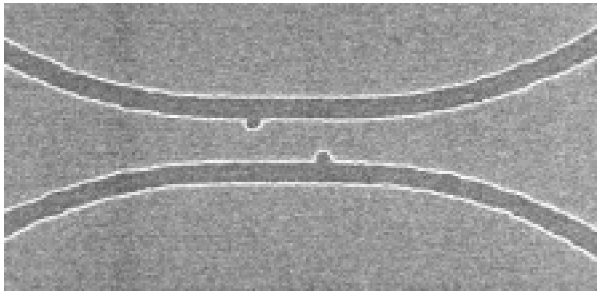
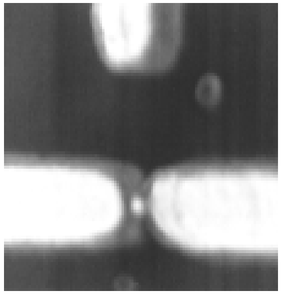
KIAS-KAIST 2003 Workshop on QI and QC, 21 Aug- 22 Aug, Seoul

Nano devices for single photon source and qubit





김 남, 김진희

전자소자 그룹
한국표준과학연구원

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K. Gloos, P. Utko, P. Lindelof
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KRISS

Soo-Hyun Park, Myung-Hwa Jung
KBSI

Hey-Mi So, Ju-Jin Kim
Chonbuk National University

Outline

Part I. Solid state source of single photon

1. *Acousto-electric single photon source: 2DEG*
2. *Future plan with nanotube and nanowire*

Part II. Qubit

1. *Superconducting qubit*
2. *Future plan: qubit with CNT and molecules*

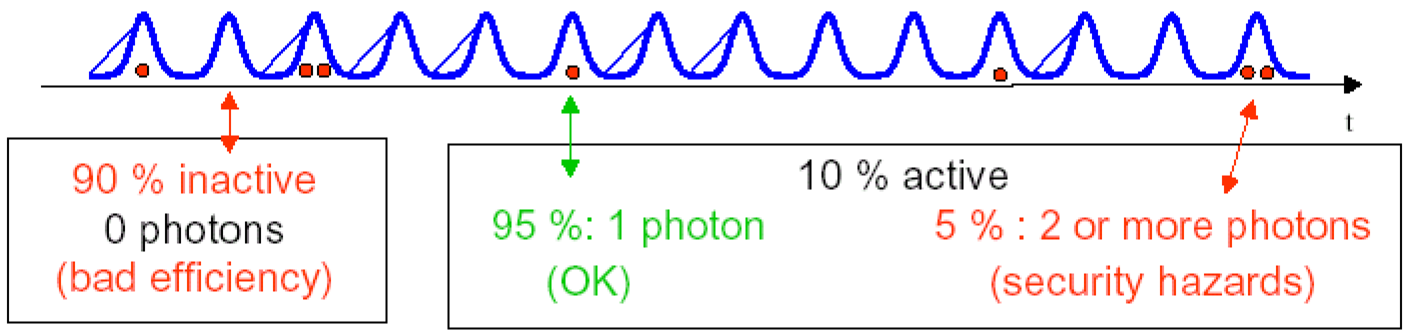
Part I. Solid state source of single photon

Single Photon Source

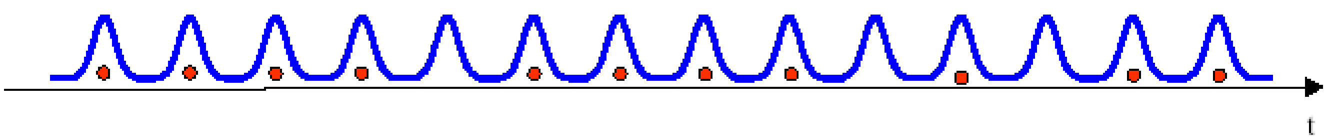
[Ref. I. Abram, CNRS, France]

WHY?

- Attenuated laser pulses have Poisson statistics.



- Truly single photon trains



Better efficiency and better security.

Single photon sources (so far reported)

	spatial	2. coh.	Intensity	temperature
• Parametric downconversion	good	---	10^7/s (10 mW)	room
• Atomic micro-maser	good	(0.17)	---	1 K
• NC diamond color center	bad	0.13	$2 \cdot 10^4$/s	room
• Single molecules	bad	0.27	$5 \cdot 10^6$/s	room
• Turnstile device	bad	---	10^7/s	50 mK
• Quantum dots	bad	< 0.07	$8 \cdot 10^7$/s	5 K

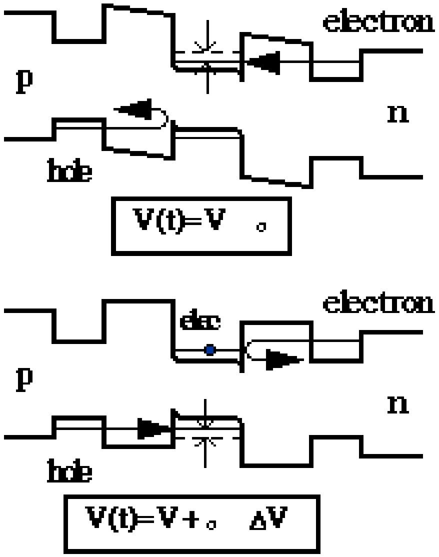
Ref. Michael M. Petersen (NBI)

Single-photon turnstile device

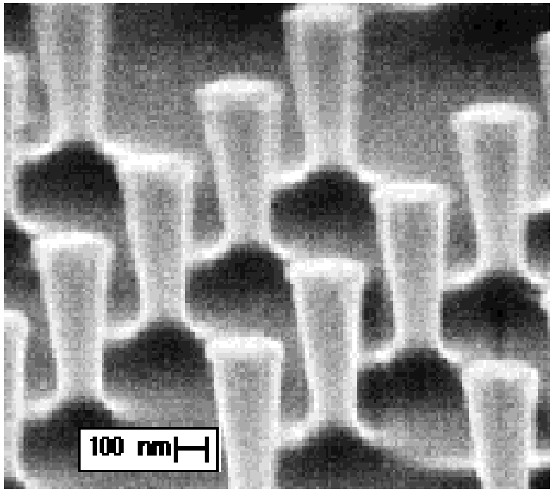
[Kim et. al., Semicond. Sci. Tech., 13, 8A, Stanford, 1998]

Simultaneous Coulomb blockade for electrons and holes in a p-n junction

(a)

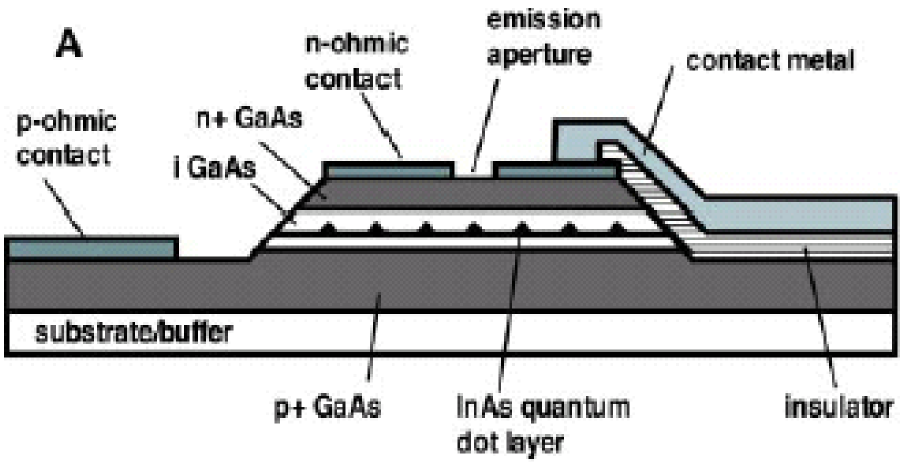


(b)



Semiconductor quantum dots

[Yuan et. al., Science, **295**, Cambridge, 2002]

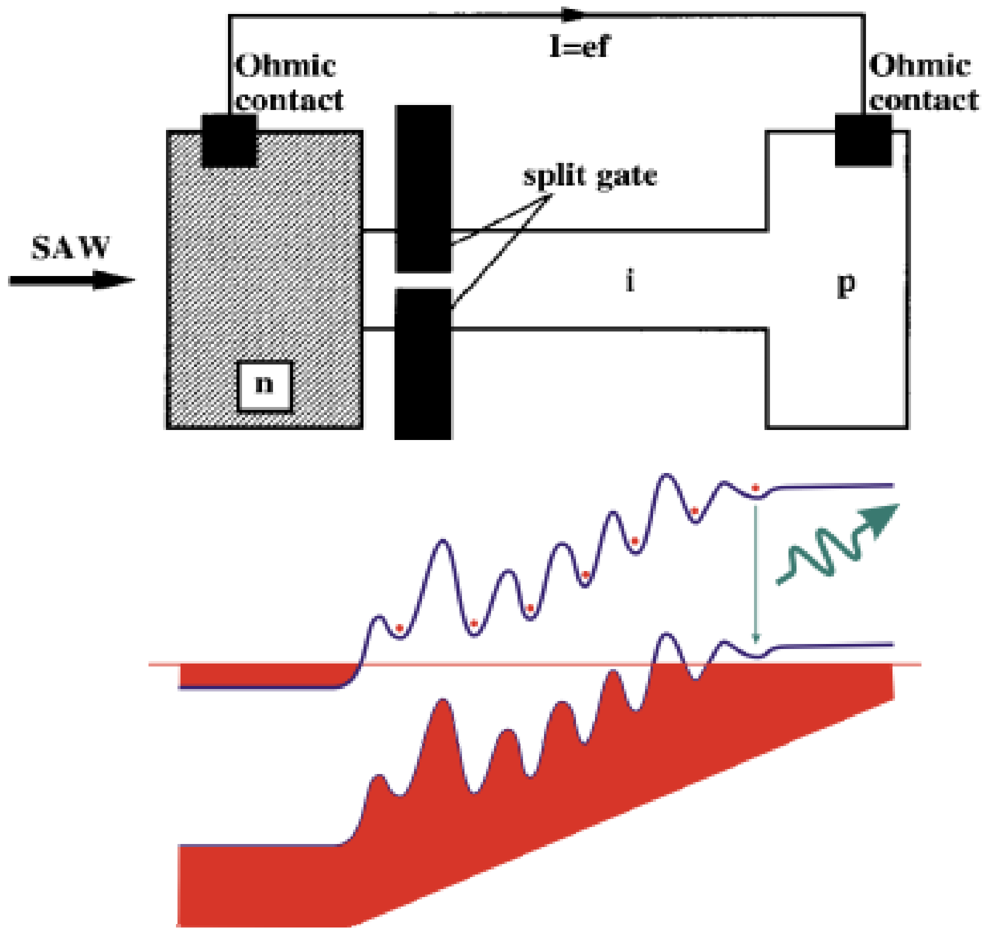


p-i-n diode containing
InAs quantum dots
on a GaAs substrate.

