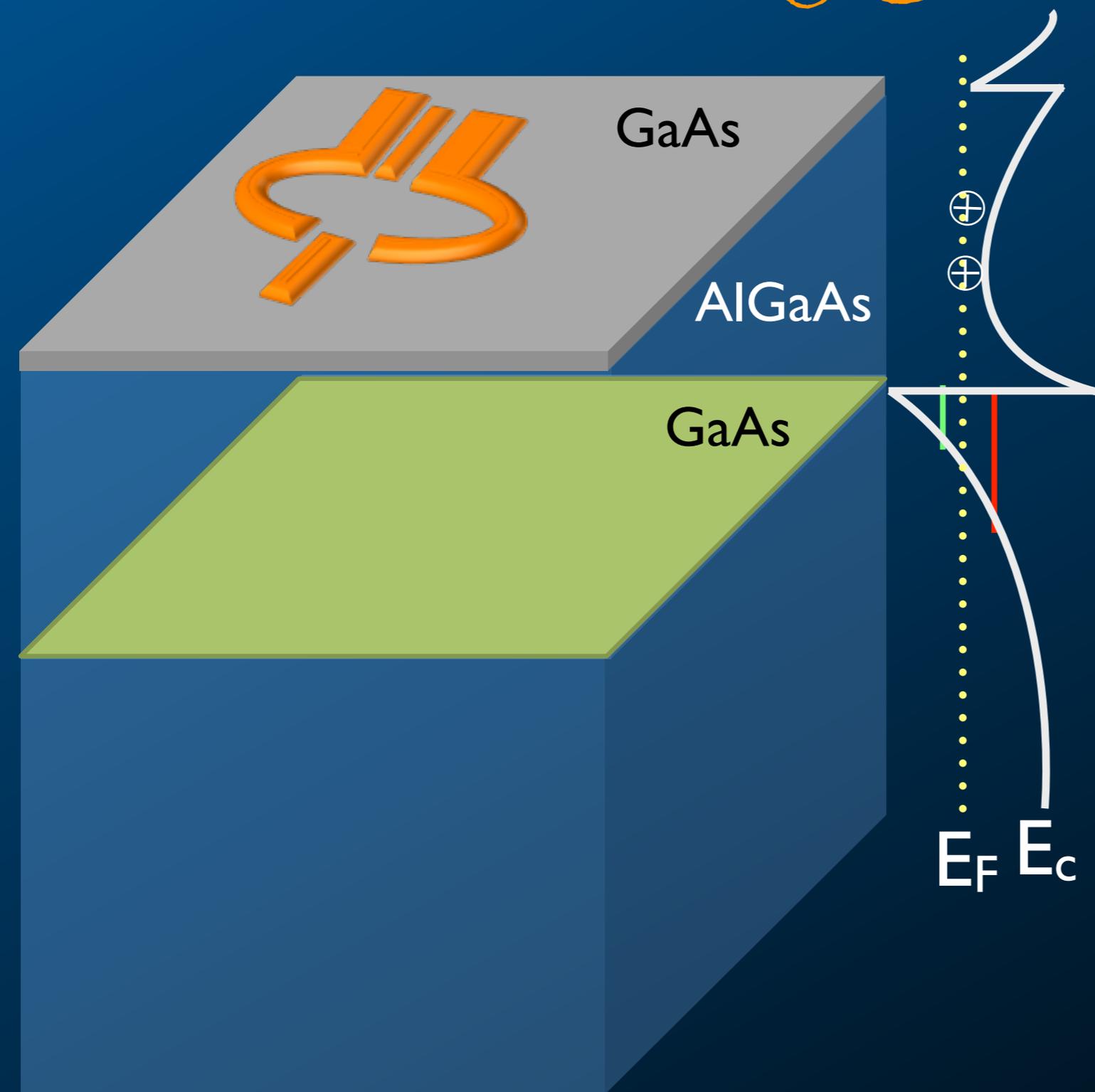


Electrostatically gated devices



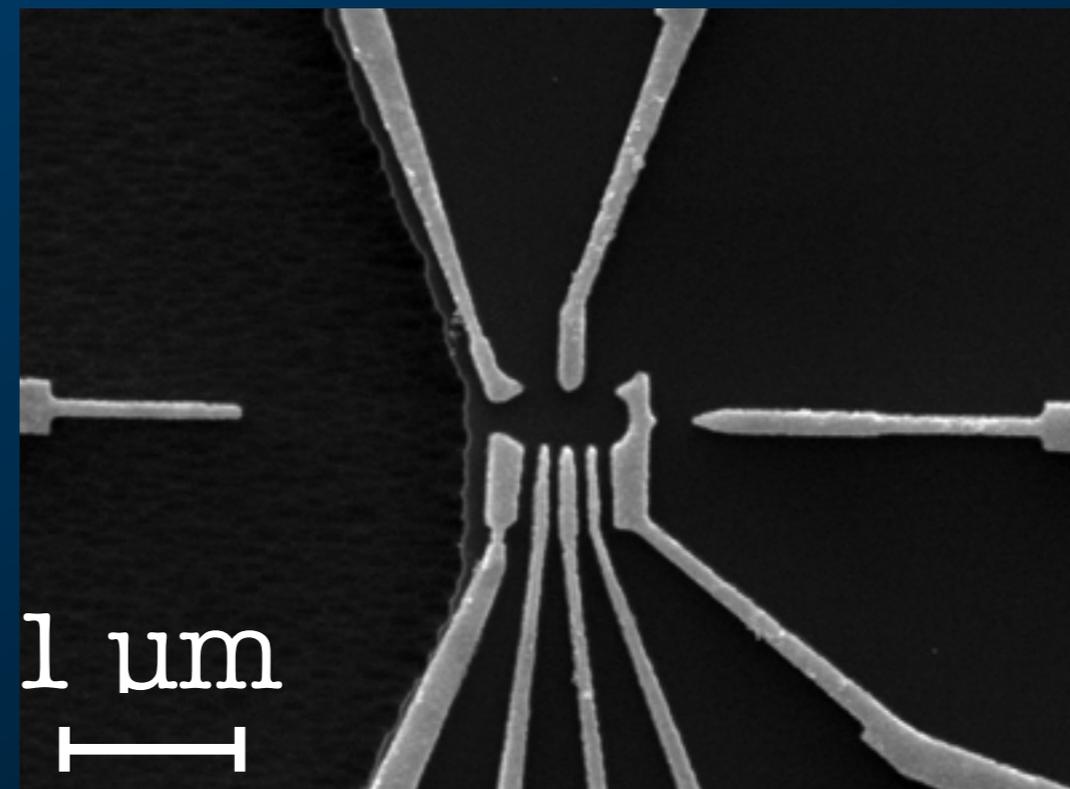
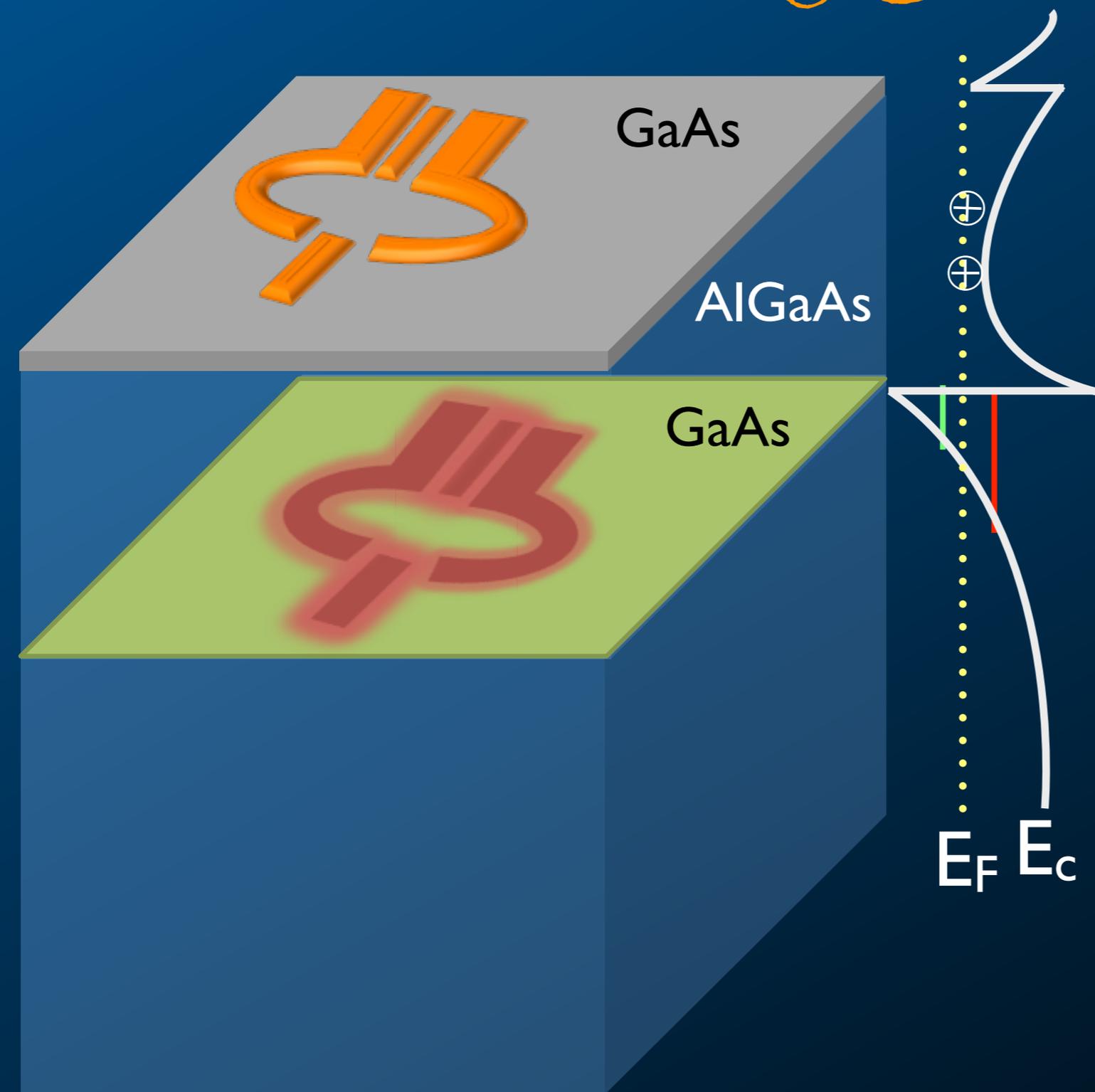
The electric field
landscaping of
density of
electrons
in the 2DEG

Electrostatically gated devices



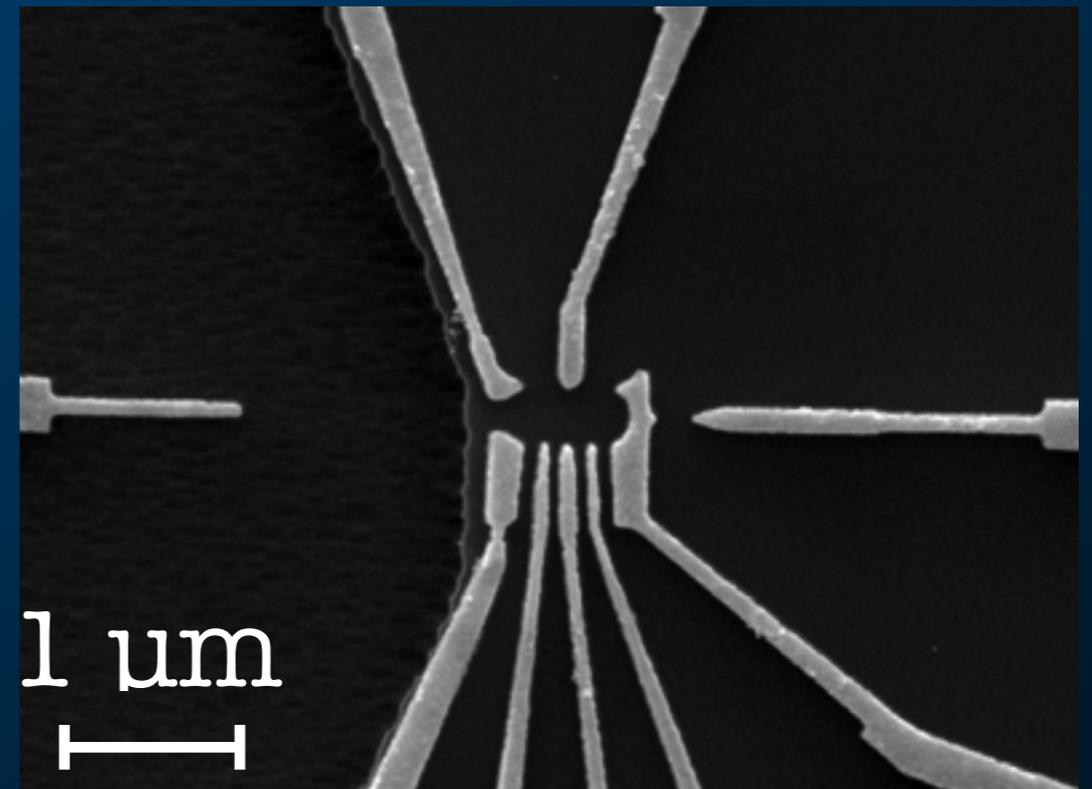
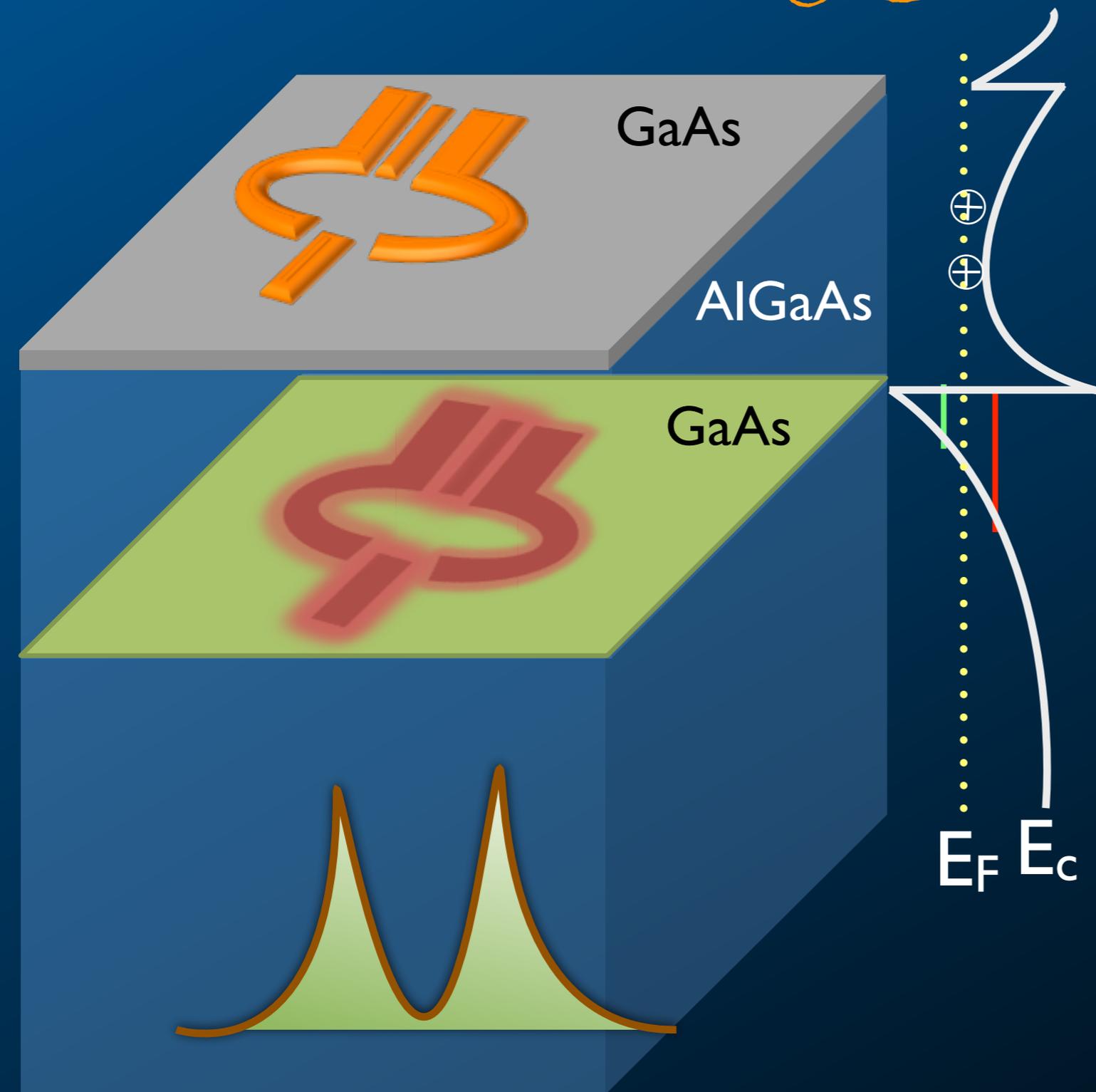
The electric field
landscaping of
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Electrostatically gated devices



