FIRST
最先端研究開発支援プログラム
量子情報処理プロジェクト

wpi MANA NIMS

*Meeting (2011. Dec. 13-16)*

# Toward the development of quantum media interface from optical to superconducting state:

# Report of recent progress


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# Outline

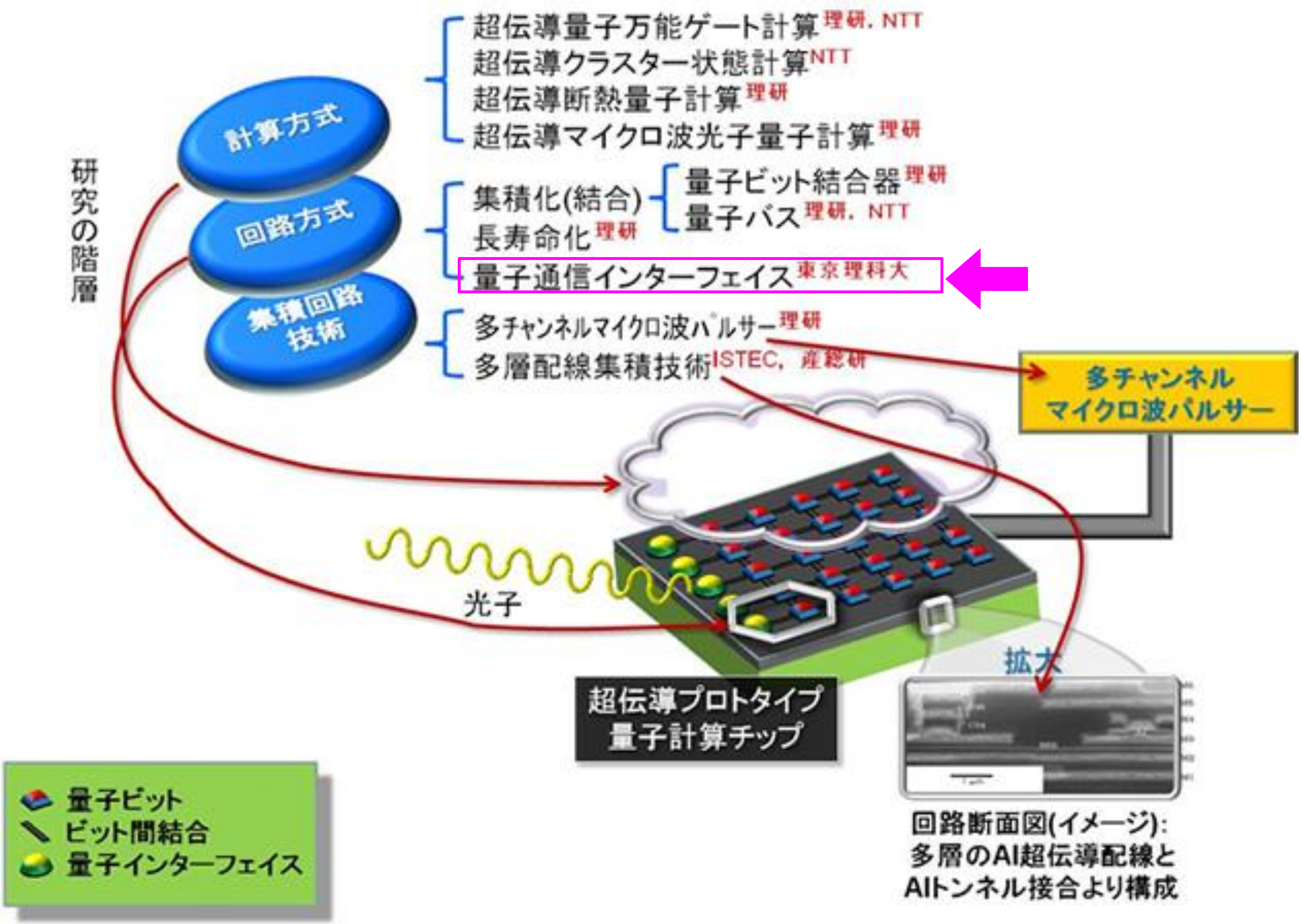
I. Research motivation

II. single quantum dot (QD) coupled to SQUID

III. QD with SIS SQUID

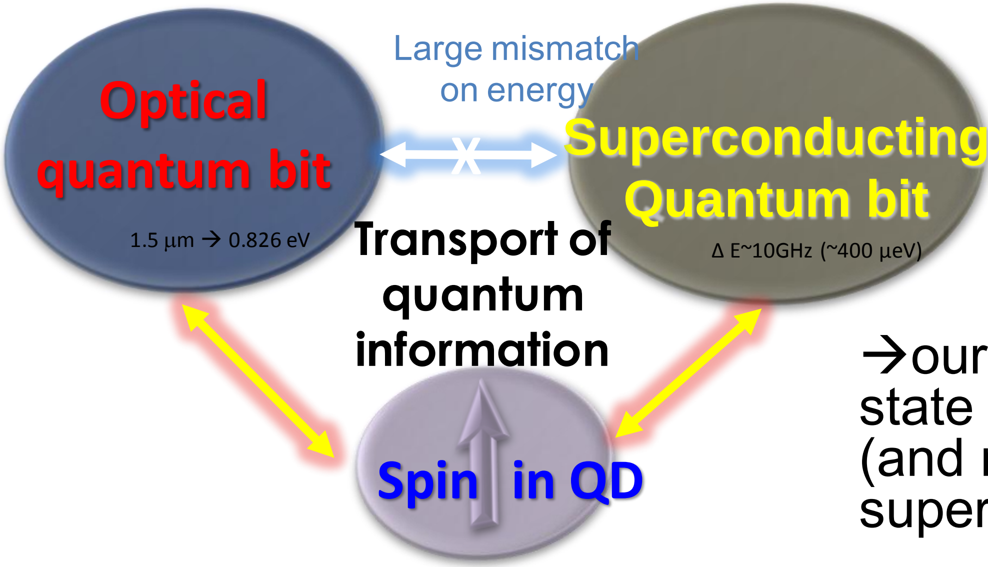
IV. Preliminary experiment for optical excitation of QD spin

# Superconducting qubit team




From website of FIRST project "http://first-quantum.net/subgroups/superconductingQcom/index.html"