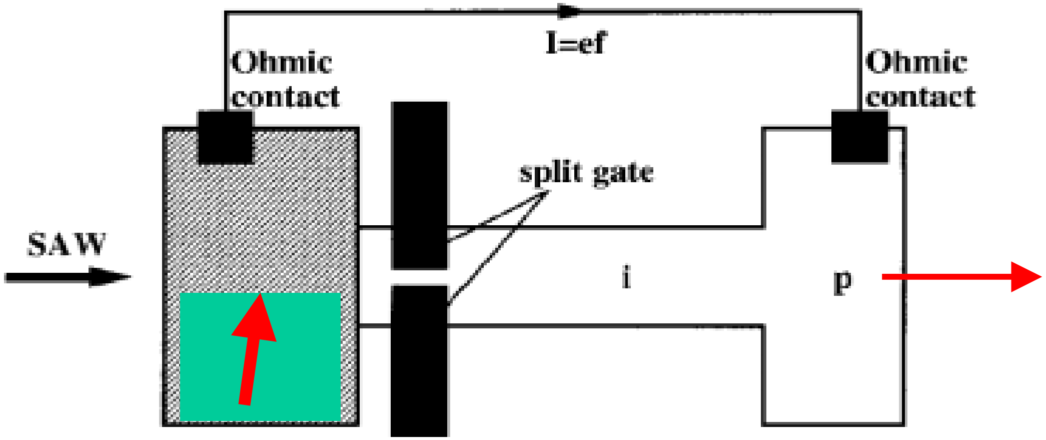
Acousto-electric single-photon source

[Cambridge group (PRA 62, 01183, 2000)]

2DEG n-i-p junction

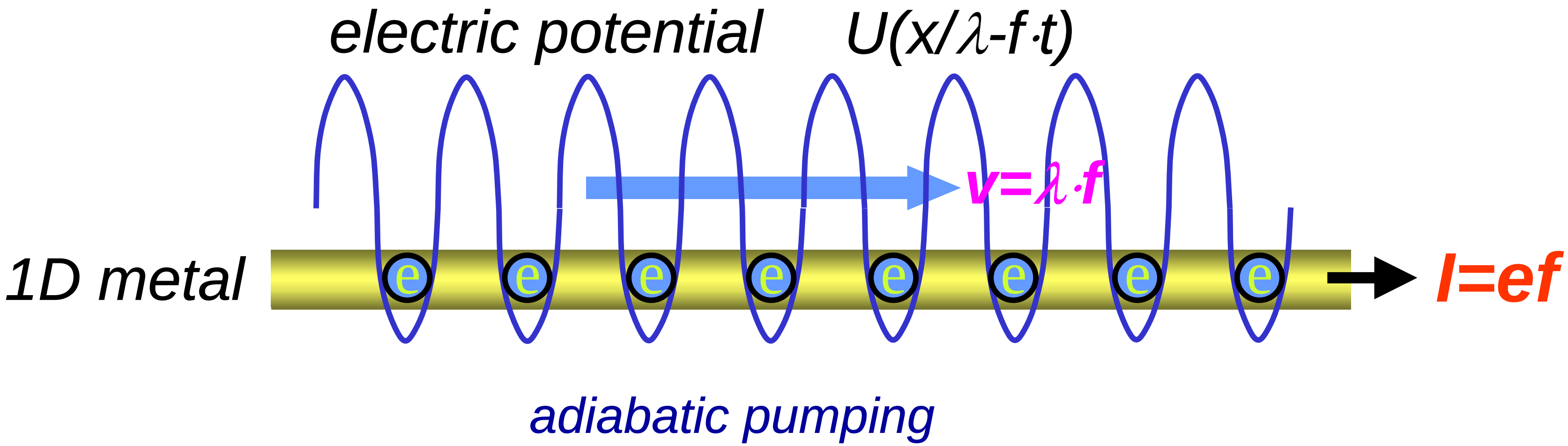


Polarized single photon



Principle of adiabatic single electron pumping

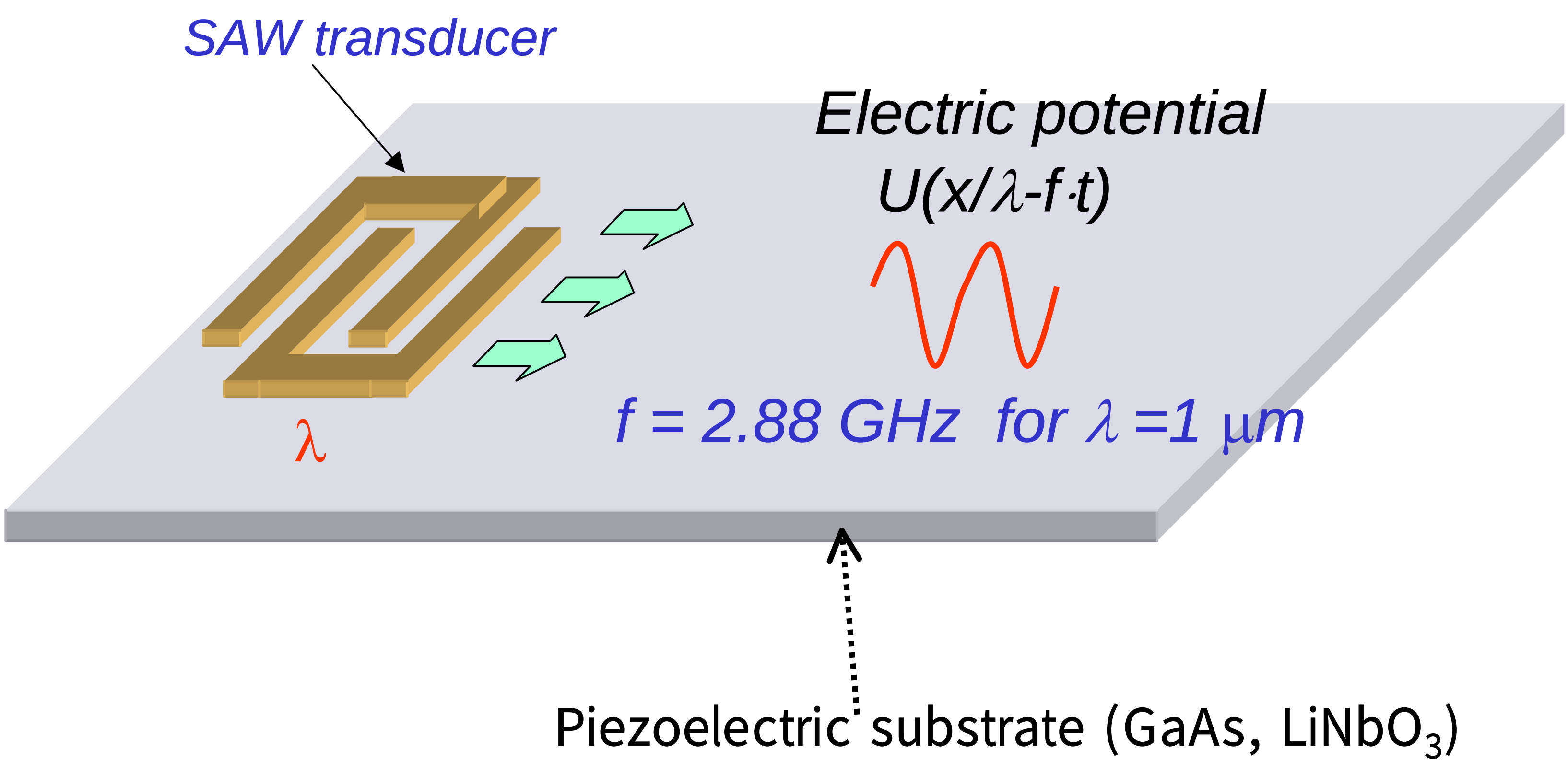
[Altshuler and Glazman, Science(1999)]



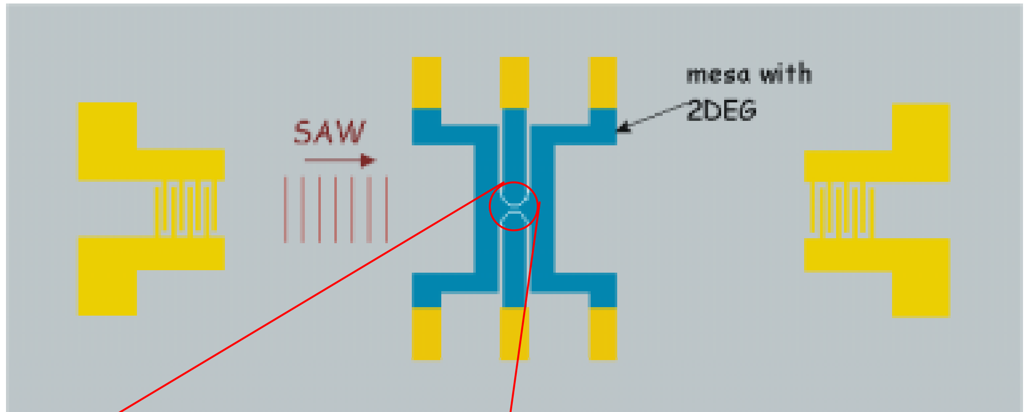
DC current, *I = ef*

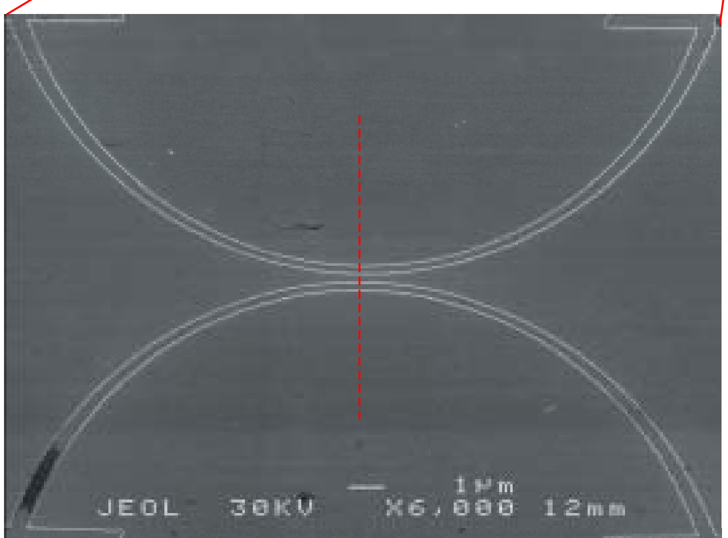
SAW-induced electric potential

(SAW=surface acoustic wave)