The electric field
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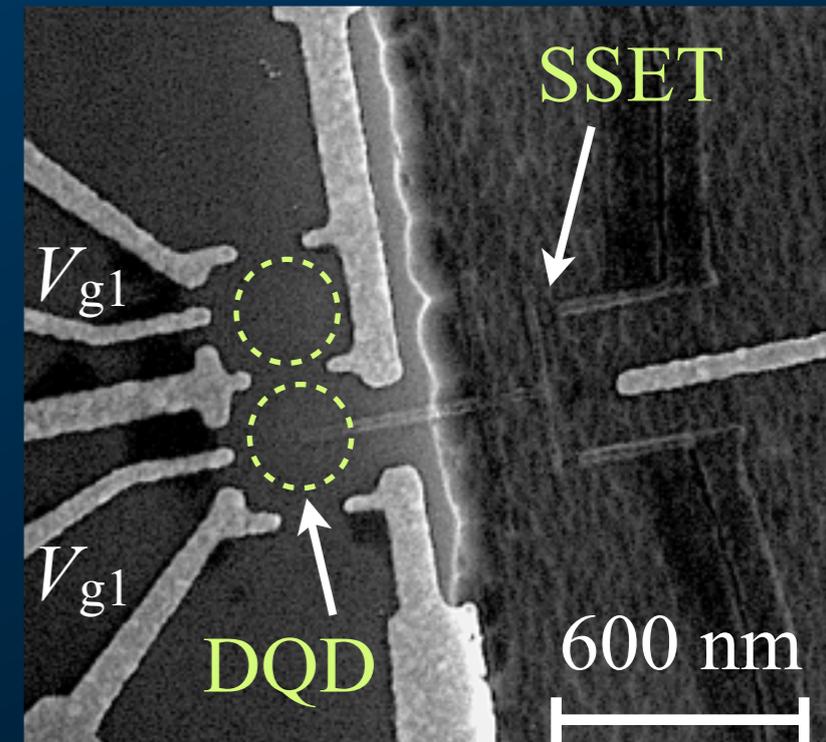
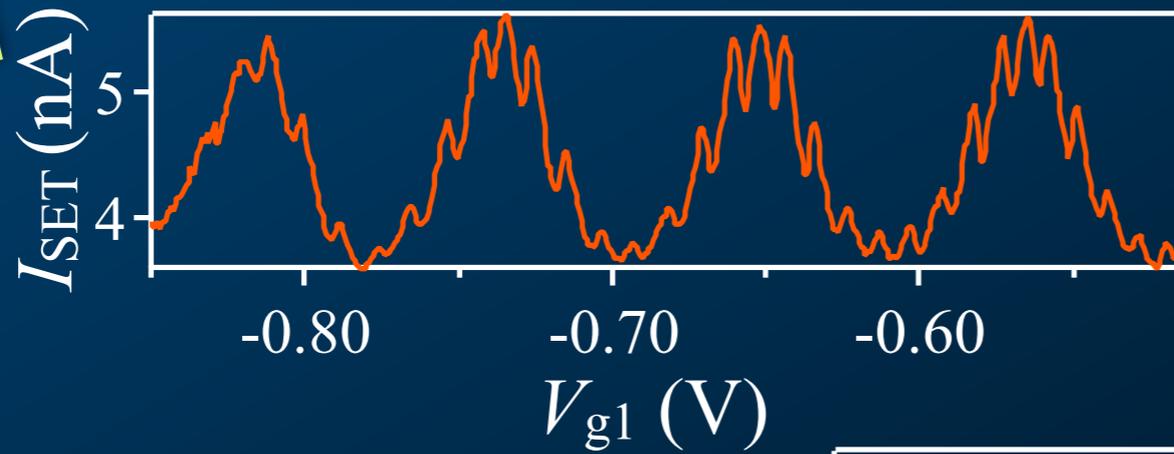
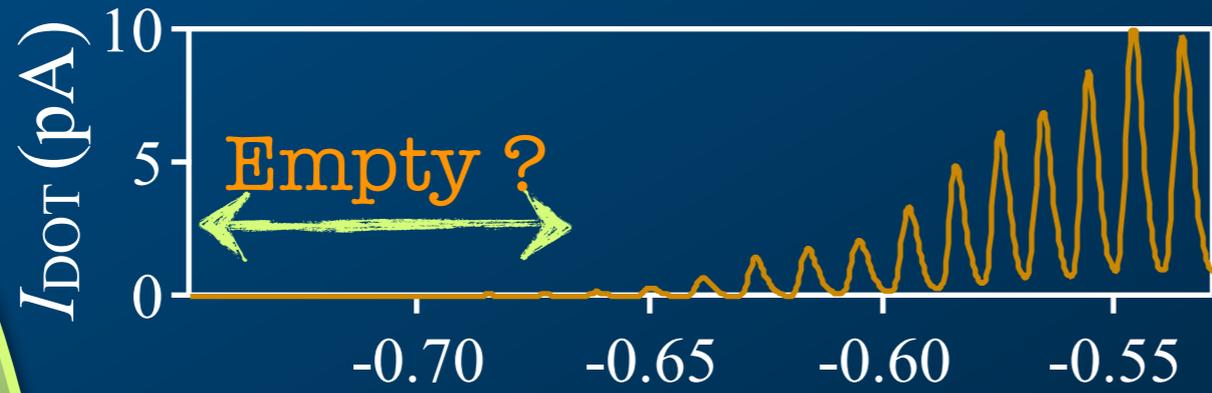
Electrostatically gated devices



The electric field
landscaping of
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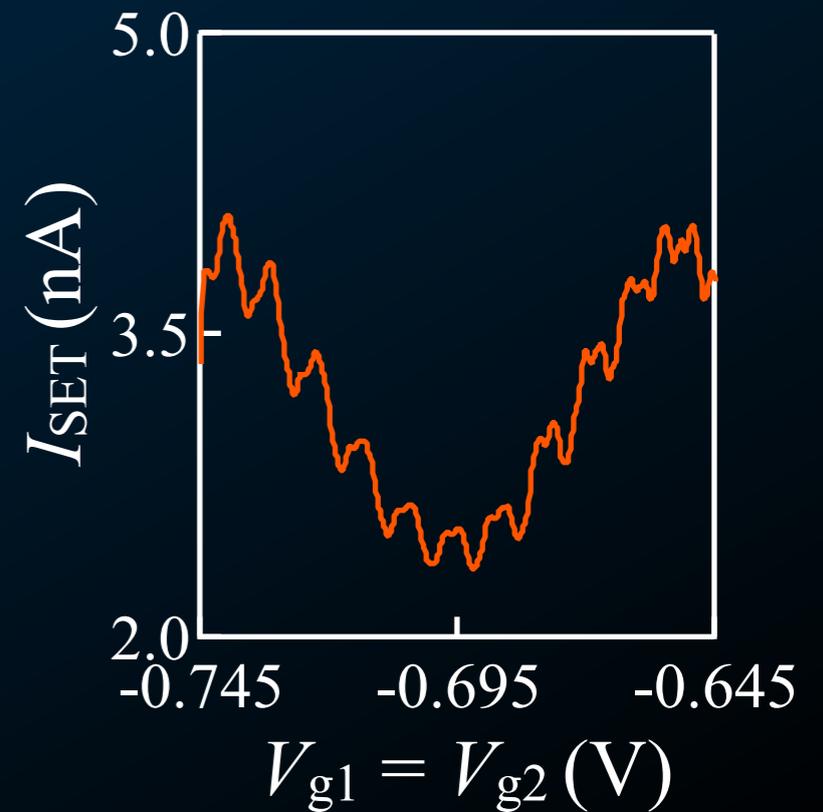
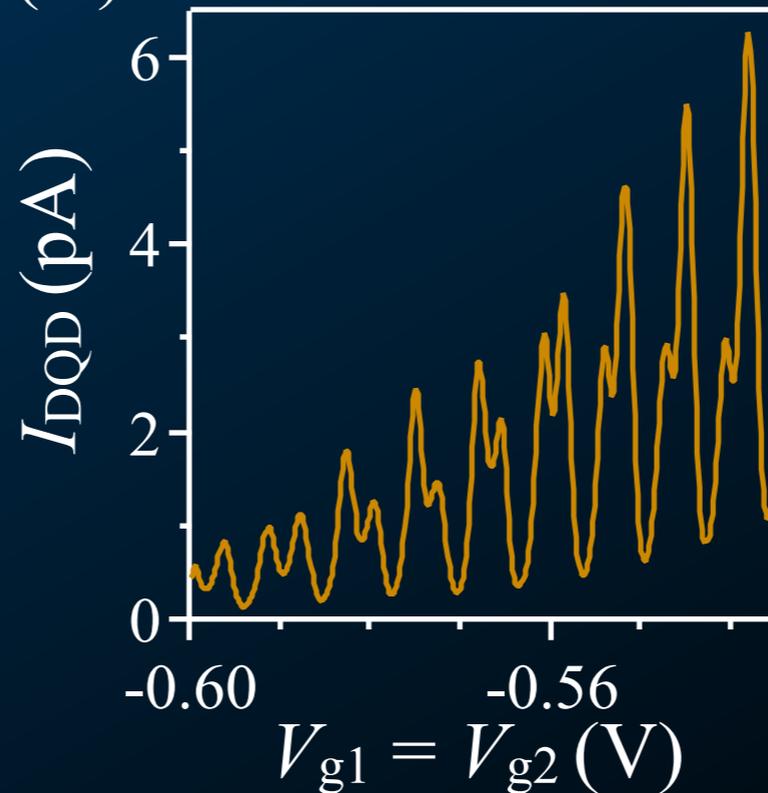
Double quantum dot-SSET system

Single QD



Double QD

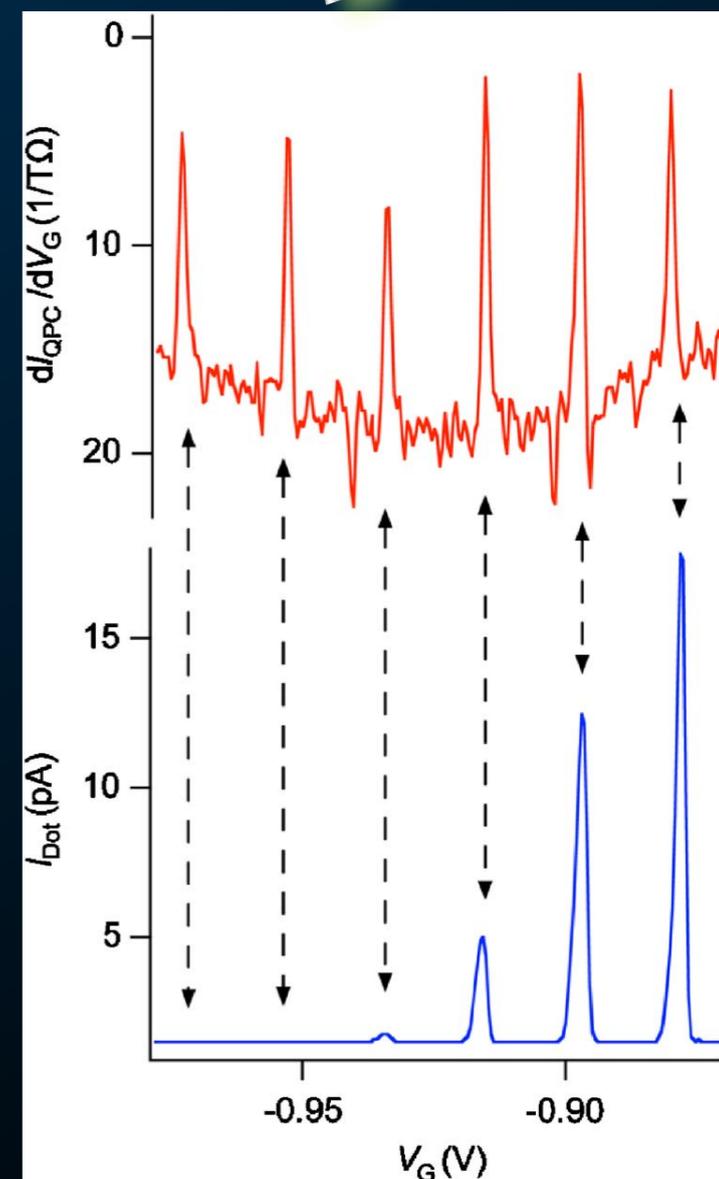
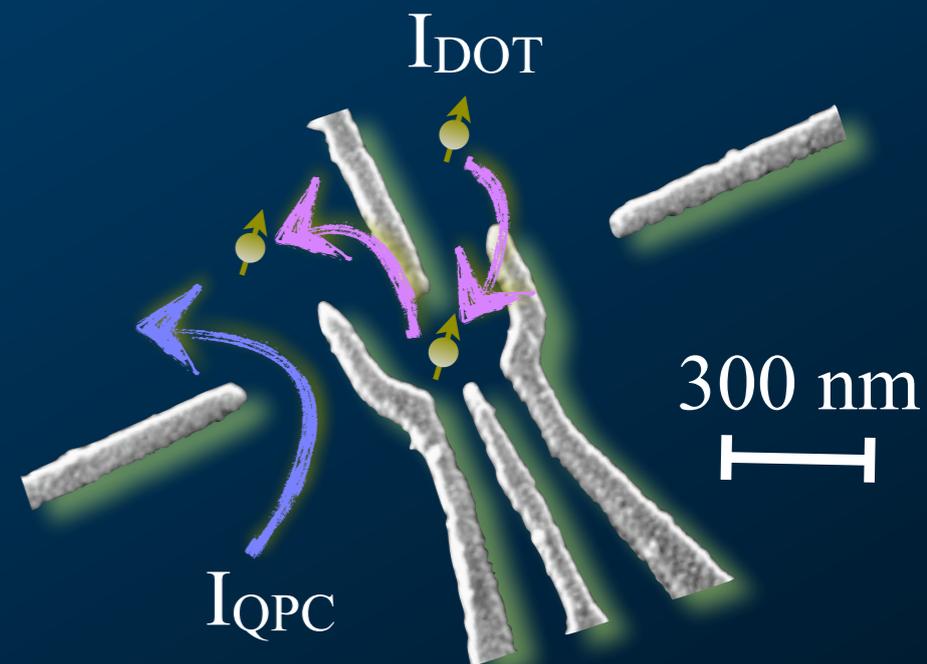
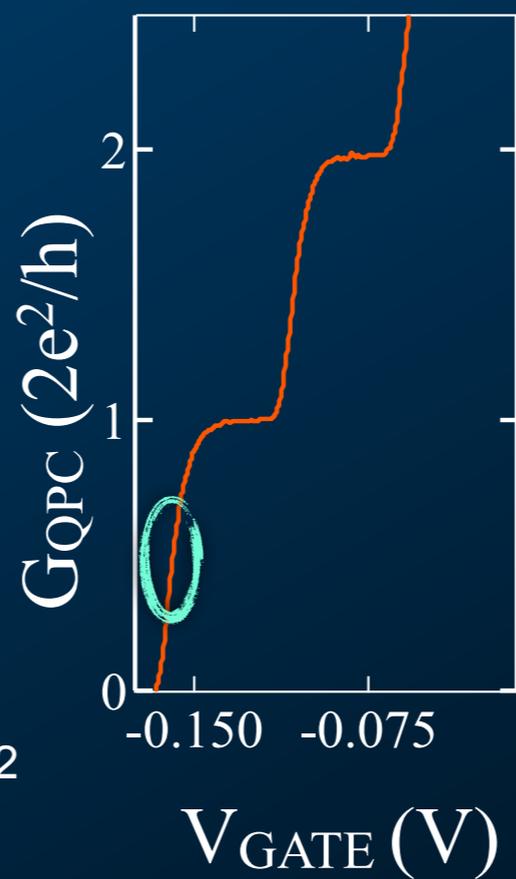
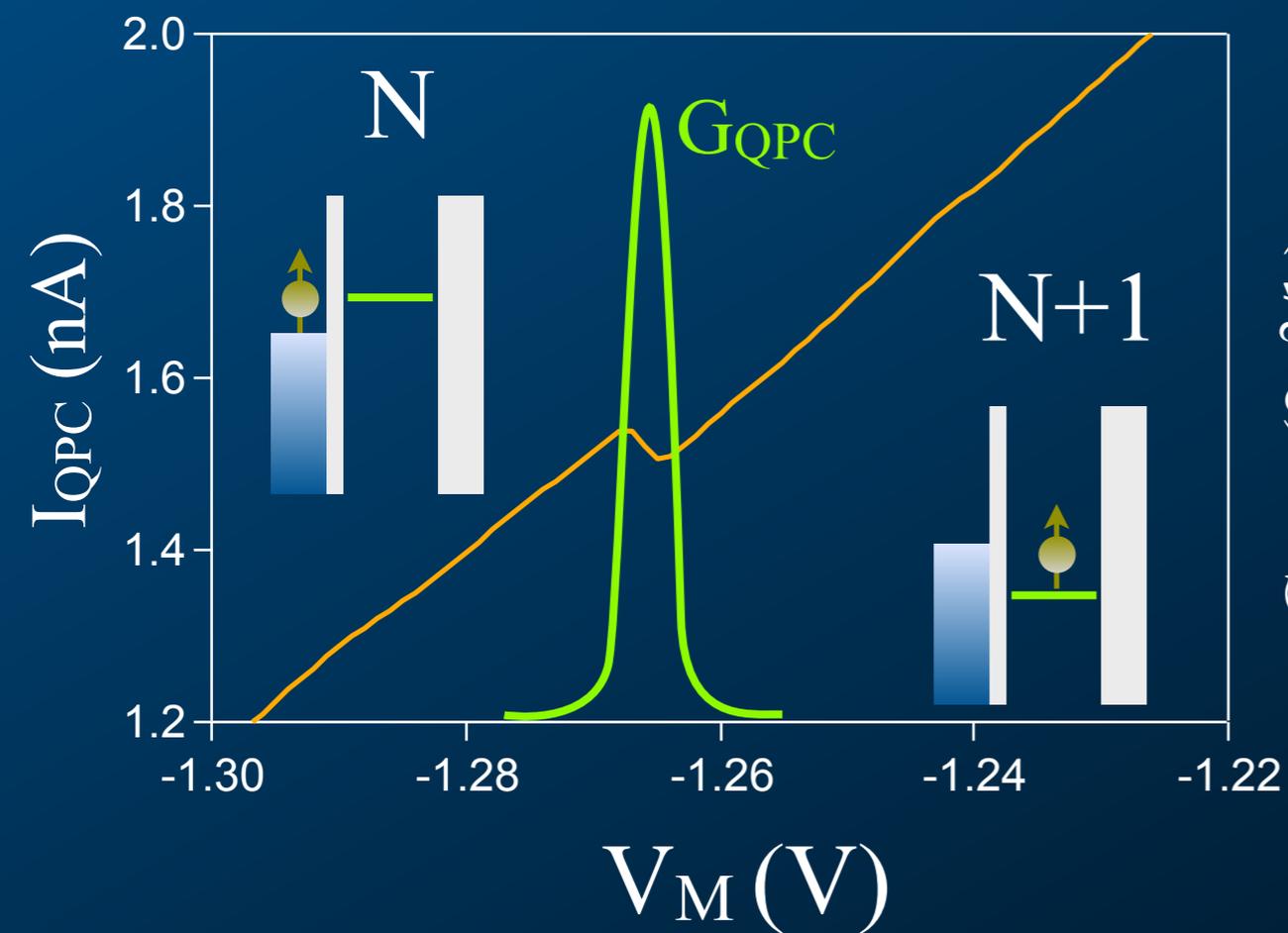
Sensor signal is not limited by the tunnel rate in the quantum dot



Unpublished data

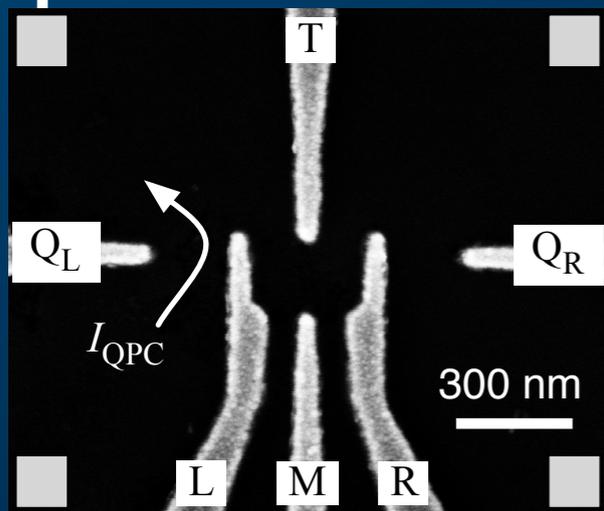
Quantum Point Contact charge amplifiers

Si/SiGe system

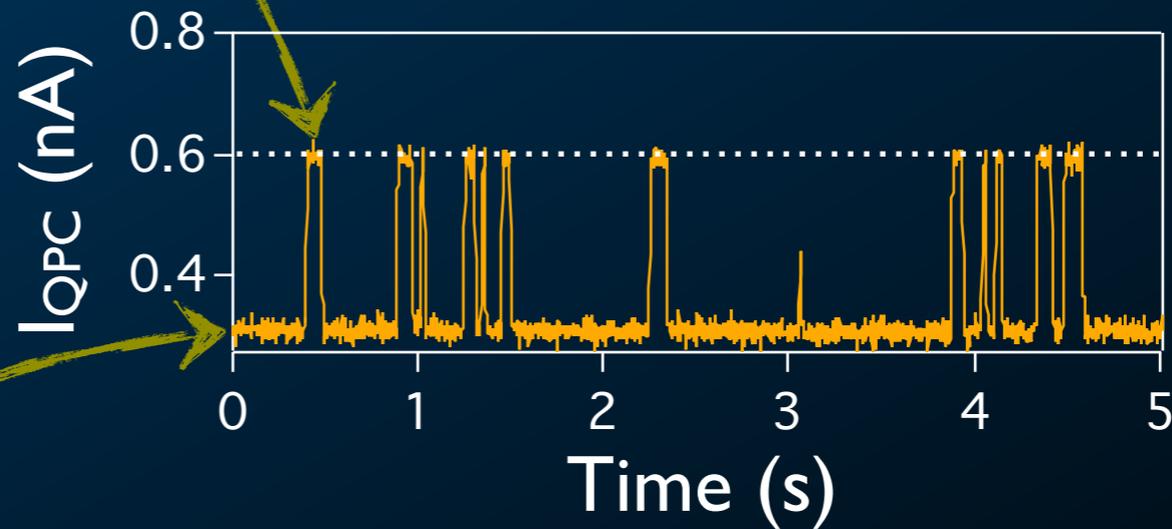
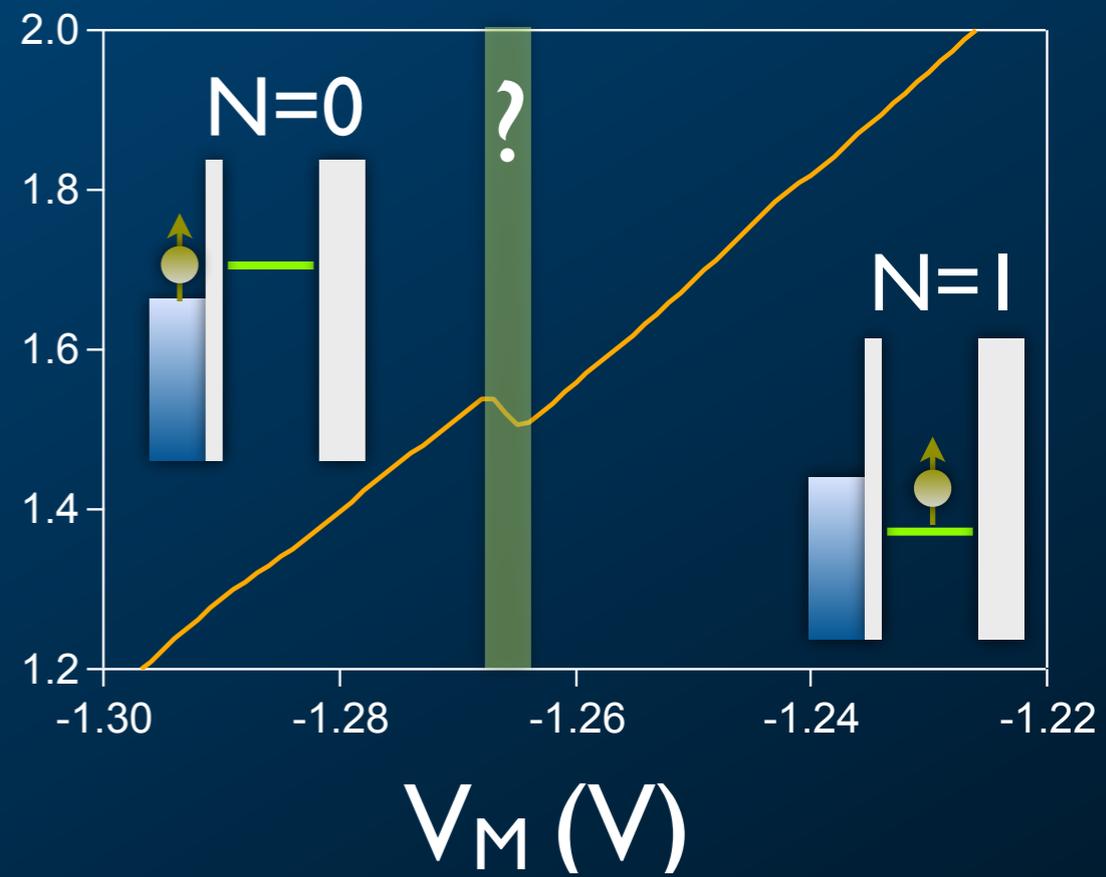


- Single-electron detection in Solid states devices.
- Ease of fabrication and operation
- Qubit readout

Observing electrons in real-time

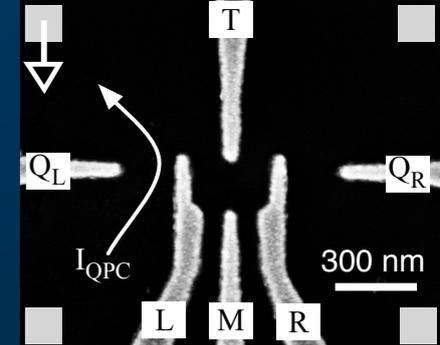
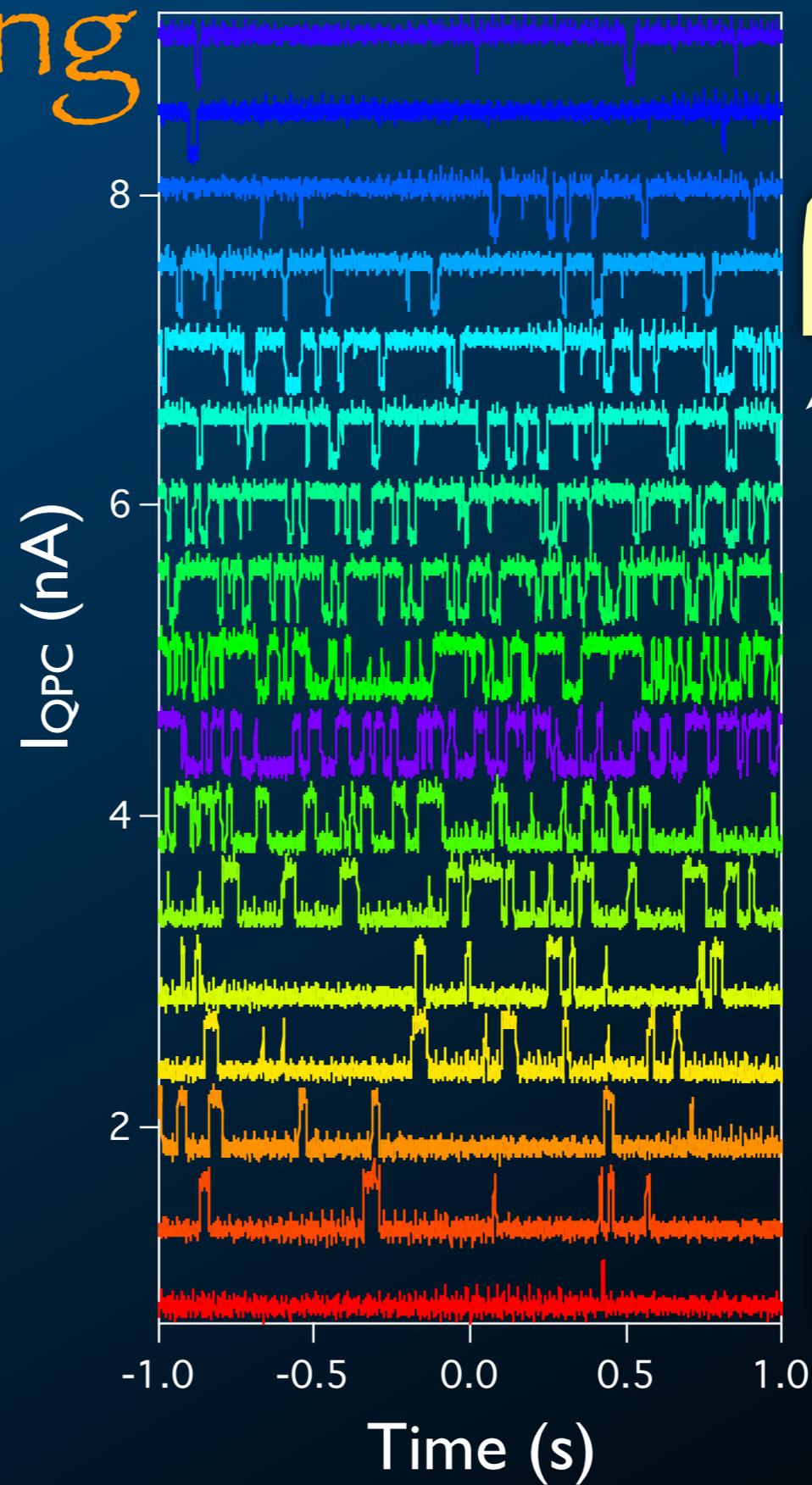


I_{QPC} (nA)