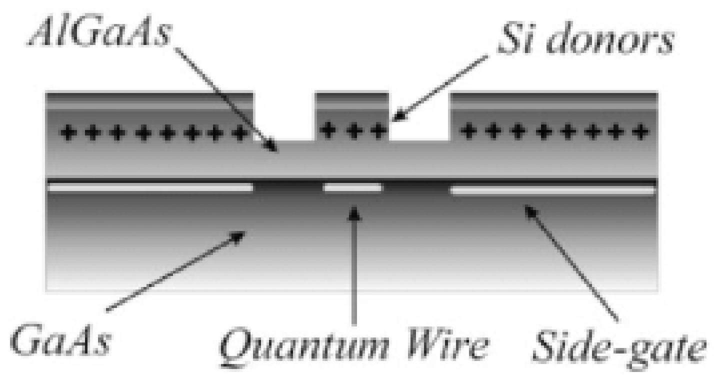


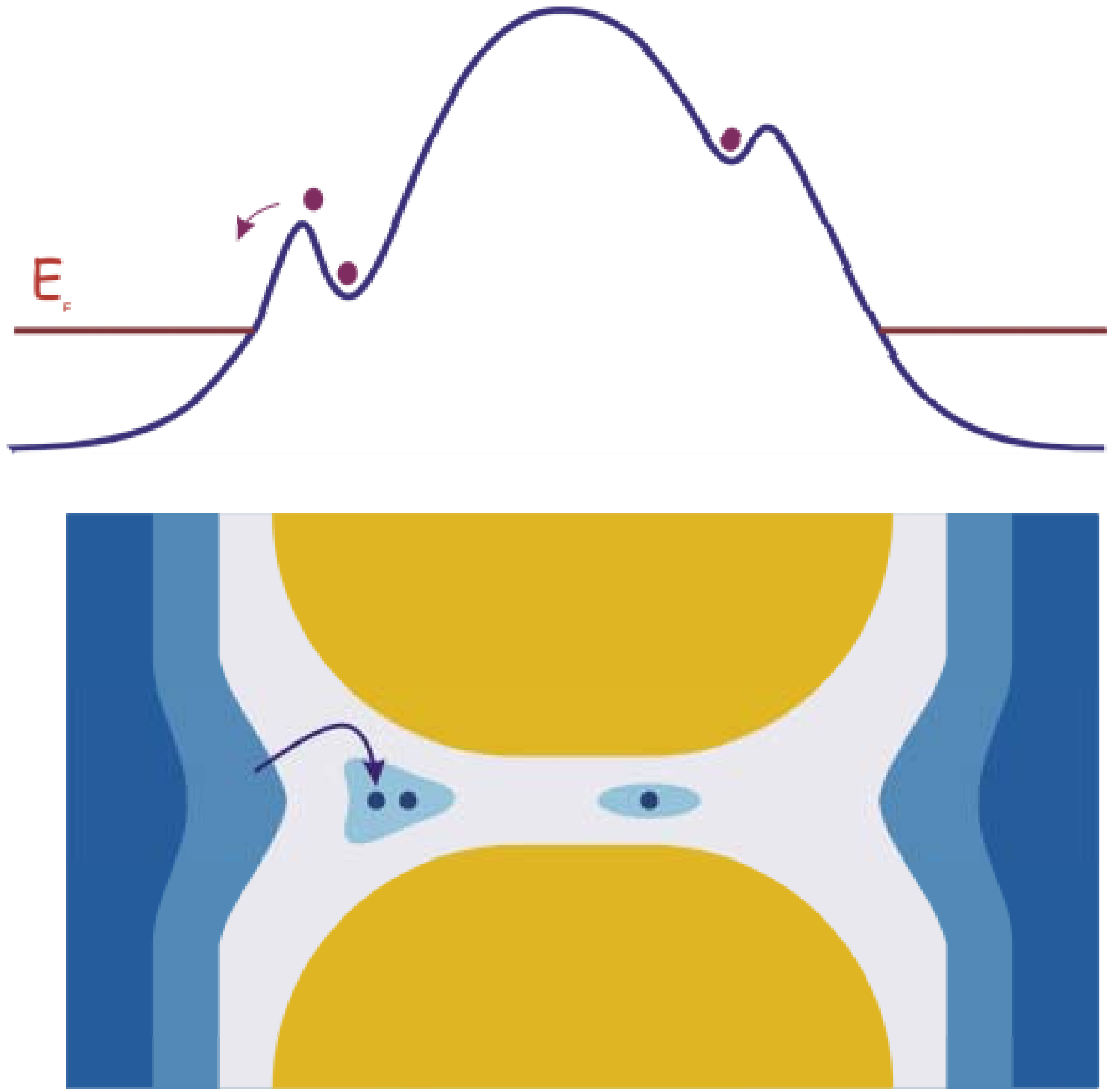
SAWPHOTON (Project IST-2000-26020, QIPC)
[NBI, Cavendish lab., Scuola Nomale Superiore, Toshiba Europe]

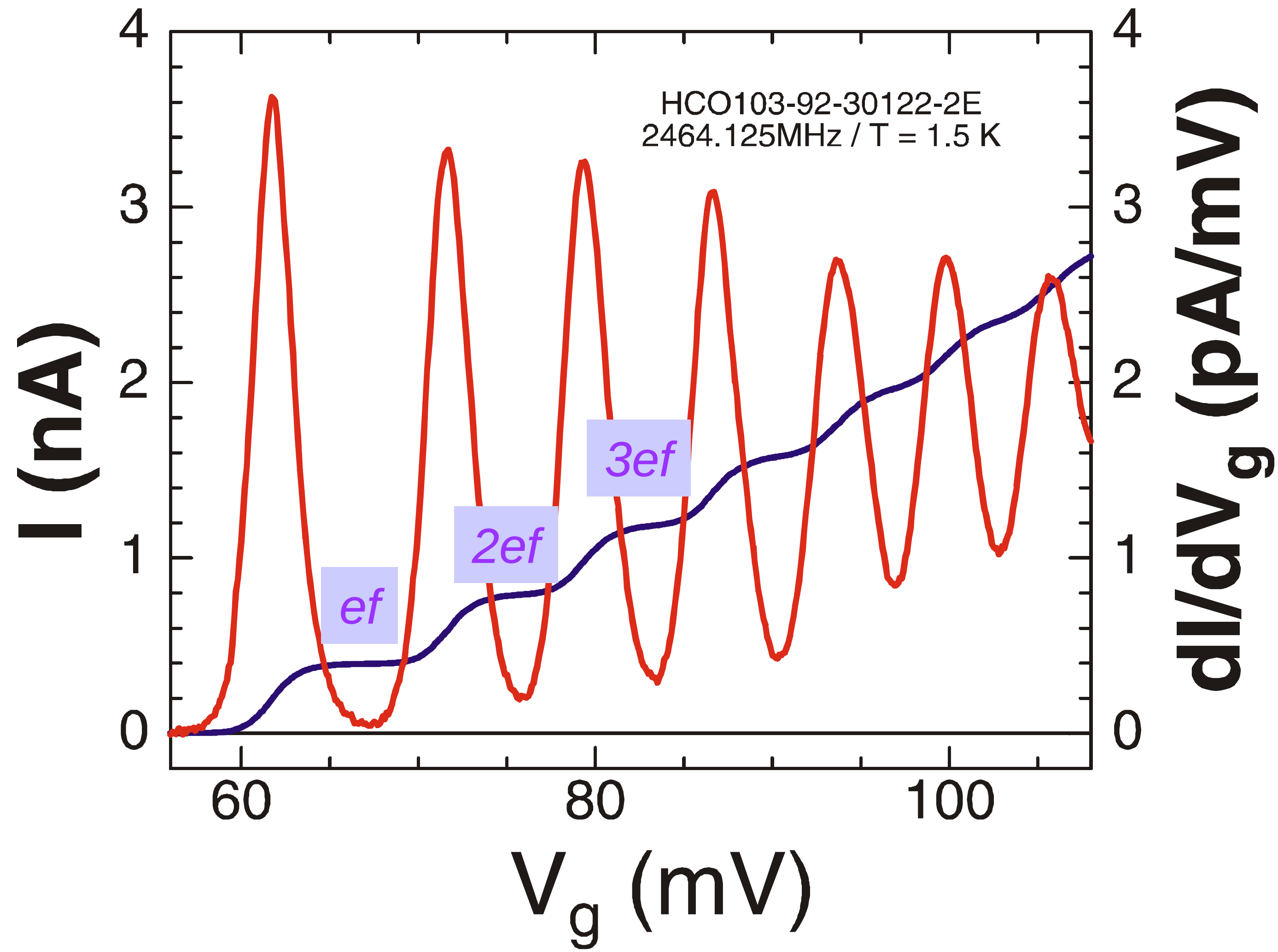




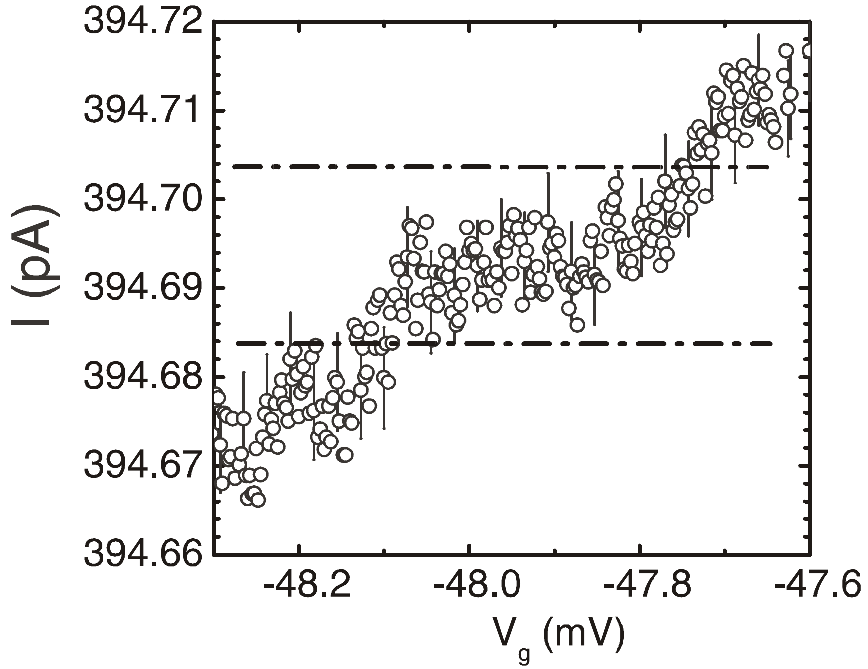
Cross section




E
F


HCO103-92-30122-2E
2464.125MHz / T = 1.5 K
ef
2ef
3ef
I (nA)
dI/dV_g (pA/mV)
V_g (mV)
0
1
2
3
4
60
80
100

error of ef = 25 ppm

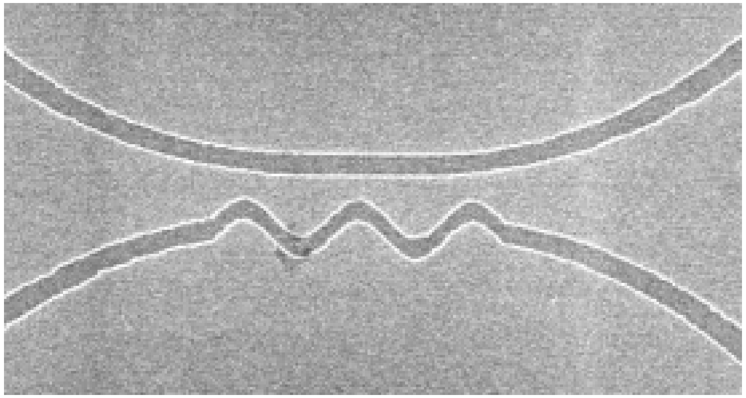


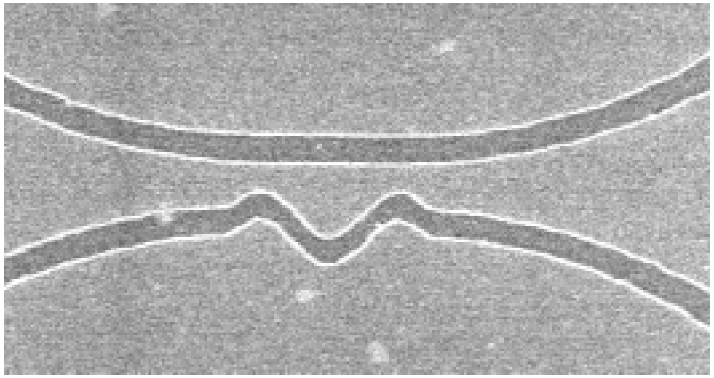
Problems to be solved

- Electron injection rate > e-h recombination rate

(300 ps) (1000 ps for GaAs)

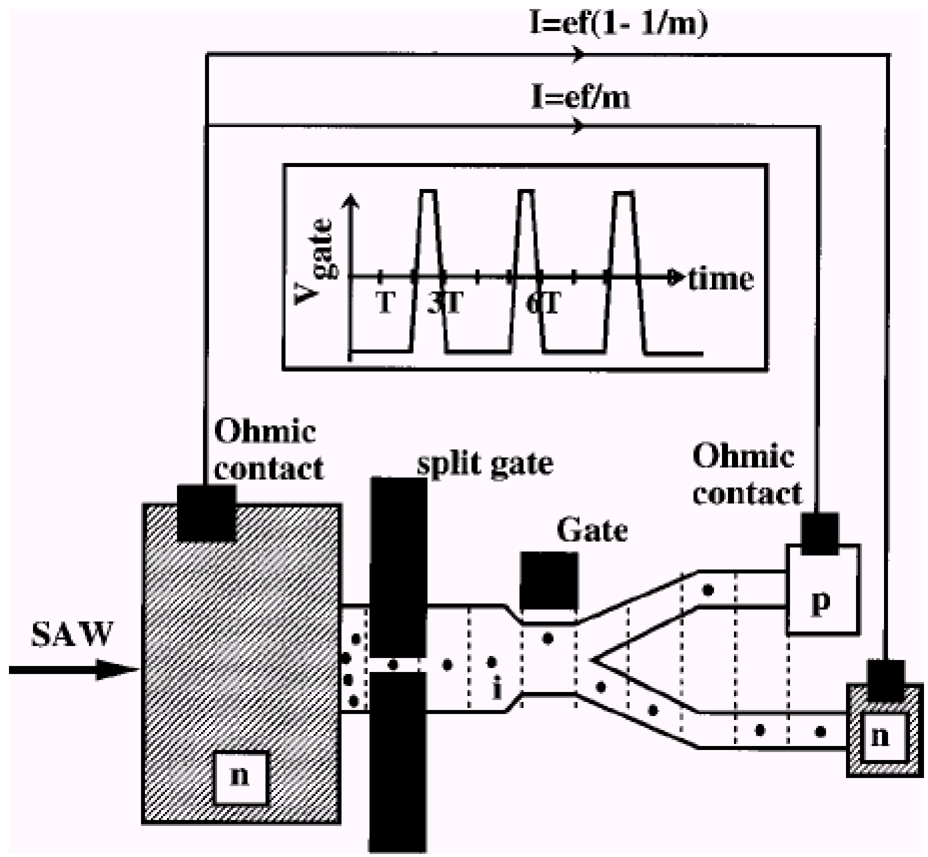
• *Slow down the single electron injection rate*



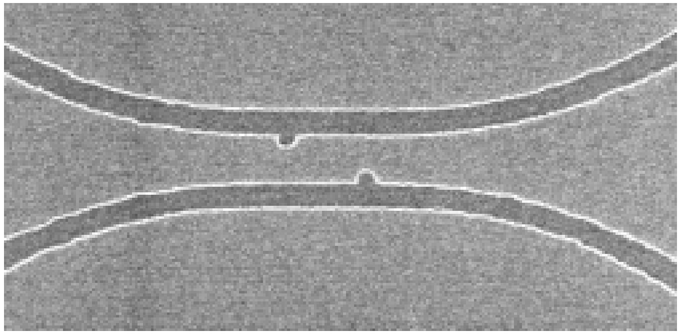


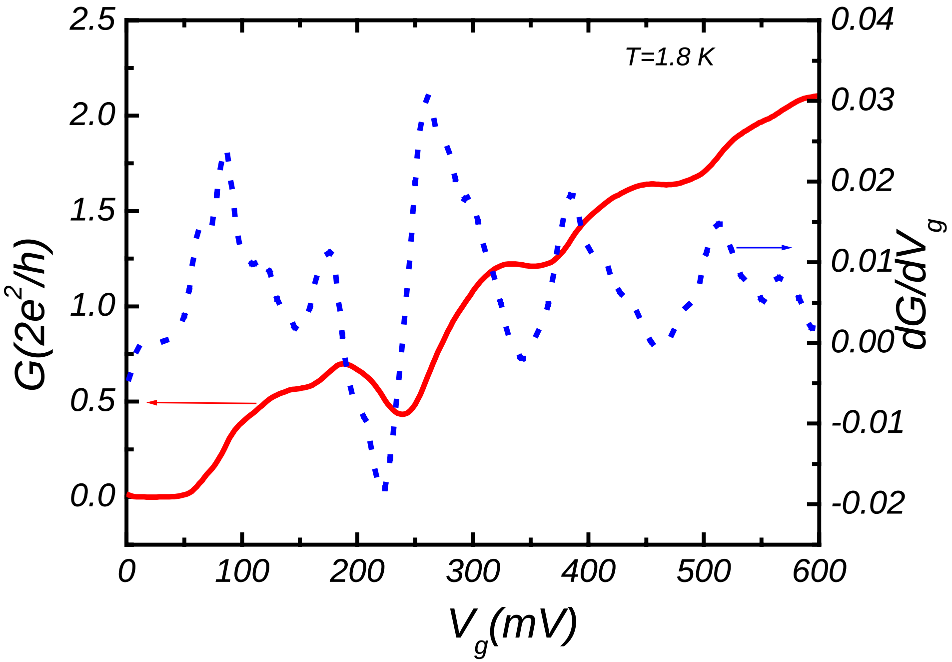
High-frequency acousto-electric single-photon source

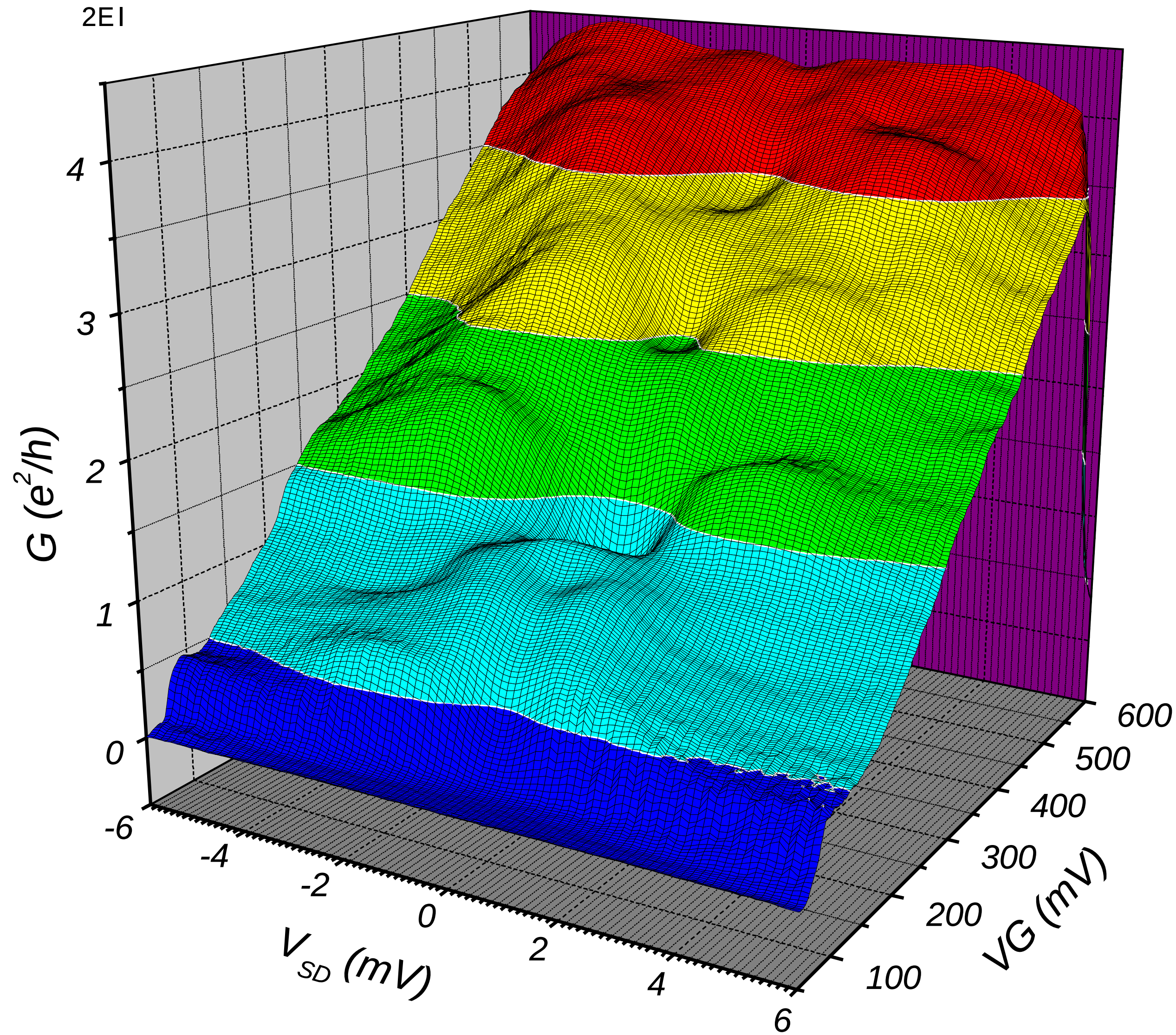
C. L. Foden,[1] V. I. Talyanskii,[2] G. J. Milburn,[3] M. L. Leadbeater,[1] and M. Pepper[1,2]
[1]*Cambridge Research Laboratory, Toshiba Research Europe Ltd., 260 Cambridge Science Park,*



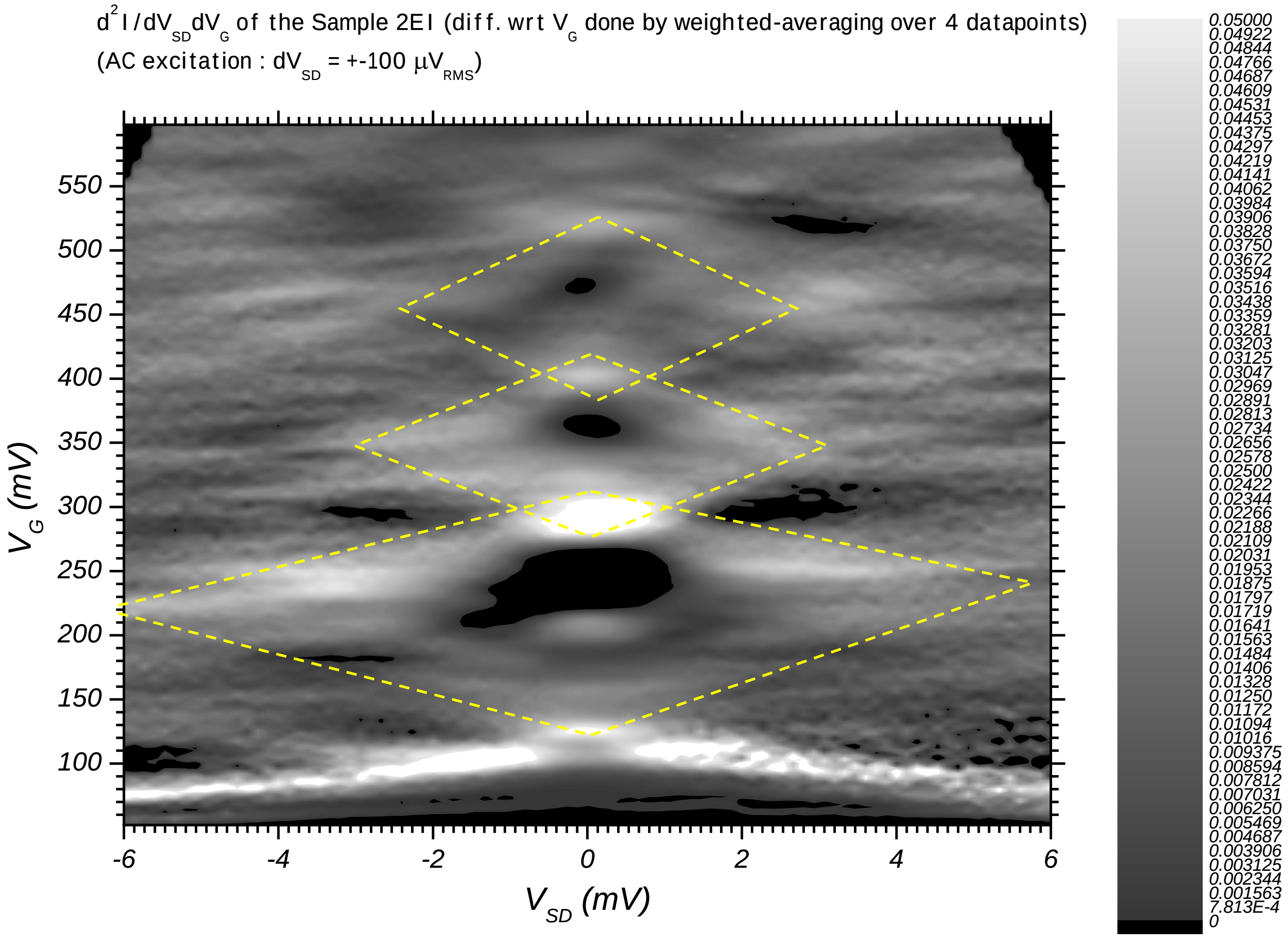
Preliminary results (NBI & KRISS)