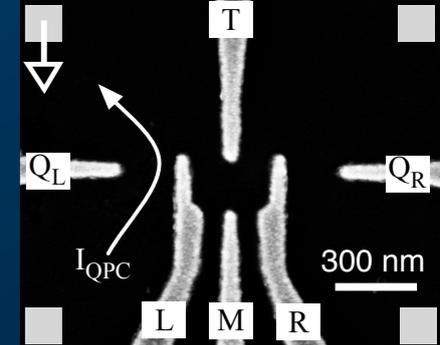
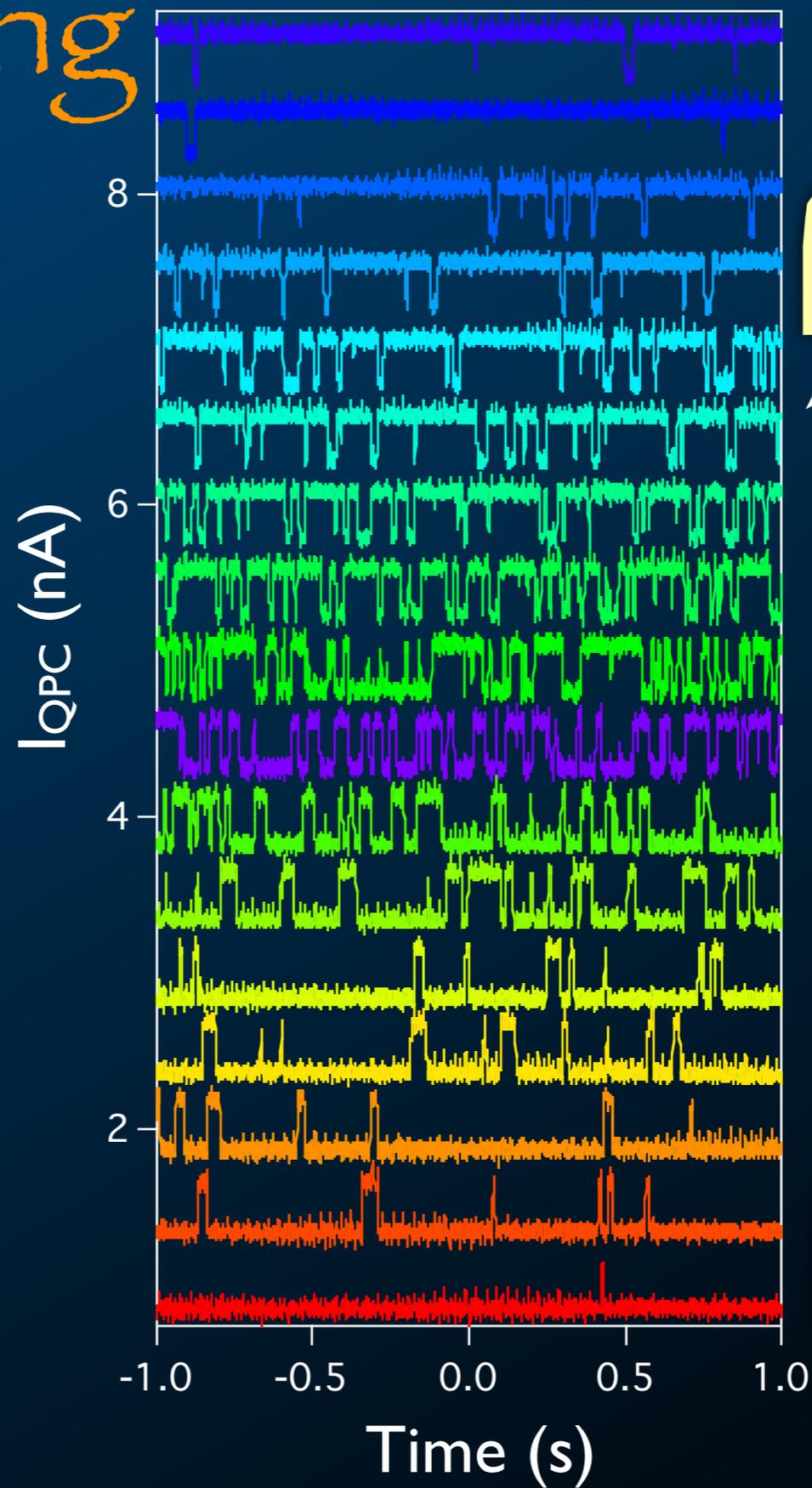
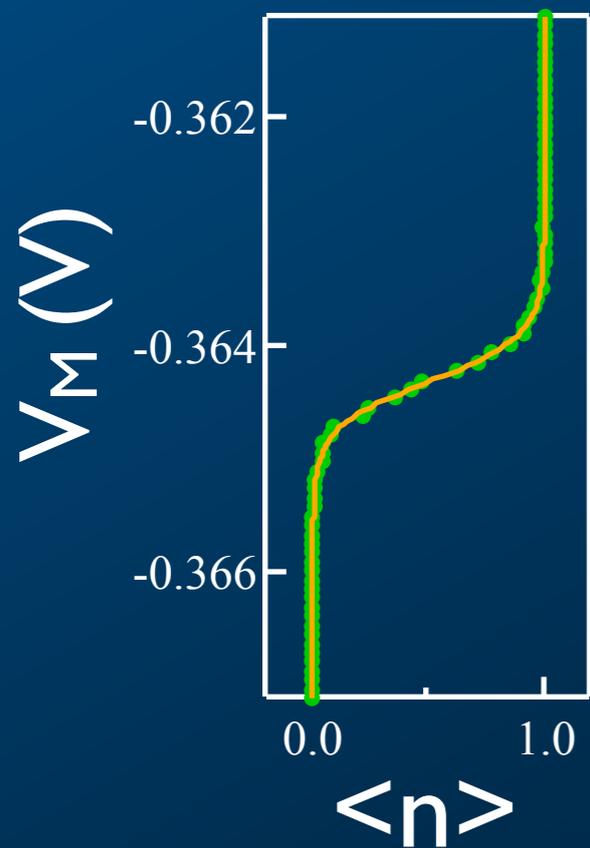


- 1 ms time resolution
- SNR ≈ 31

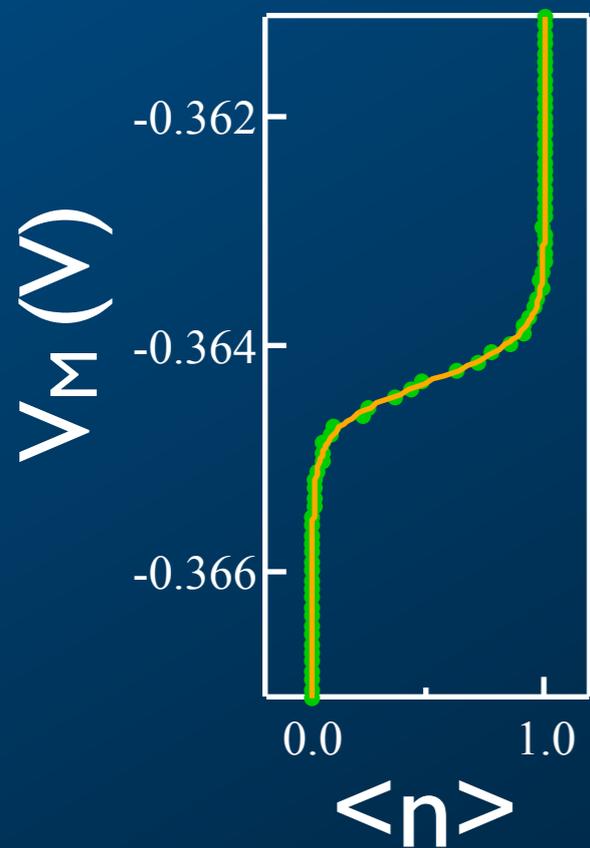
Fermi-Dirac statistics from electron counting



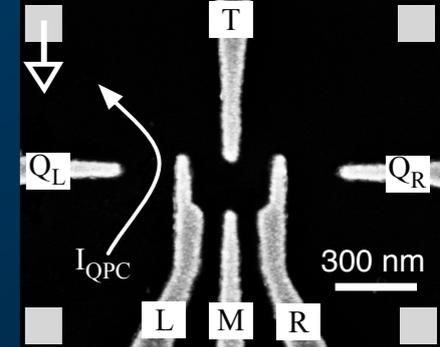
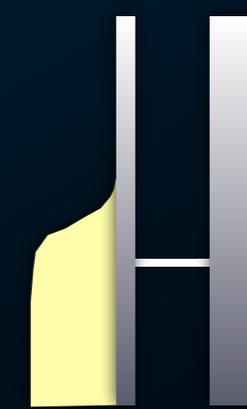
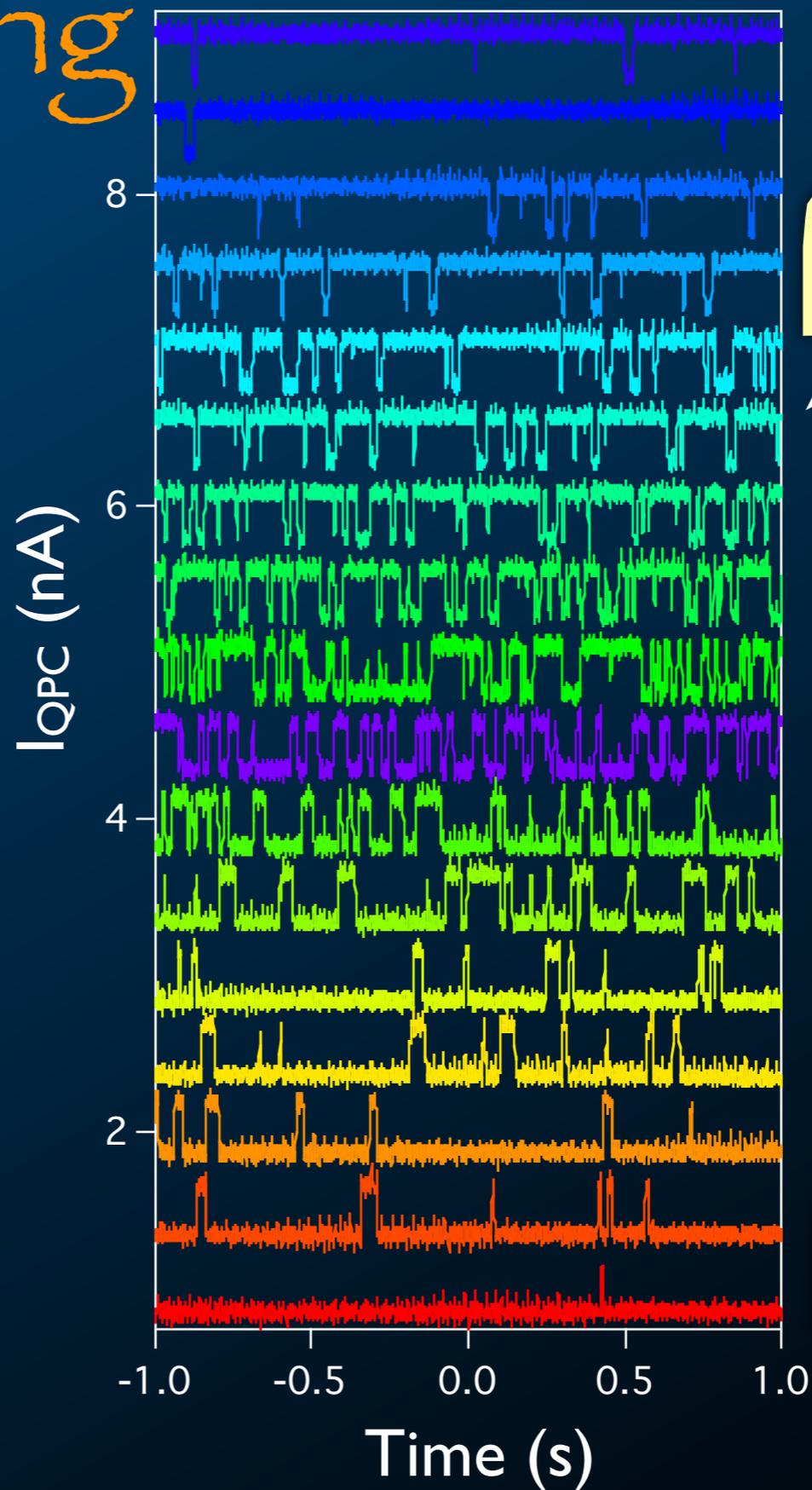
Fermi-Dirac statistics from electron counting



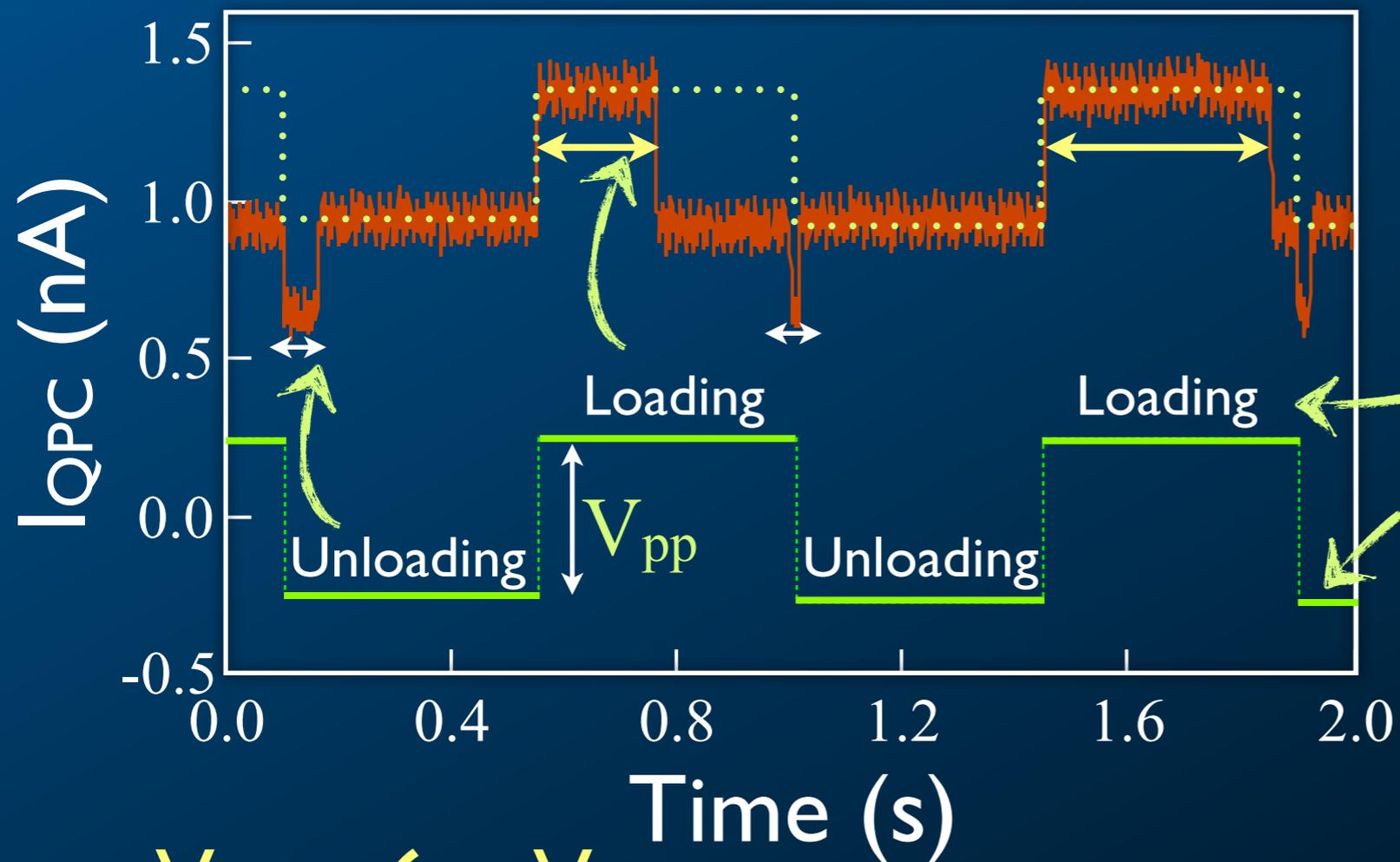
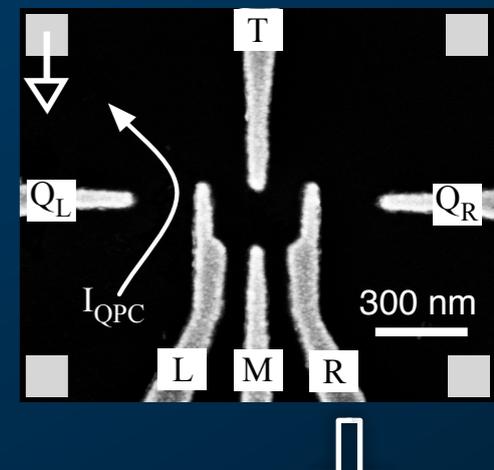
Fermi-Dirac statistics from electron counting