2EI
G (e²/h)
0
1
2
3
4
-6
-4
-2
0
2
4
6
V_SD (mV)
100
200
300
400
500
600
VG (mV)



d²I/dV_SD dV_G of the Sample 2EI (diff. wrt V_G done by weighted-averaging over 4 datapoints)
(AC excitation : dV_SD = +-100 μV_RMS)
V_G (mV)
550
500
450
400
350
300
250
200
150
100
V_SD (mV)
-6
-4
-2
0
2
4
6
0.05000
0.04922
0.04844
0.04766
0.04687
0.04609
0.04531
0.04453
0.04375
0.04297
0.04219
0.04141
0.04062
0.03984
0.03906
0.03828
0.03750
0.03672
0.03594
0.03516
0.03438
0.03359
0.03281
0.03203
0.03125
0.03047
0.02969
0.02891
0.02813
0.02734
0.02656
0.02578
0.02500
0.02422
0.02344
0.02266
0.02188
0.02109
0.02031
0.01953
0.01875
0.01797
0.01719
0.01641
0.01563
0.01484
0.01406
0.01328
0.01250
0.01172
0.01094
0.01016
0.009375
0.008594
0.007812
0.007031
0.006250
0.005469
0.004687
0.003906
0.003125
0.002344
0.001563
7.813E-4
0

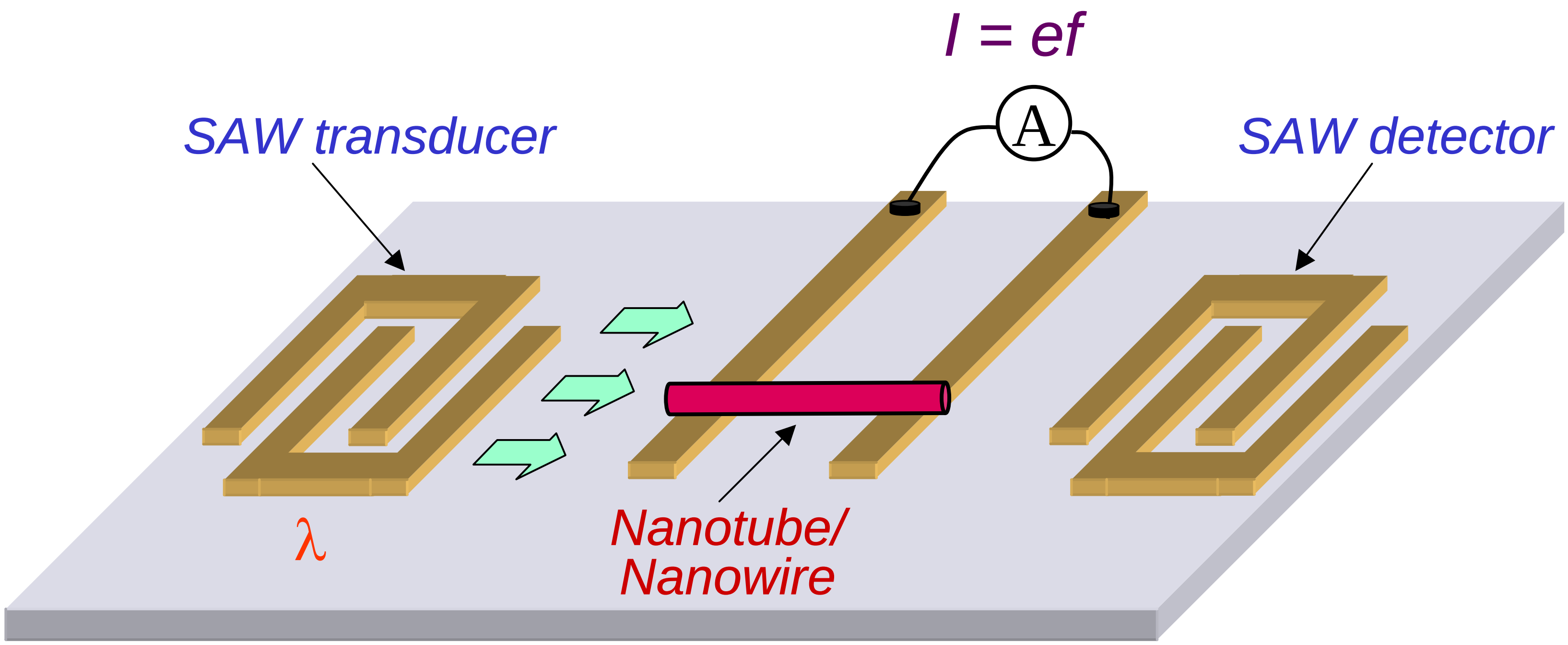
Problems to be solved

- *difficult to cool down below 1 K due to high rf power*

↓

2DEG on top of $LiNbO_3$
(NBI & KRISS)

SAW를 이용한 1D 나노선 전류발생기

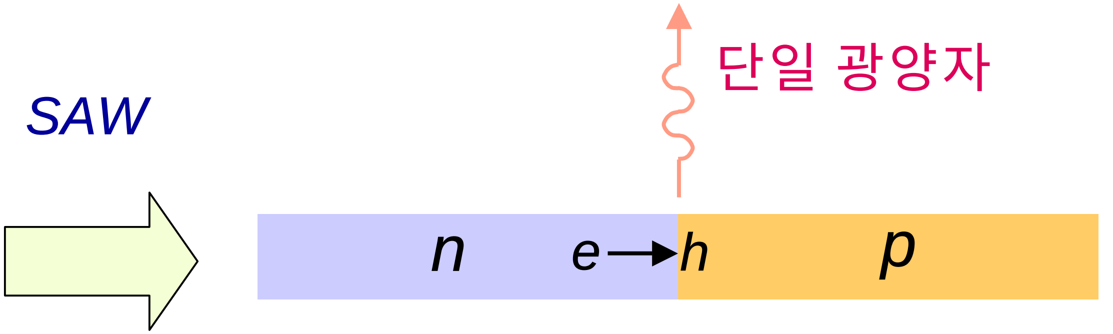


$$f = v/\lambda, \quad v = 2.8 \text{ km/s}$$

i.e., f = 2.88 GHz for λ =1 μm ⇒ I = ef = 0.46 nA

SAW 단일광양자 발생기

1 D pn 접합

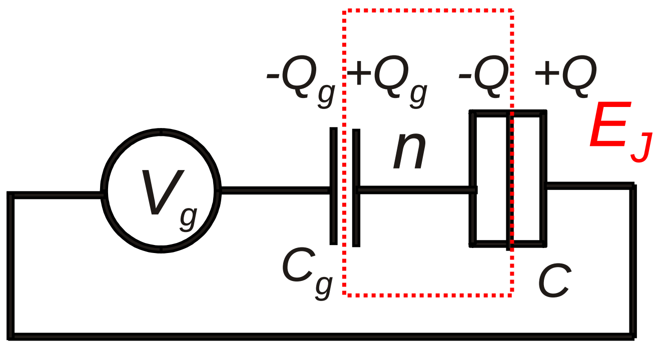


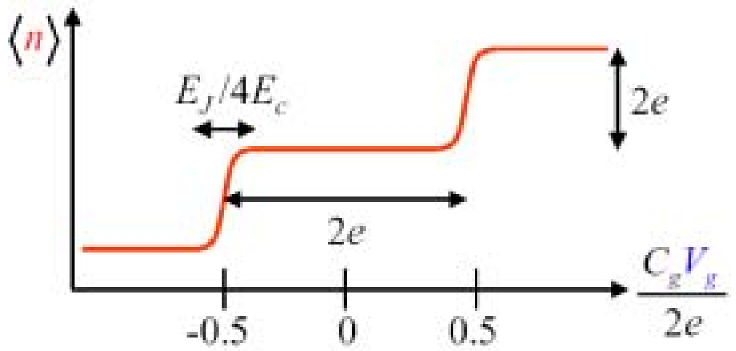
Part II. Qubit

NMR	*7 qubits (MIT)*
Trapped Ions	*4 qubits (NIST)*
Photons	*3 qubits (ENS Paris)*

Cooper pair	*2 qubit (NEC, Saclay, Chalmers)*
Flux qubit	*2 qubit (Delft)*
Quntum dot	*1 qubit*