$T_e \approx 220$ mK

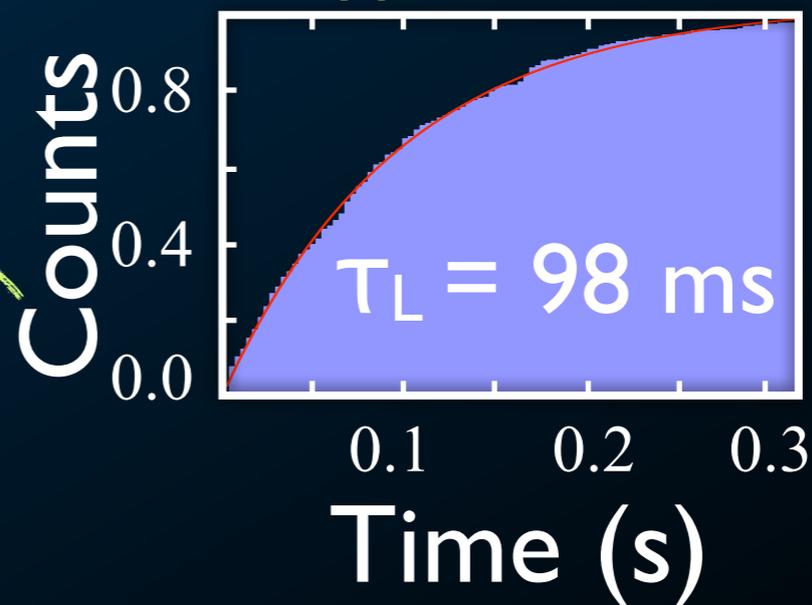
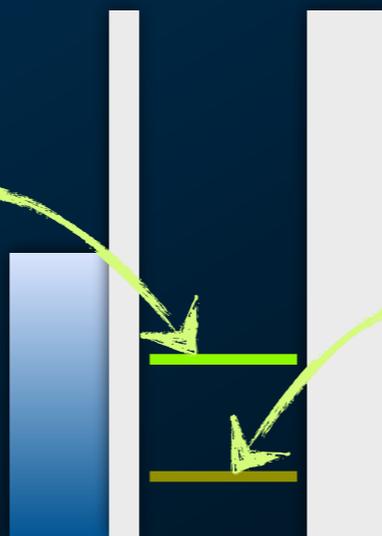
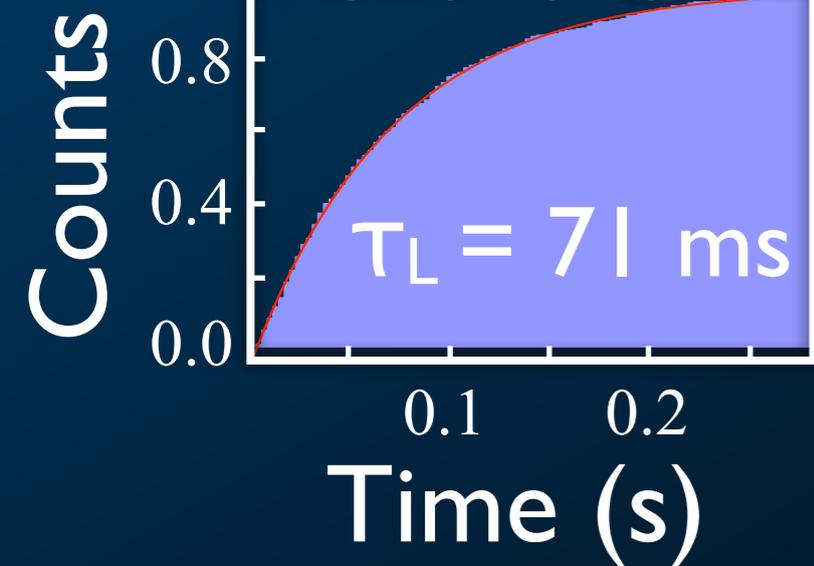


Controlled loading experiments

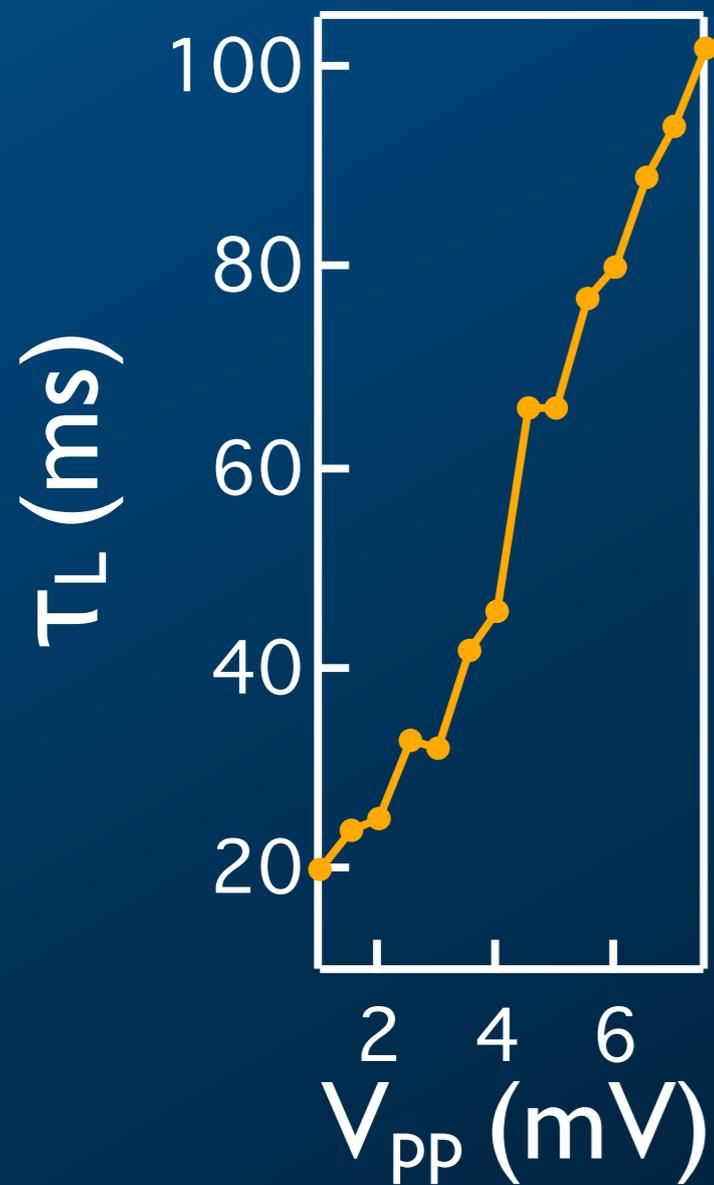
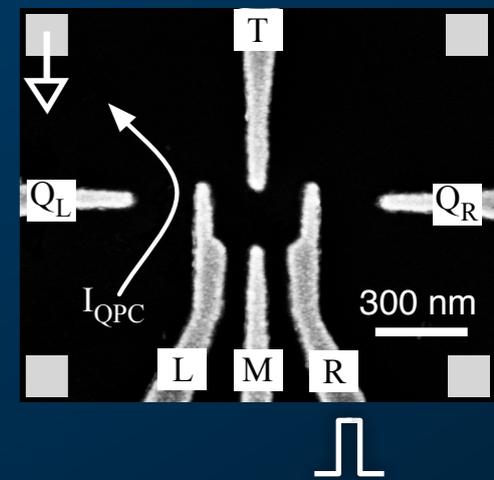


$V_{pp} = 6$ mV

$V_{pp} = 8$ mV

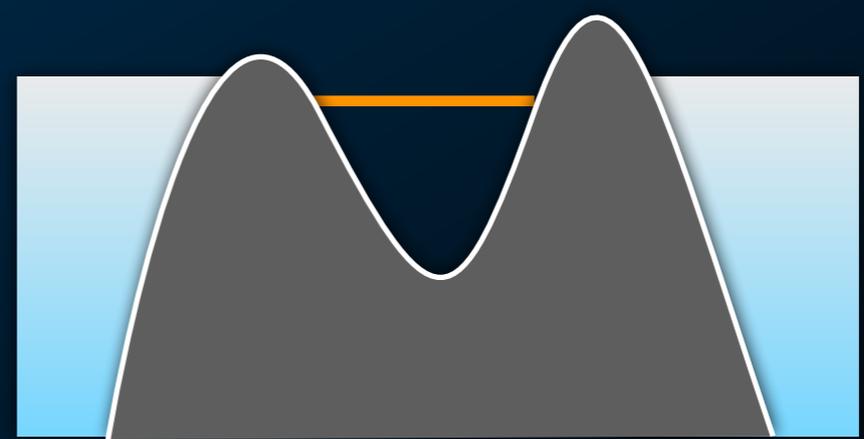
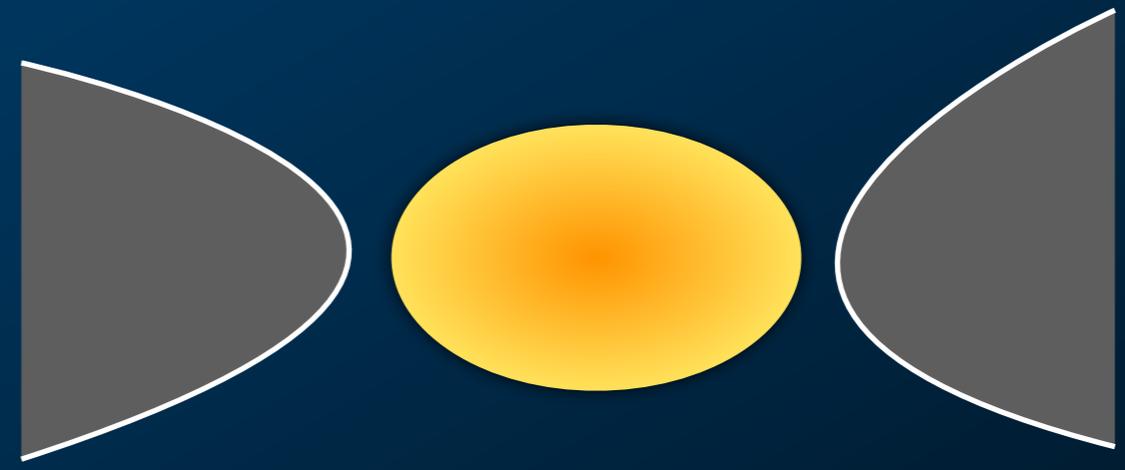
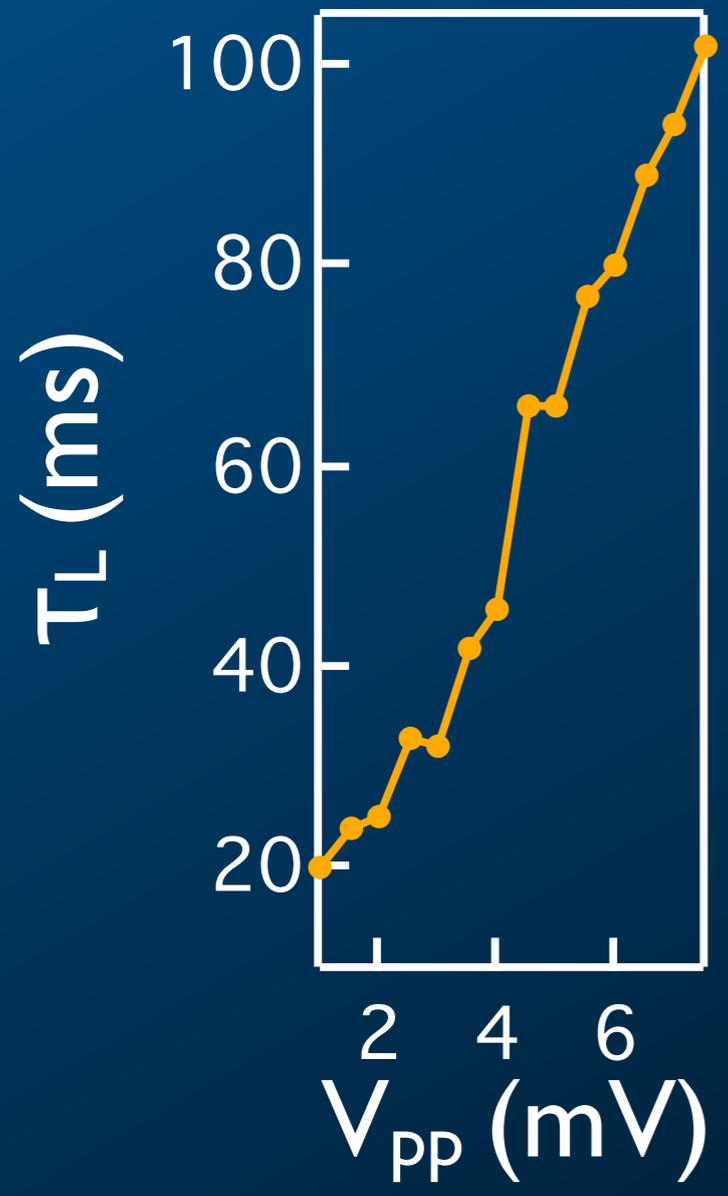
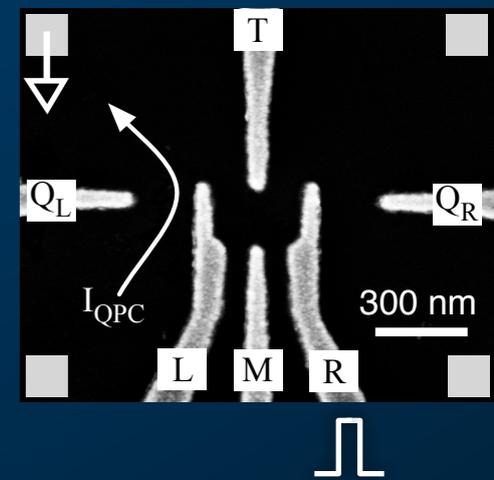


Energy dependent tunneling



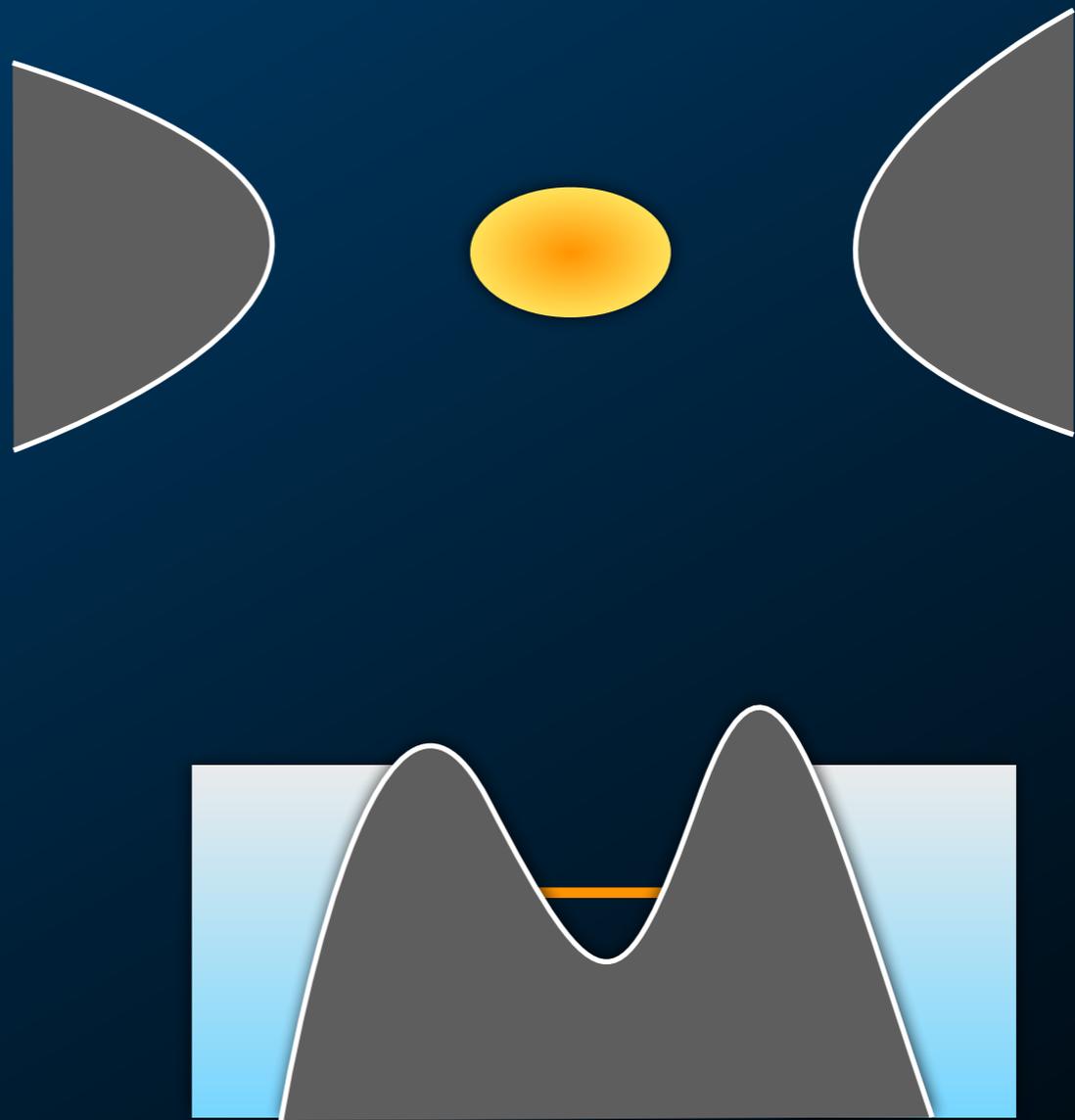
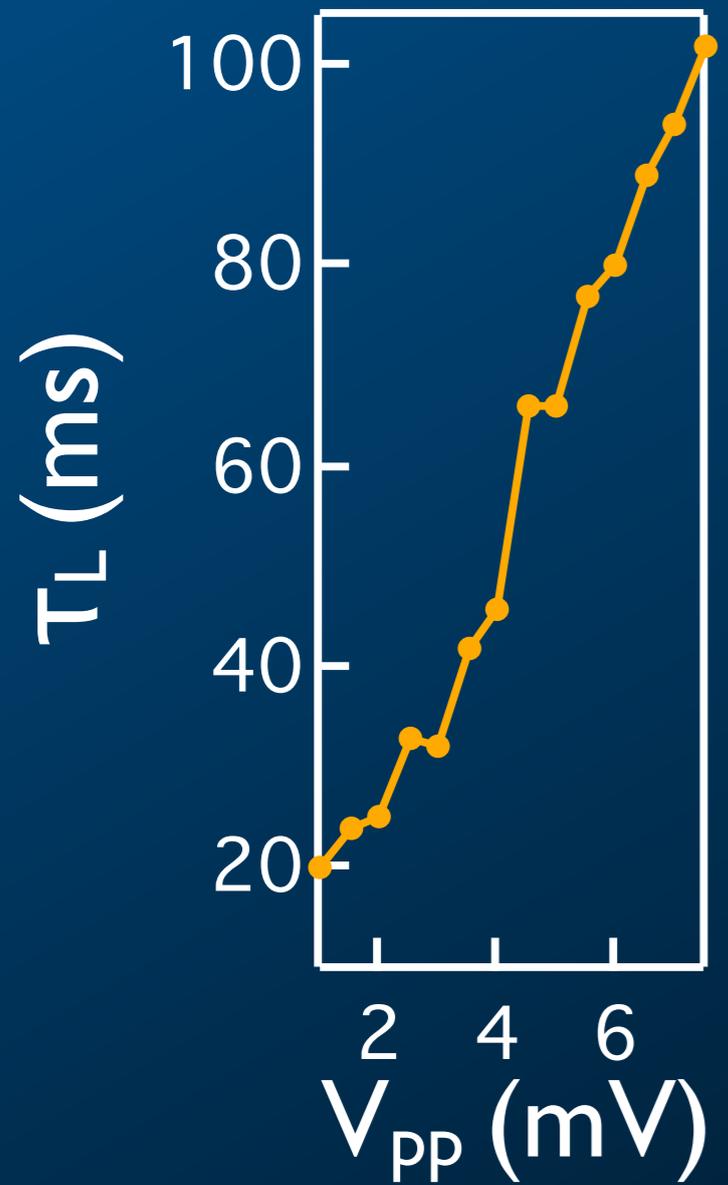
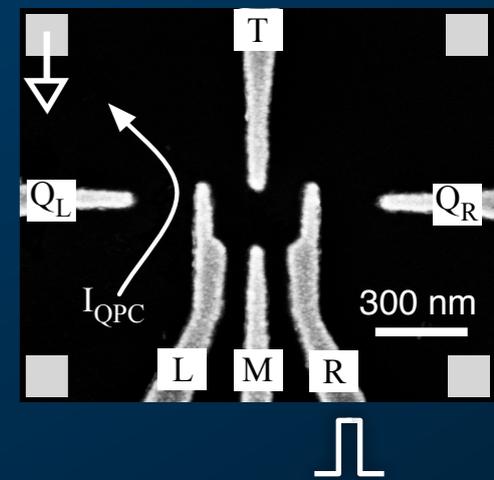
An important aspect for energy selective loading, readout schemes

Energy dependent tunneling



An important aspect for energy selective loading, readout schemes

Energy dependent tunneling



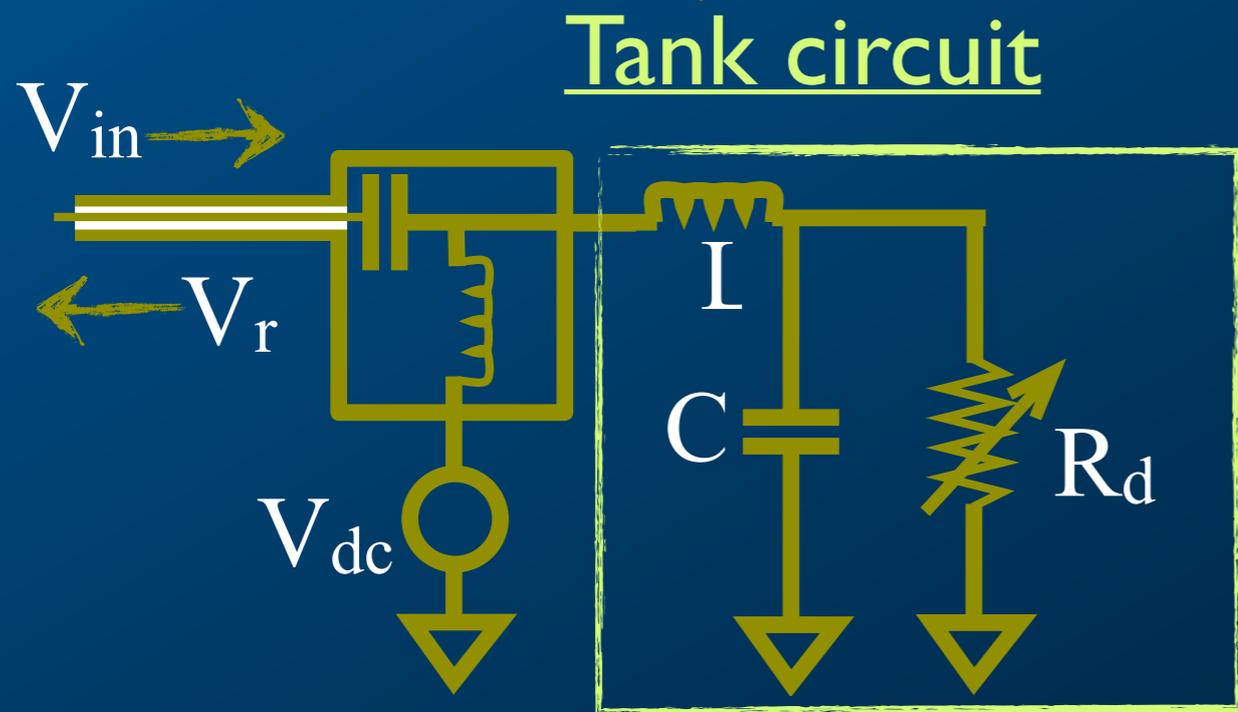
An important aspect for energy selective loading, readout schemes

Bandwidth Limitations



- Intrinsic band width is in 10s of GHz
- Impedance mismatch
- RC time constant
- Limited to < 1 ms time-scale
- Low frequencies, $1/f$ noise, SNR

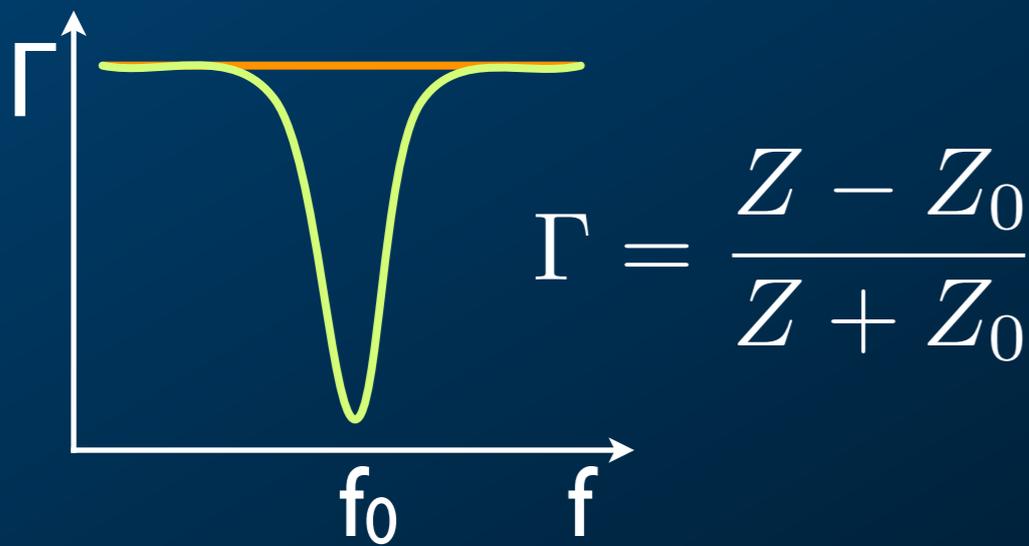
Radio-frequency operation



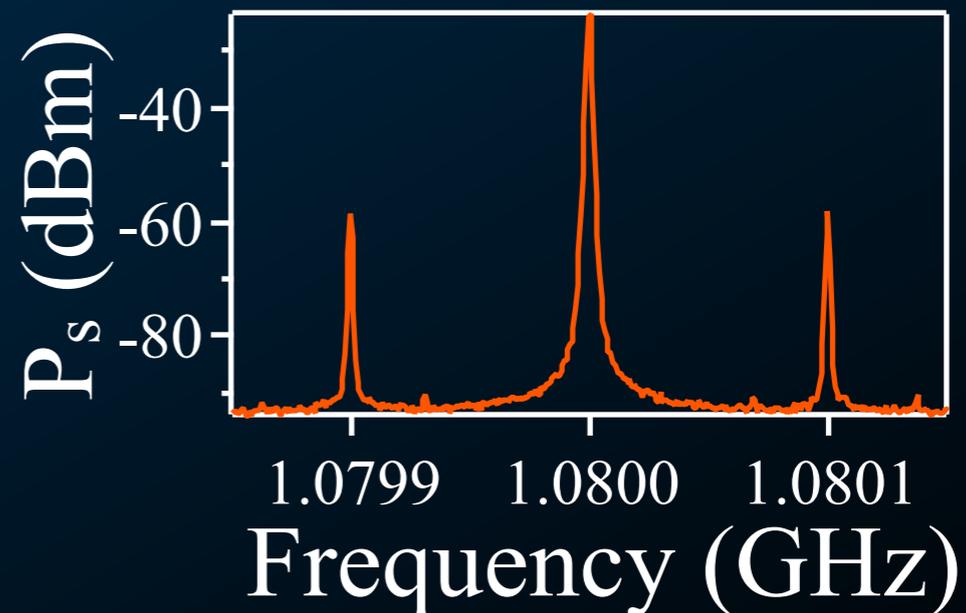
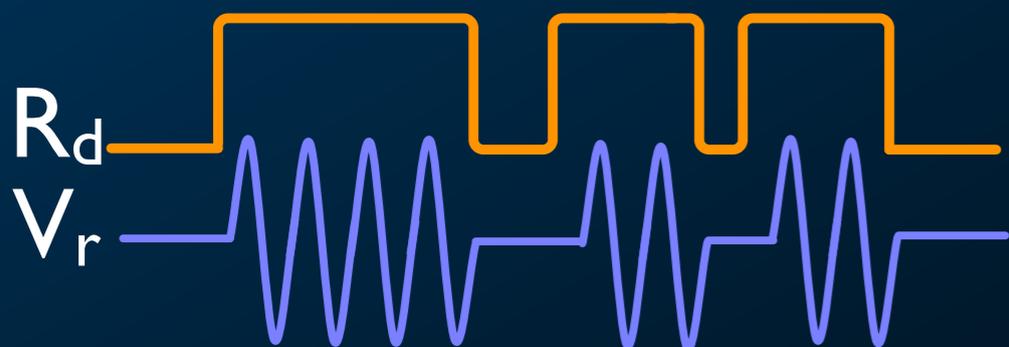
$$Z = i\omega L + \frac{R_d}{1 + i\omega C R_d}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Z = \frac{L}{C R_d}$$

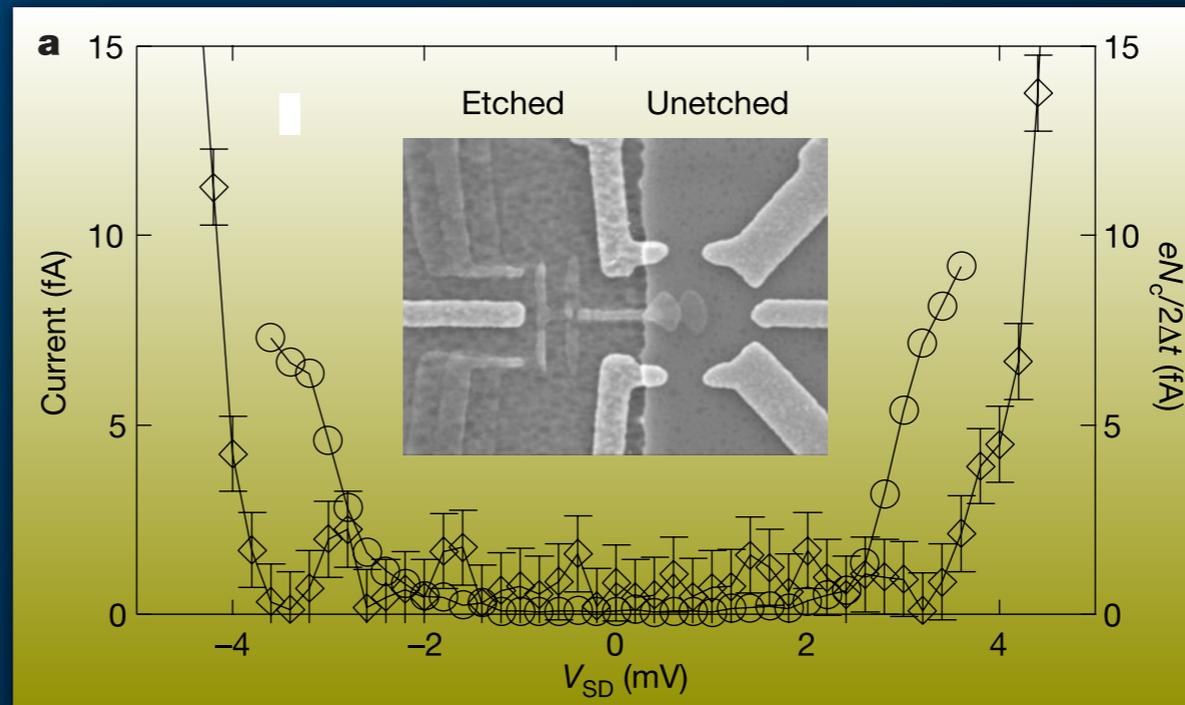
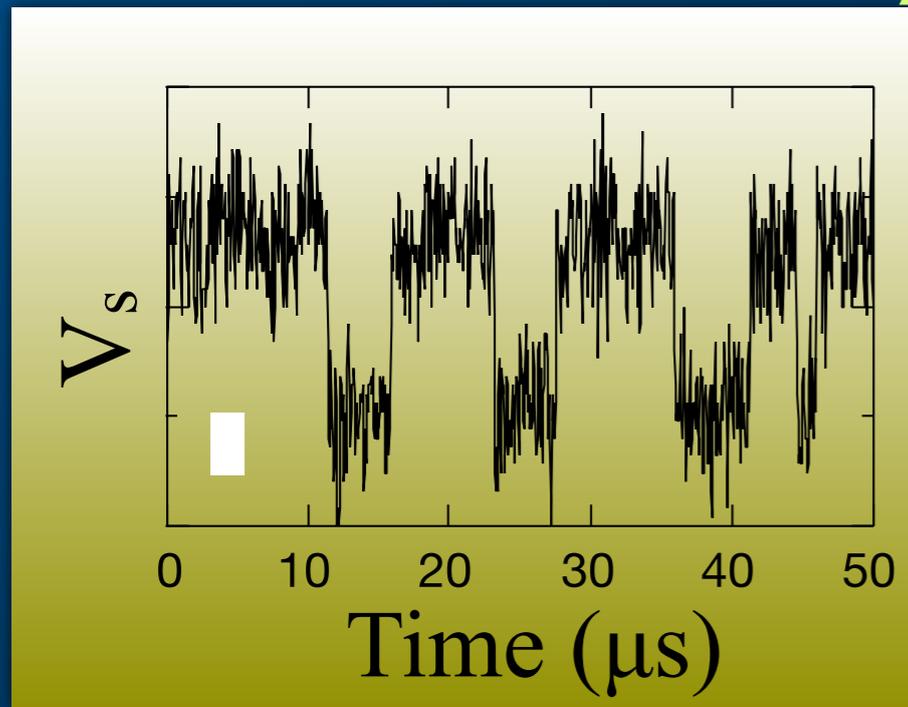