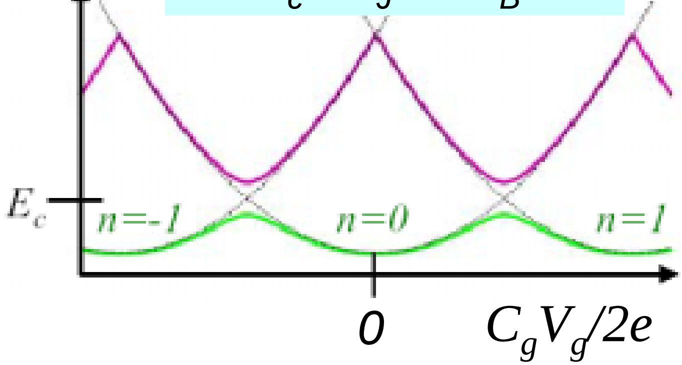
Single Cooper pair box





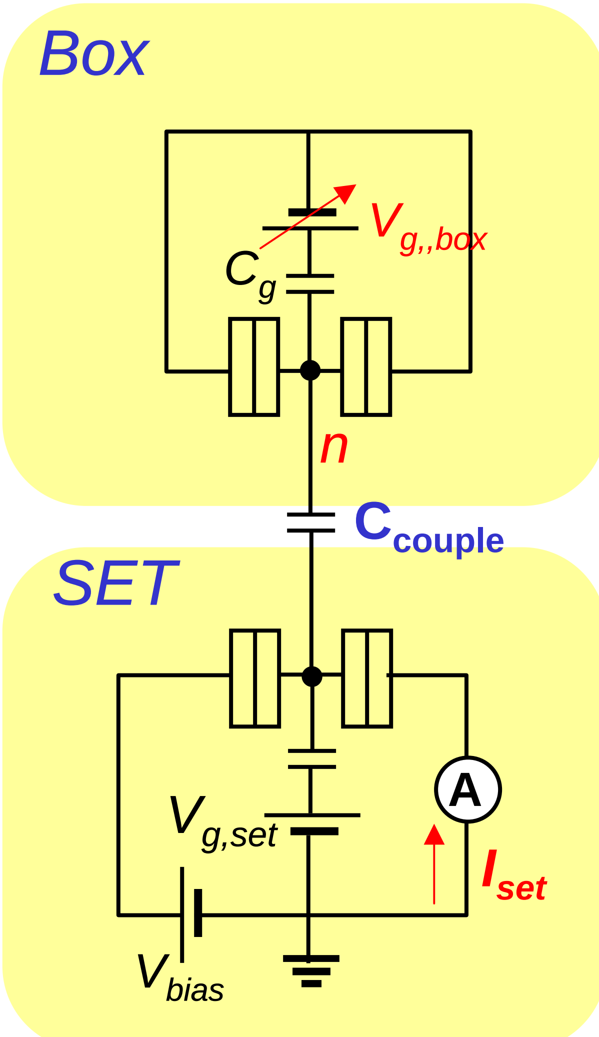
$$E=4E_c(n-Q_g/2e)^2-E_J\cos\phi$$

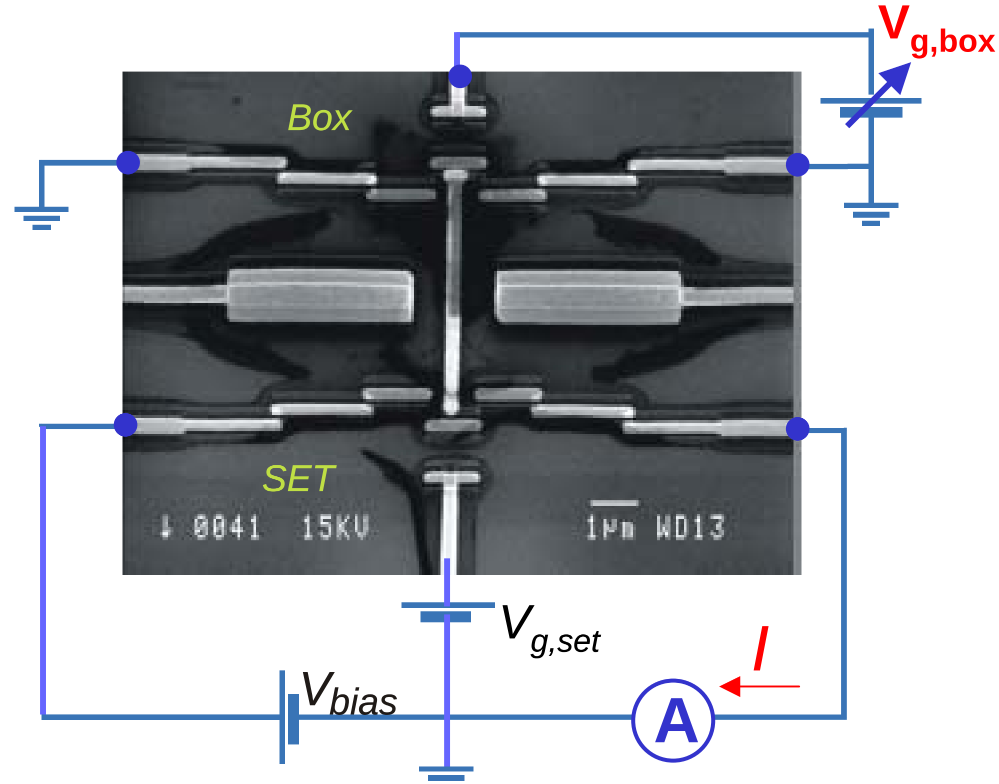
$\Delta > E_c > E_J >> k_B T$

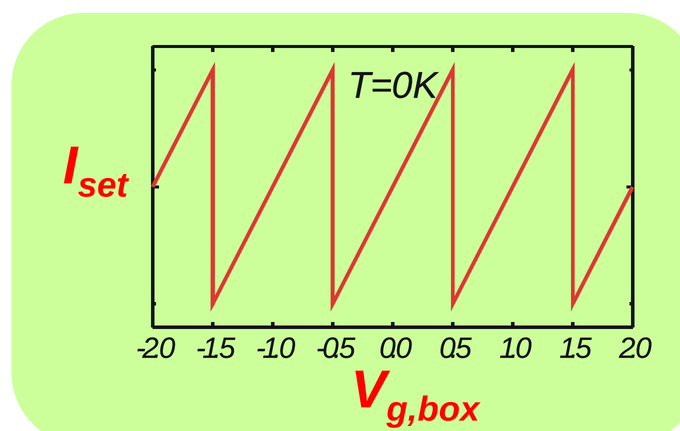


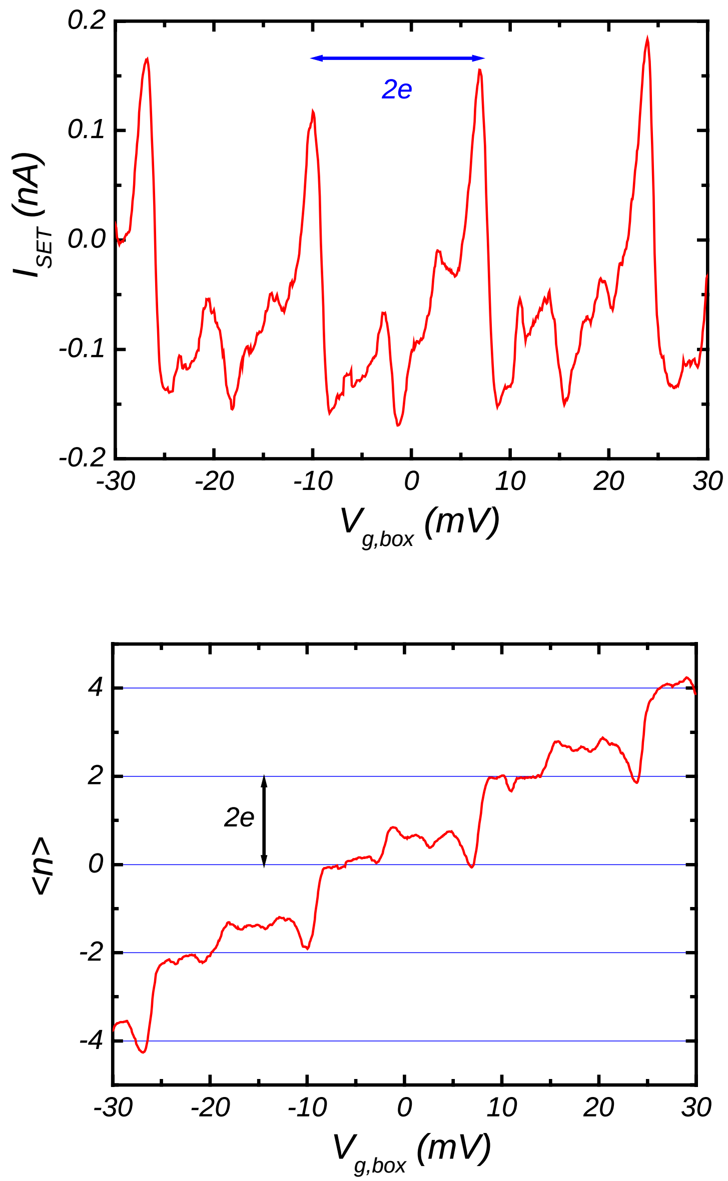
$\Rightarrow$ Qubit

Single superconducting Qubit









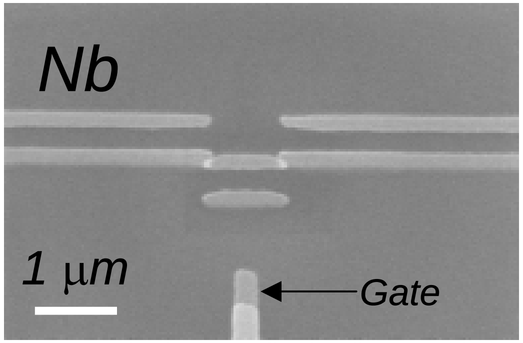
$E_c \sim 170\ \mu eV$

$\Delta_{Al} \sim 200\ \mu eV$

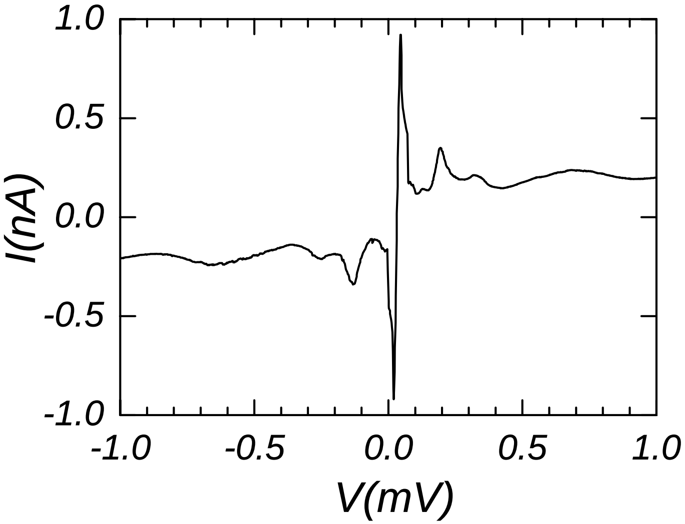
$E_J \sim 1\ \mu eV$

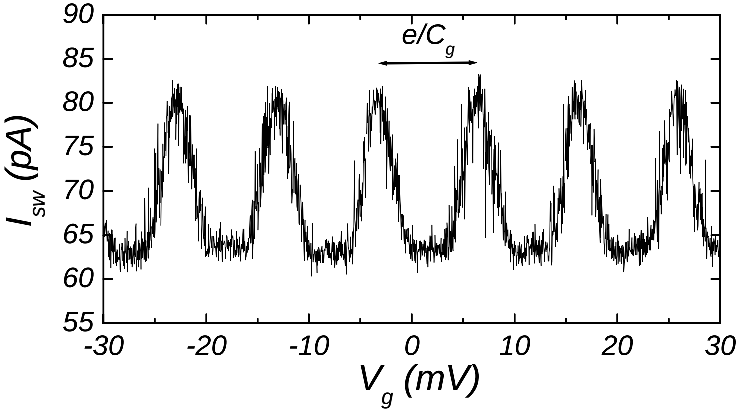
$R_T \sim 12\ M\Omega$

Single Cooper-pair transistor (SCT)
Current bias mode



$E_c \sim 30\ \mu eV$
$E_J \sim 30\ \mu eV$
$R_T \sim 80\ k\Omega$
$\Delta_{Nb} \sim 800\ \mu eV$





Superconducting qubits

	# of qubits	Qubit type	Read out	T_ϕ
NEC	2	charge	qp tunneling	~ 10 ns
Chalmers	1	charge	rf SET	~ 10 ns
Saclay	1	charge+phase	JJ	~ 500 ns
Delft	1	phase	SQUID	?
KRISS	1(?)	charge	SET (Bloch transistor)	?