Tank circuit amplitude modulates the reflected wave



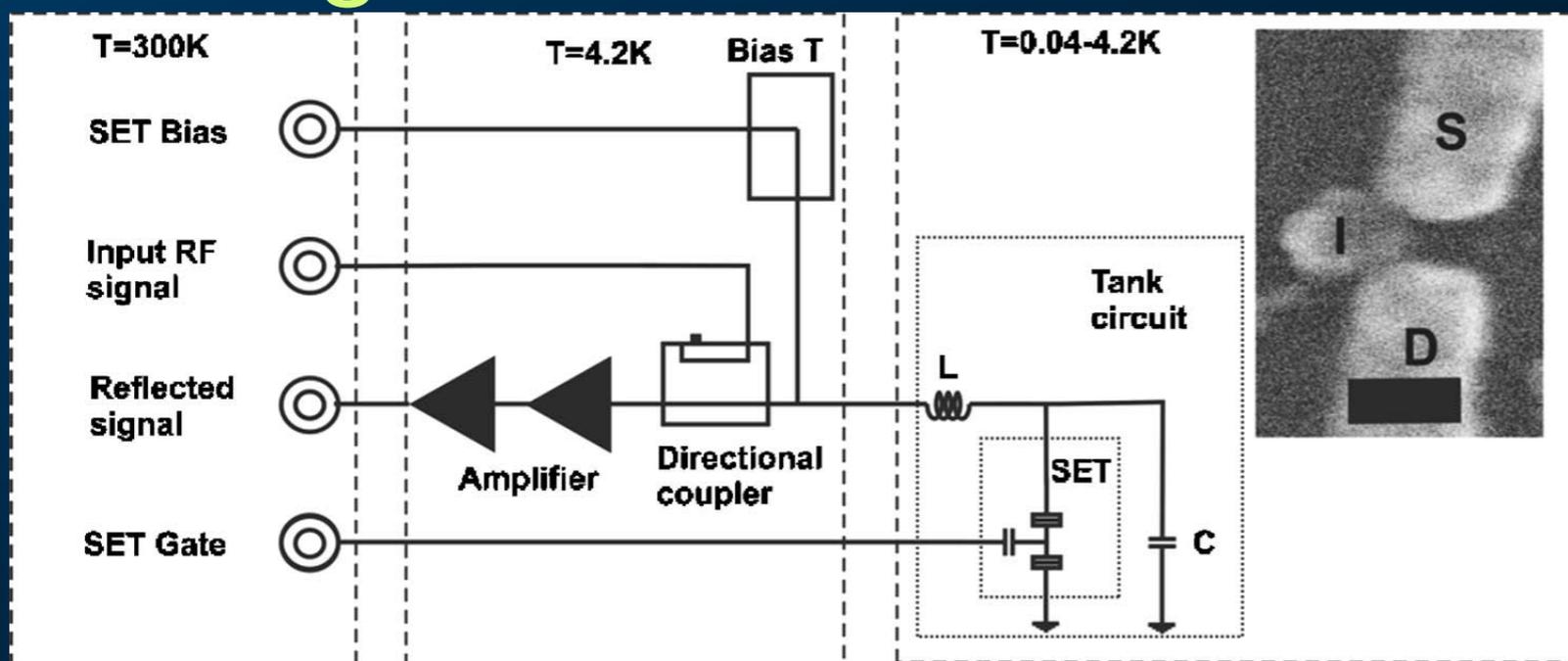
Fast charge measurements

I-V measurement by electron counting



W. Lu et al., Nature, 2003

Ultrahigh sensitive SSET

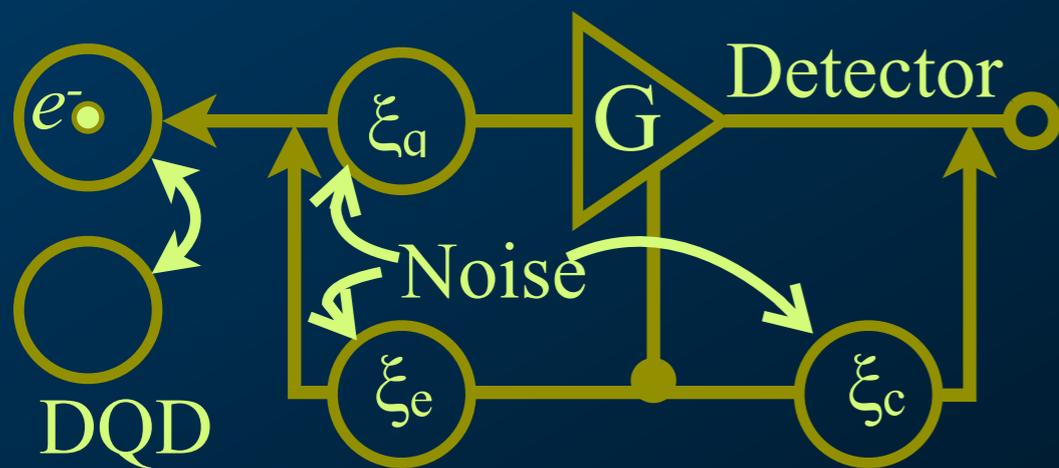


$$\delta q = 1 \mu e / \sqrt{\text{Hz}}$$

Brenning et al., APL 2006

Sensitivity & back-action

System	Sensitivity	Back-action	Limit	Limited quantity
Heisenberg microscope	Δx	Δp	$\Delta x \Delta p \geq \hbar$	<i>Action</i>
Electrical amplifier	S_v	S_I	$(S_v S_I)^{1/2} \geq \hbar \omega / 2$	<i>Noise energy</i>
Qubit readout	T_m	Γ_φ	$T_m \Gamma_\varphi \geq 1$	<i>Information</i>



ξ_q Quantum dephasing noise

ξ_e Classical dephasing noise

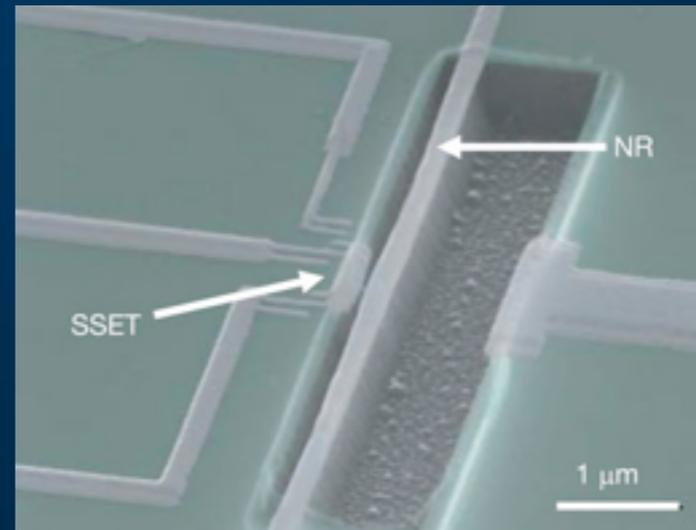
ξ_c Subsequent amplifier noise

For quantum limit: The classical noises should be kept minimal

S-SET close to the quantum limit

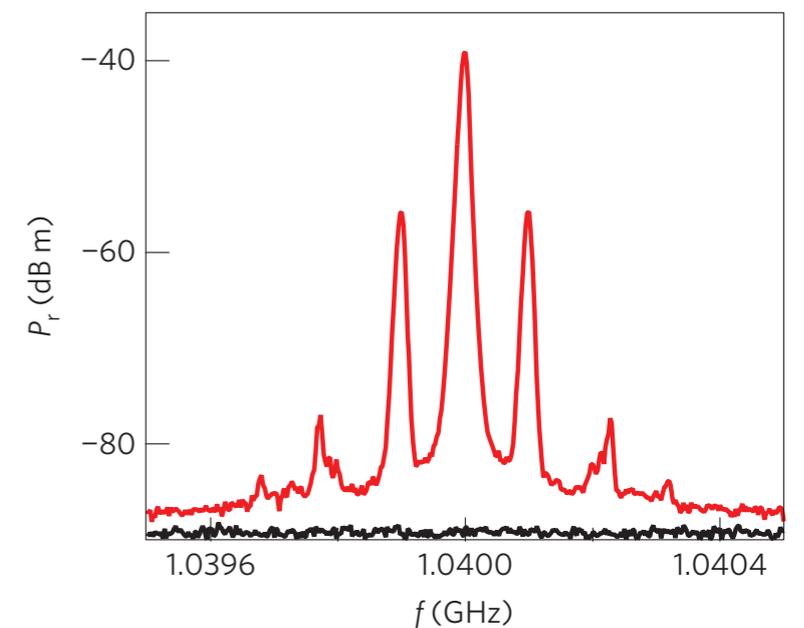
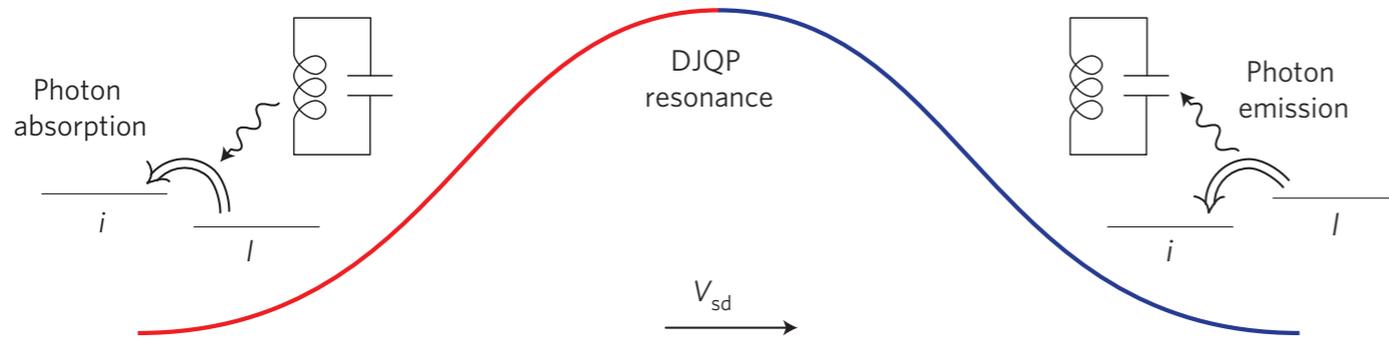
Back-action cooling

Observed cooling of the resonator from 550 mK to 300 mK



Naik et al., Nature 2006

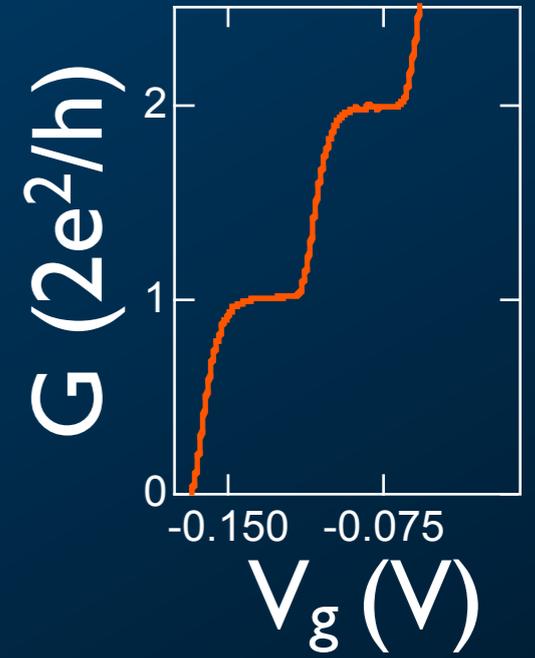
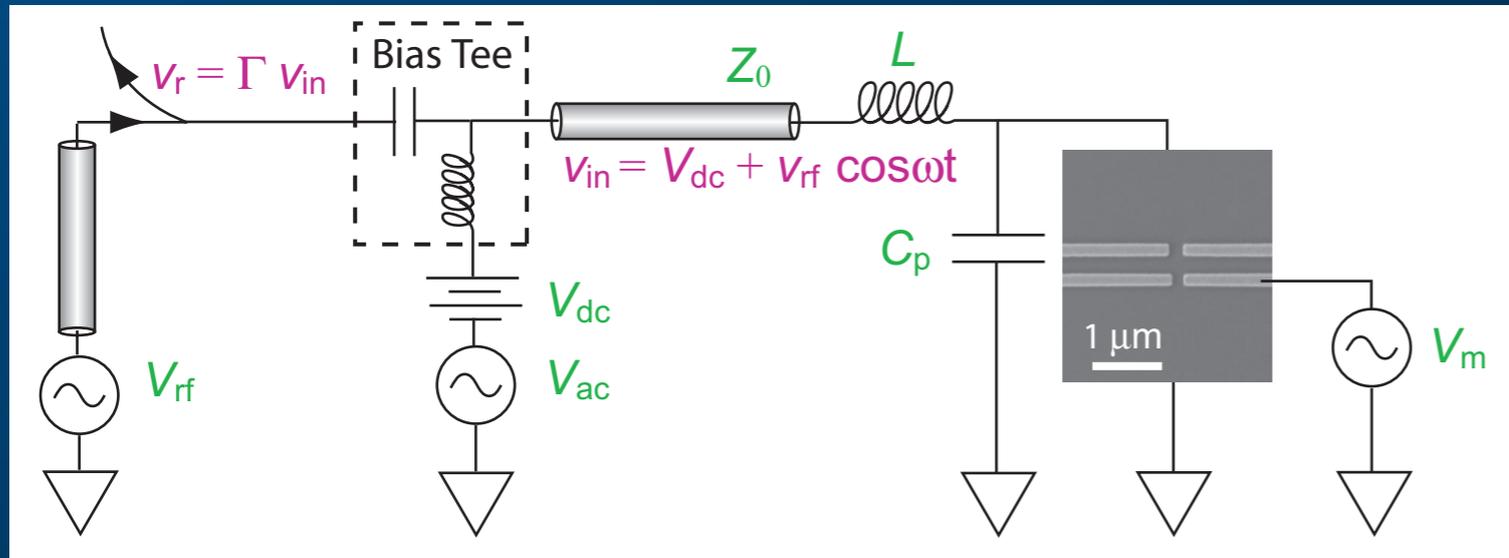
Near the quantum limit