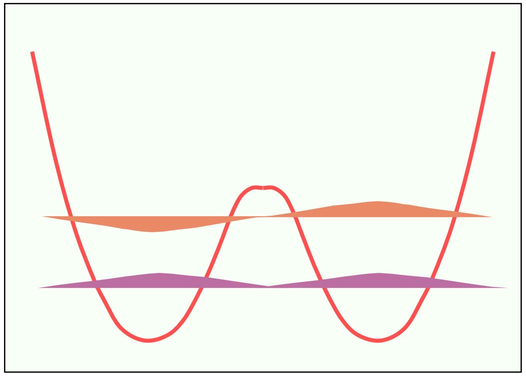
Multiple quantum dots on CNT

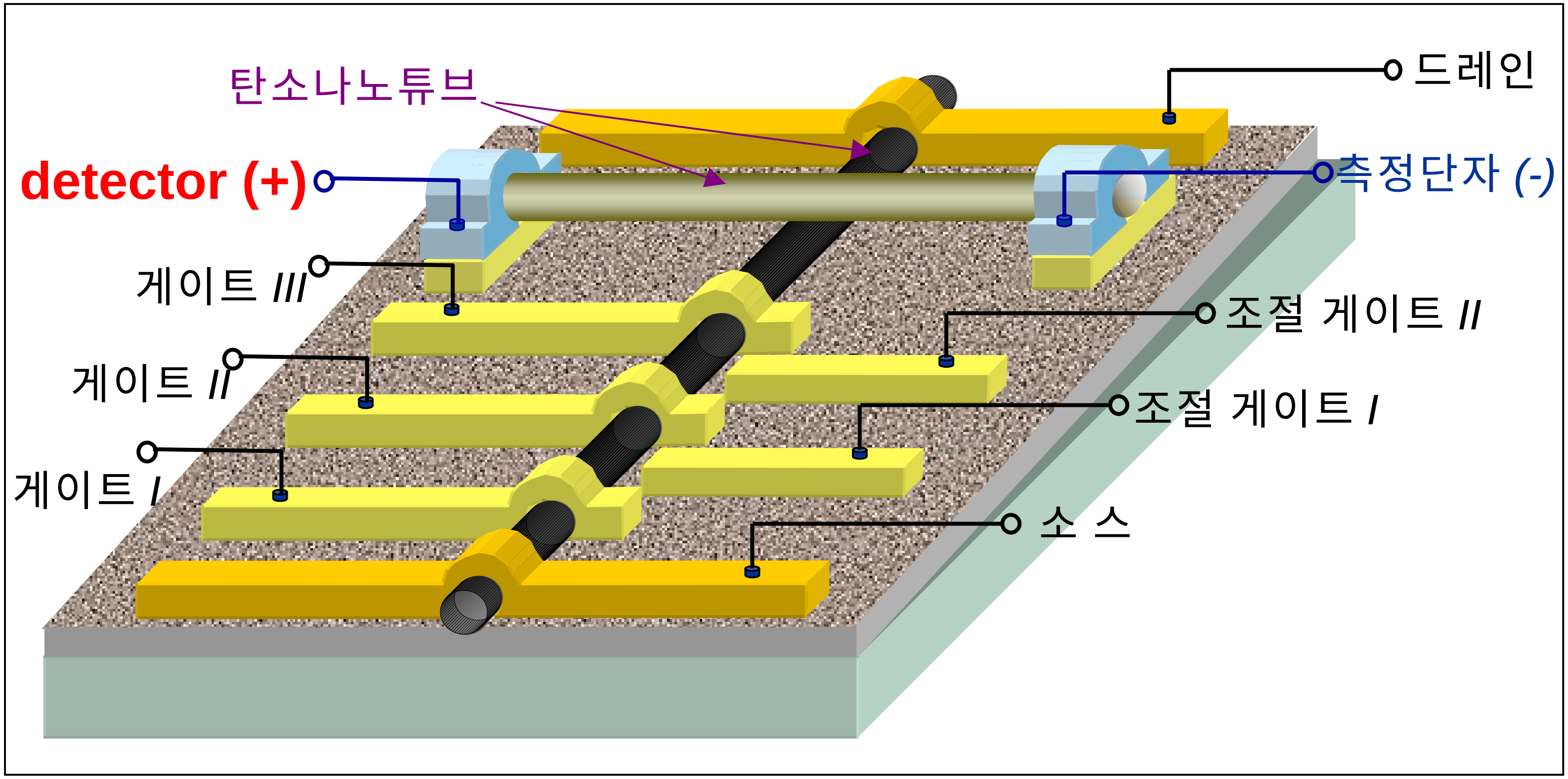
Why Carbon Nanotube ?

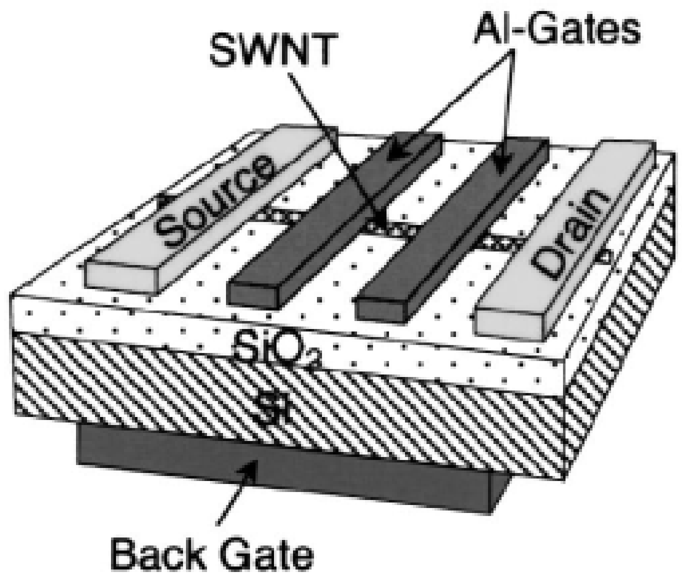
Ideal 1 D quantum conductor

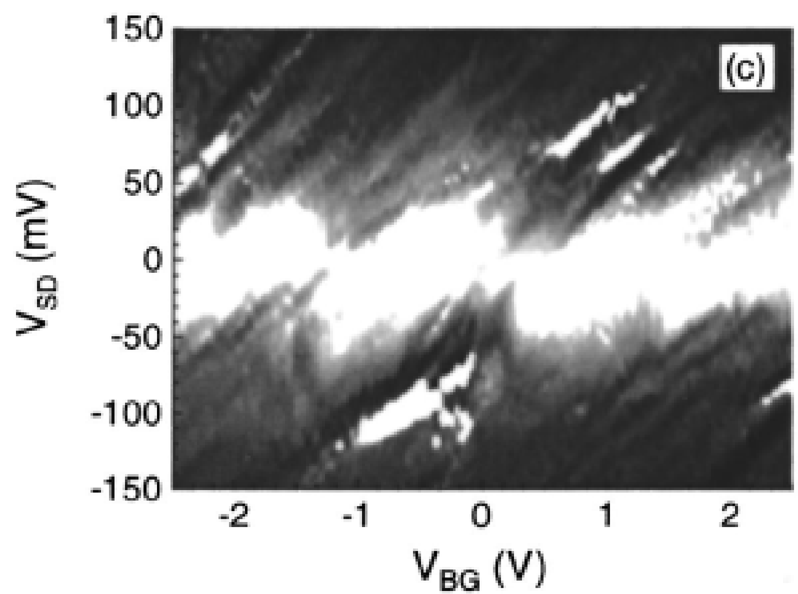
→ *ballistic, long coherent length*

→ *relatively easy to fabricate*

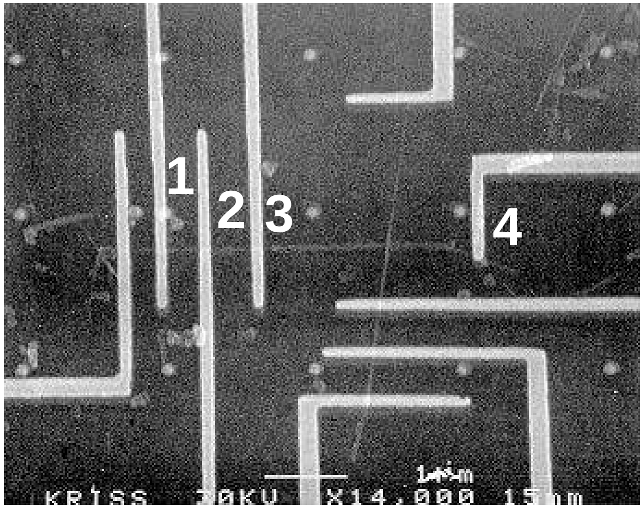


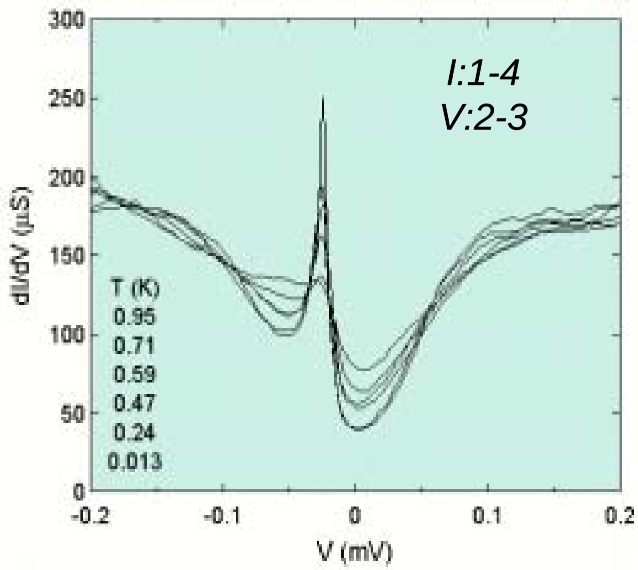


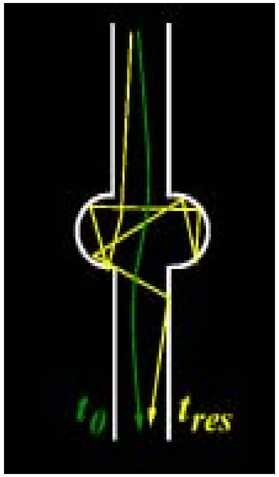

SWNT
Al-Gates
Source
Drain
SiO2
Si
Back Gate

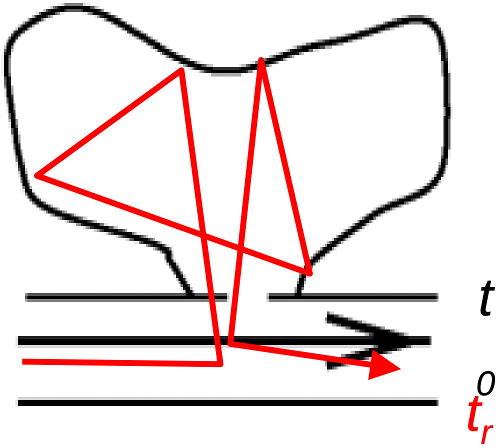

(c)
150
100
50
0
-50
-100
-150
-2
-1
0
1
2
VSD (mV)
VBG (V)

Fano resonance in crossed CNTs



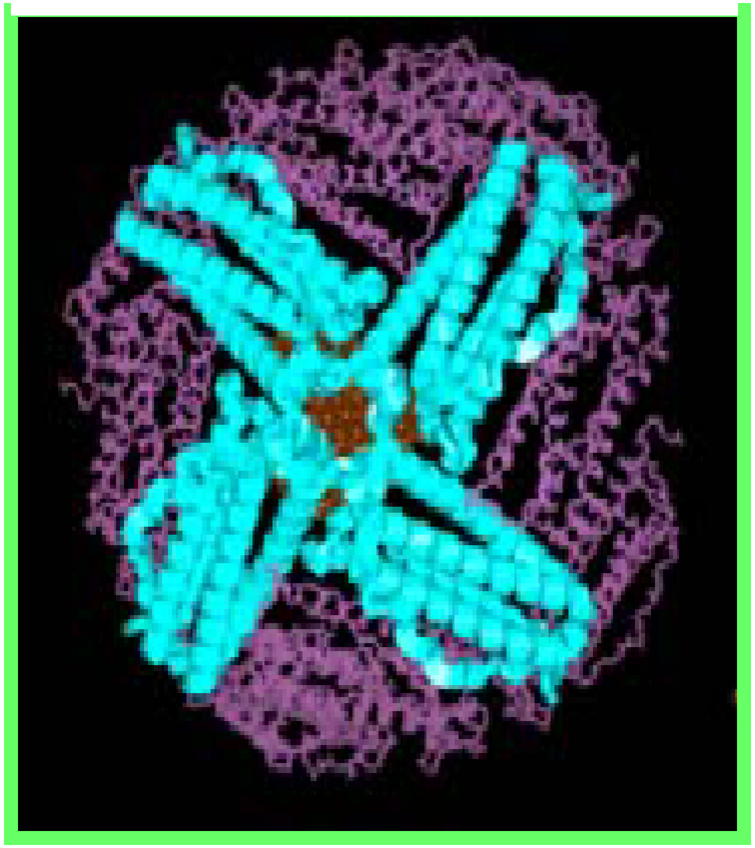




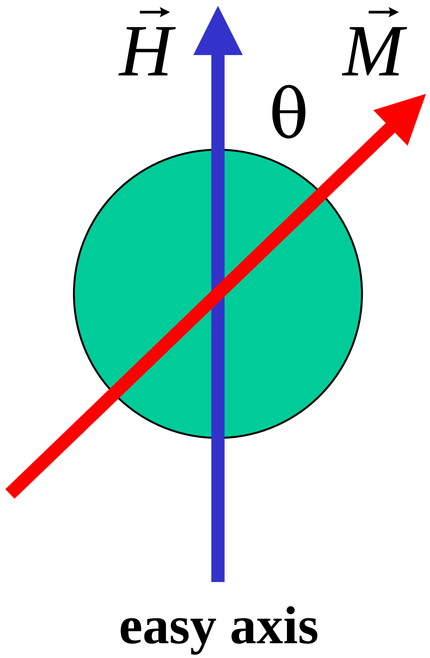


Spin qubit with a molecular magnet ?