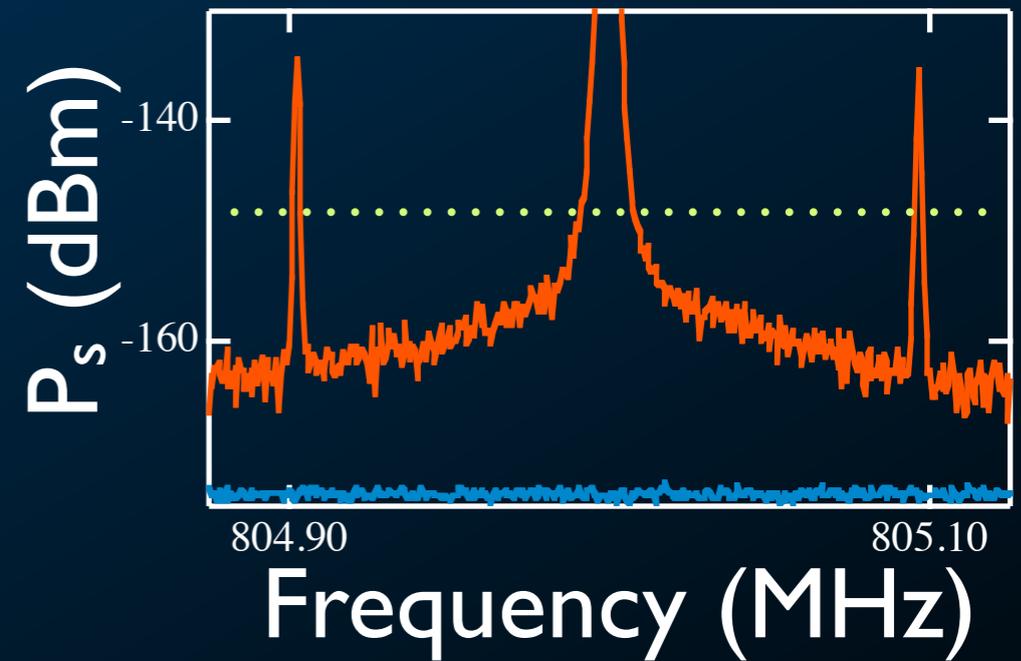
Factor of 4 close
to the quantum limit

W.W. Xue et al.,
Nature Physics 2009

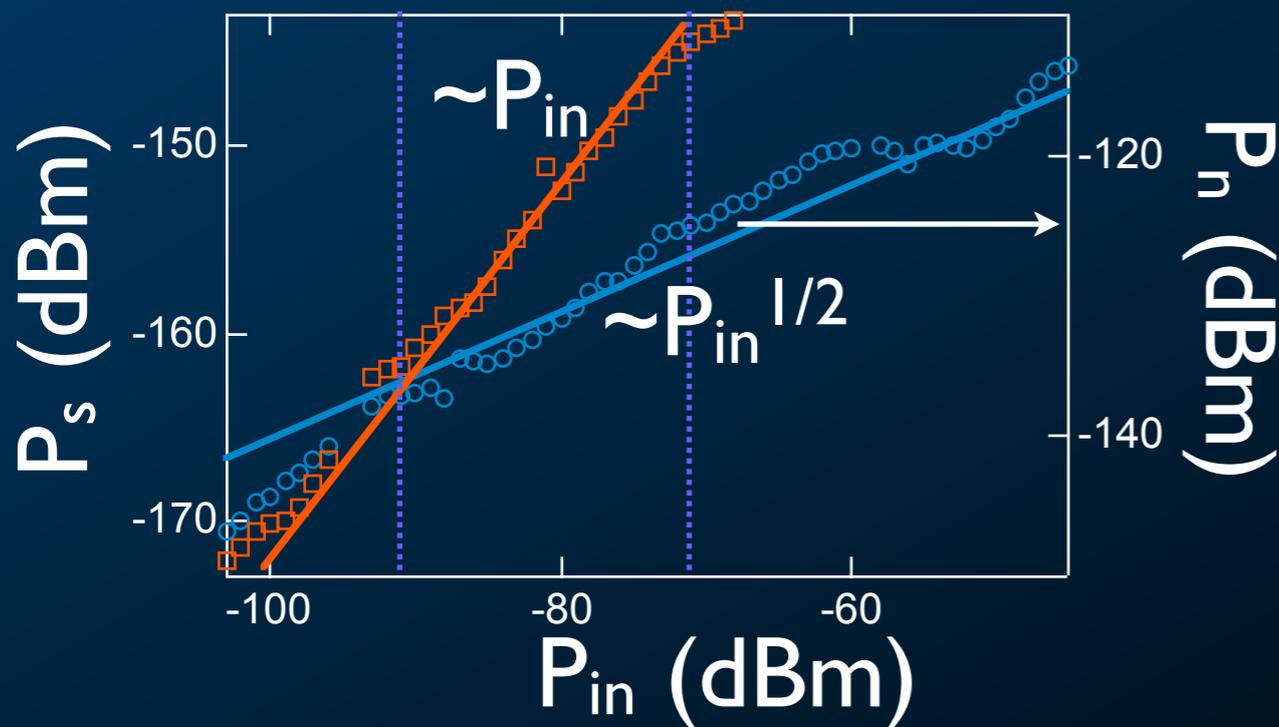
RF-QPC : Shot-noise limited amplification



Signal to noise

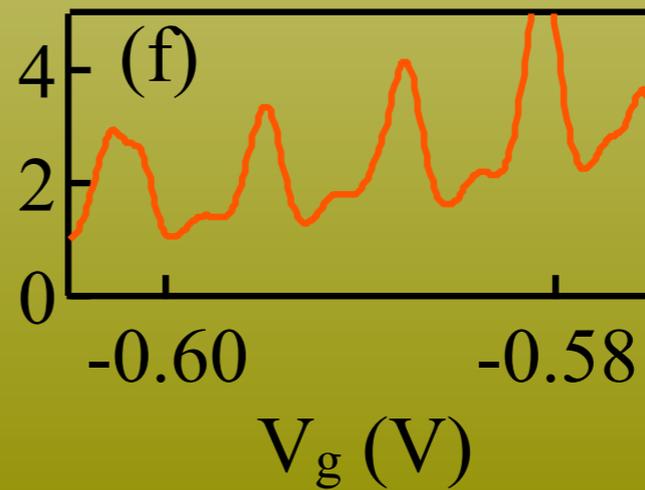
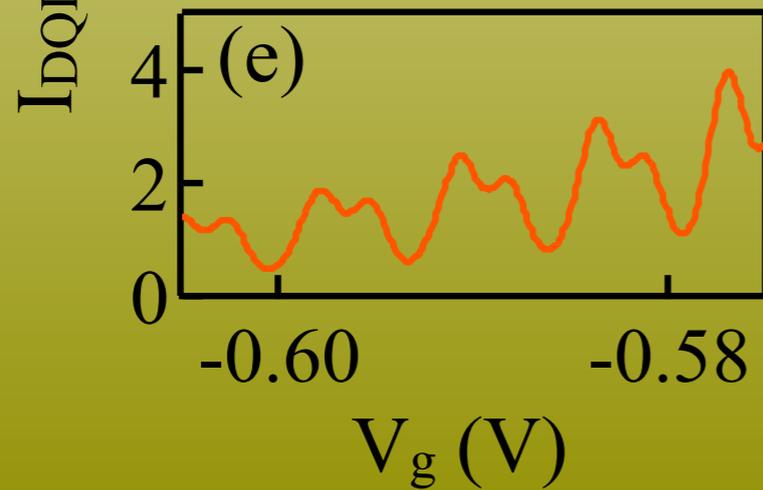
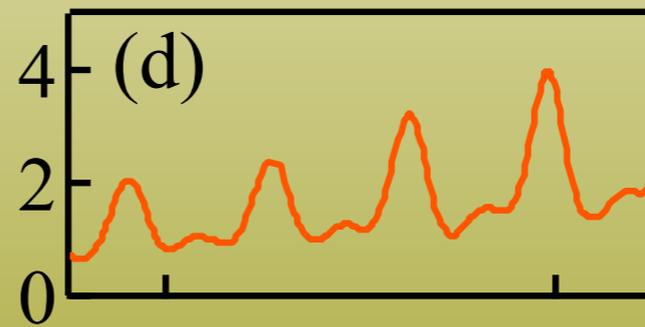
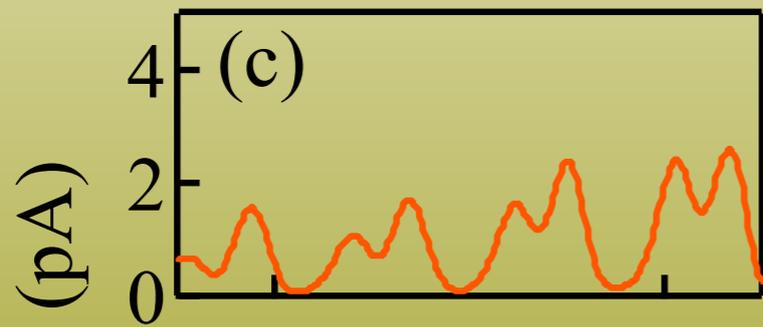
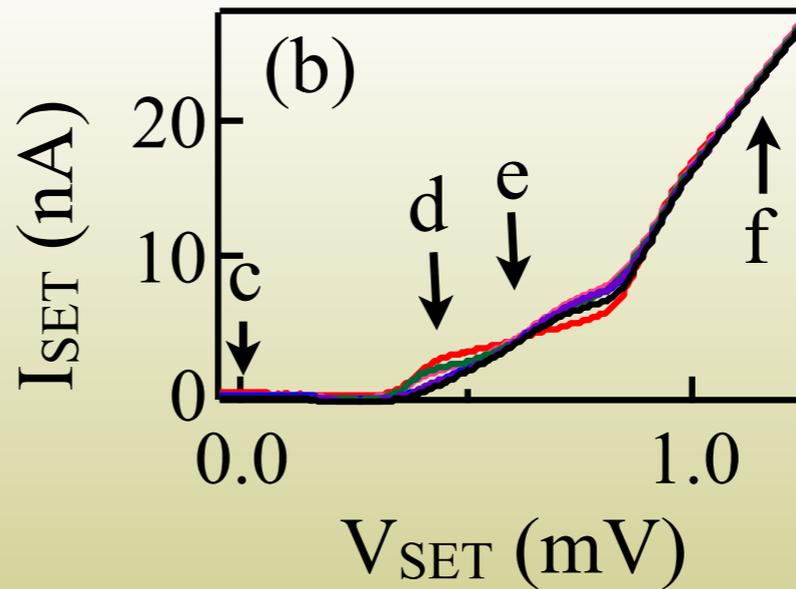
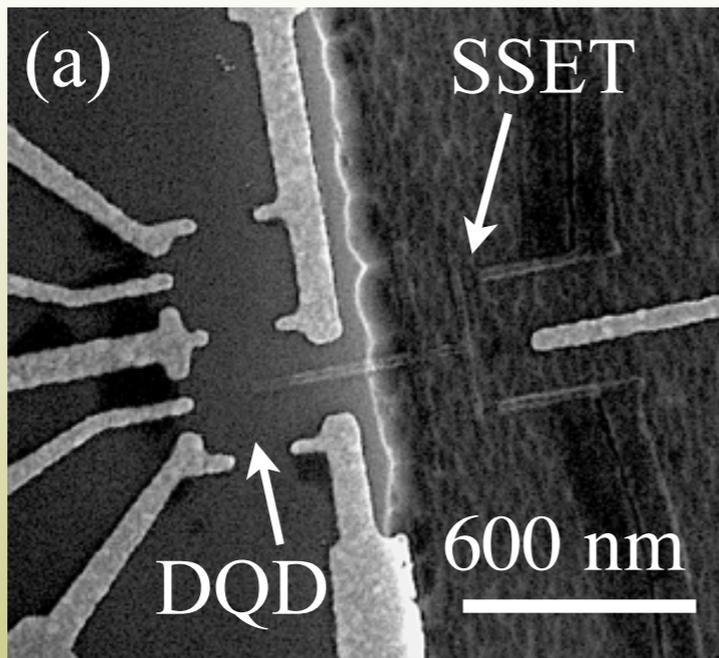


Shot noise limited operation

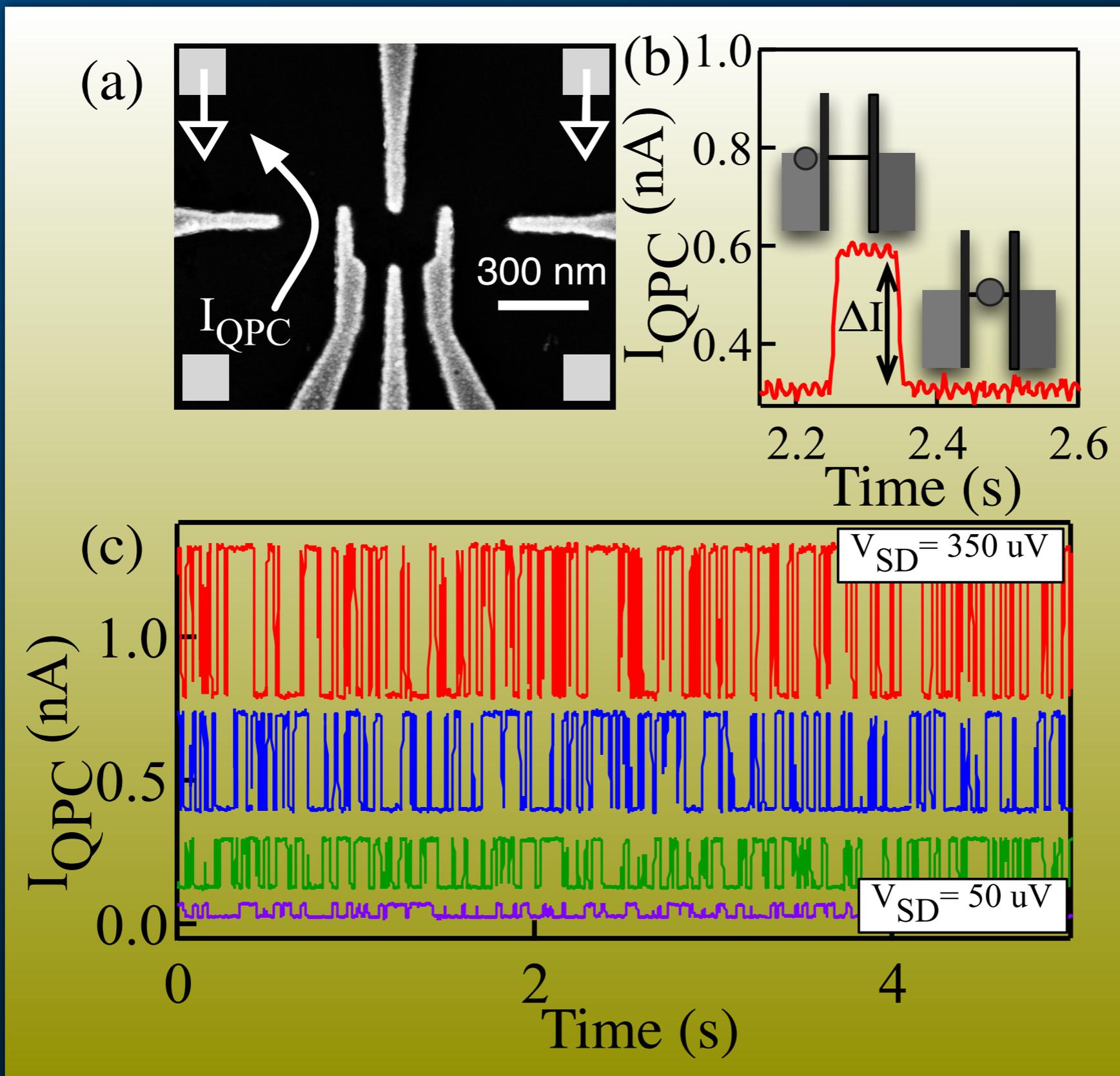


$$\delta G \approx 27 \mu G_0 / \text{Hz}^{1/2}$$

SSET back-action on DQD



QPC back-action on DQD



The proof of innocence



"You observed me speeding? Are you familiar with the Heisenberg uncertainty principle?"