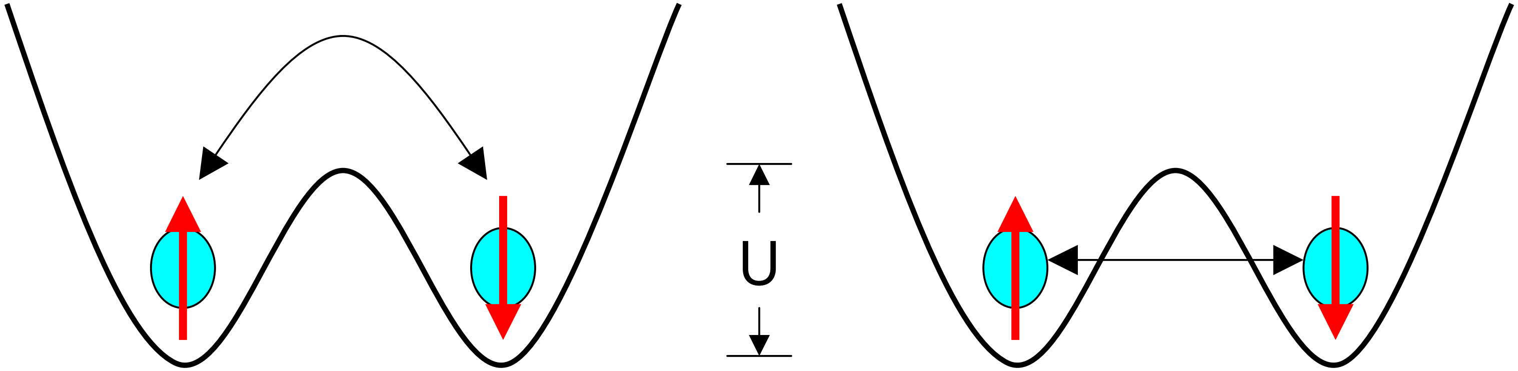
Magnetic Protein



2 nm

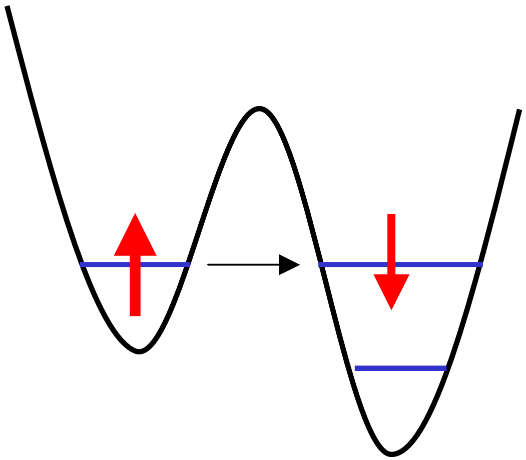


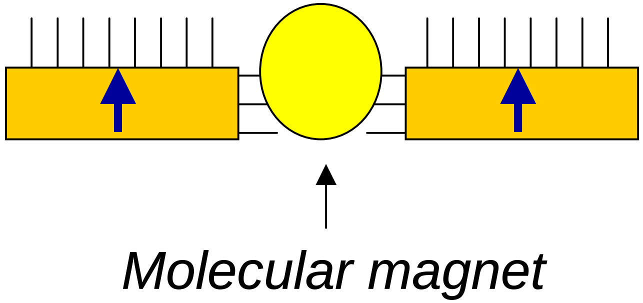
$\vec{H}$
$\vec{M}$
θ
easy axis

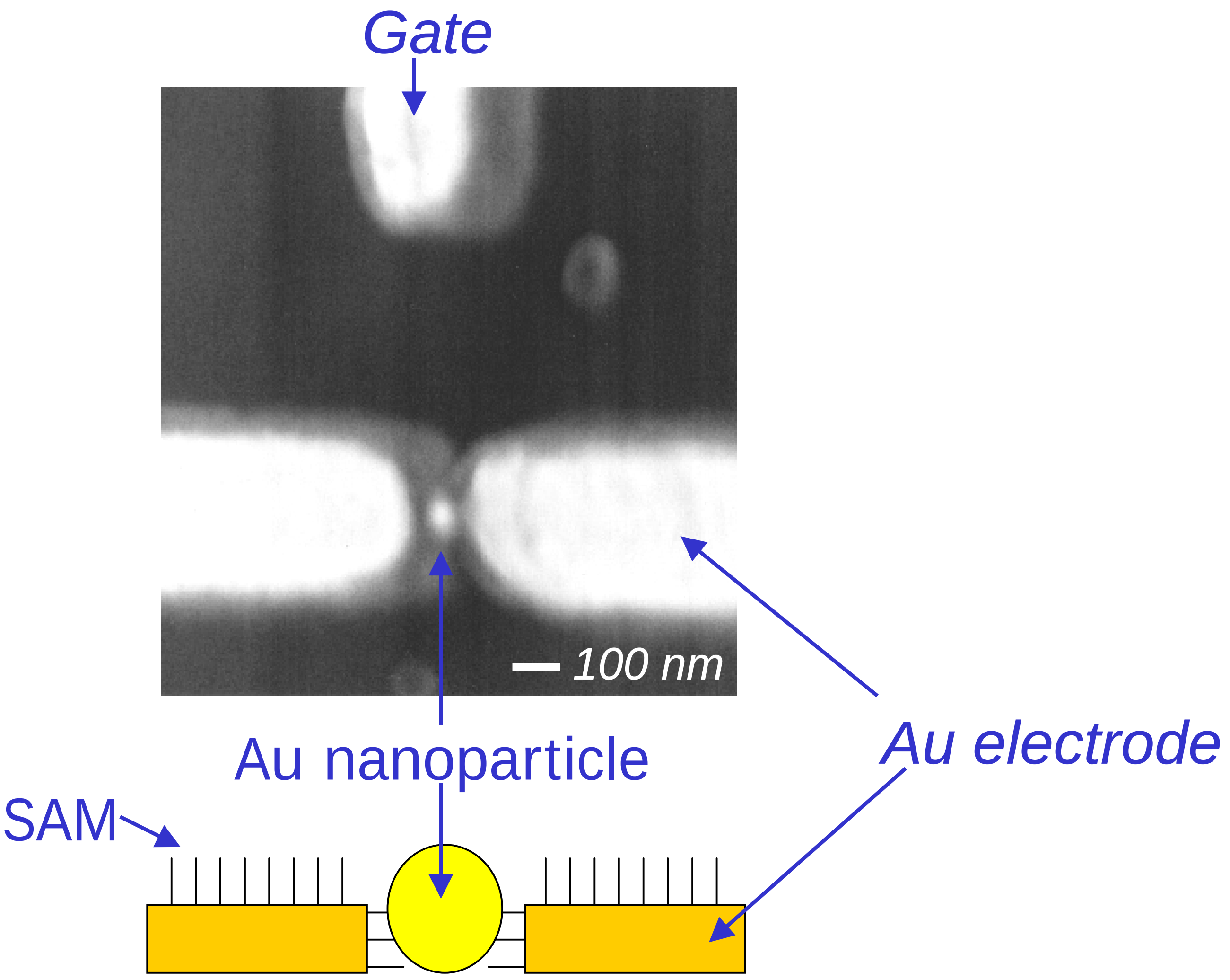


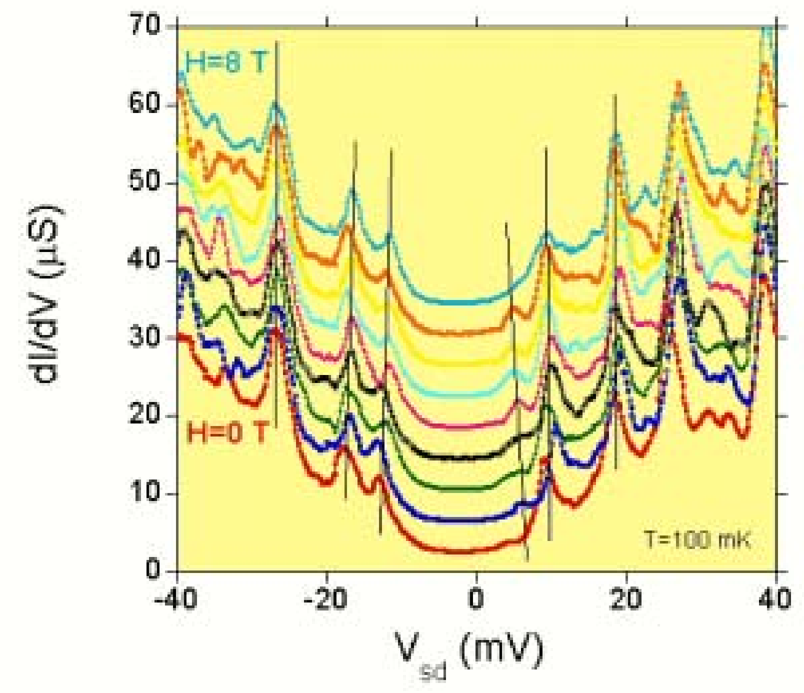
U

Measurement of spin state by injecting spin polarized electron

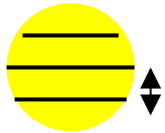





Gate
100 nm
Au nanoparticle
Au electrode
SAM



Au nanoparticle



δE

$$\delta E \approx 2\pi^2\hbar^2/mk_F V$$
$$\approx 1\text{- } 2 \text{ meV}$$

(diameter = 8-10 nm)

Nano-Fabrication Facilities

E-beam lithograph

Evaporator
(metal film)

Ion milling:etching

Sputtering machine
(magnetic material)

- Clean room facilities: PR fab process, Si-based device fab
- Chemical synthesis: nano-particle, nano-tube, nano-wire etc.

Measurement Facilities

Dilution refrigerator

UHV SPM

- *We are now attaching rf components to the dilution refrigerator*
- *We have a plan to attach photon detector to a dilution refrigerator (KBSI)*

Summary

Part I. Solid state source of single photon

1. *Acousto-electric single photon source: 2DEG*
2. *Future plan with nanotube and nanowire*

Part II. Qubit

1. *Superconducting qubit*
2. *Future plan: qubit with CNT and molecules*