# I. Research motivation




Toward the development of quantum media interface which can transfer quantum information from optical to superconducting state,

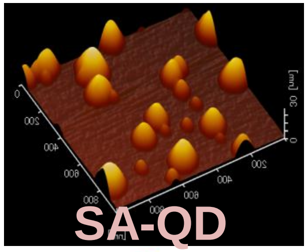
→our approach is based on the spin state of self-assembled InAs quantum dot (and ring) in hybrid semiconductor-superconductor system.

**<u>InAs Self-assembled quantums dot</u>**

-Optically excited spin (spin memory)

-Electronically coupled  and embedded into active device

- Strong spin orbit interaction
- Schottky barrier free contact
- Highly controllable electron system





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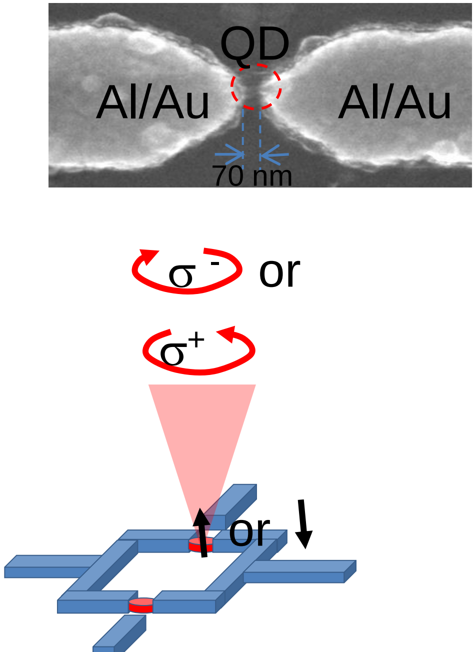
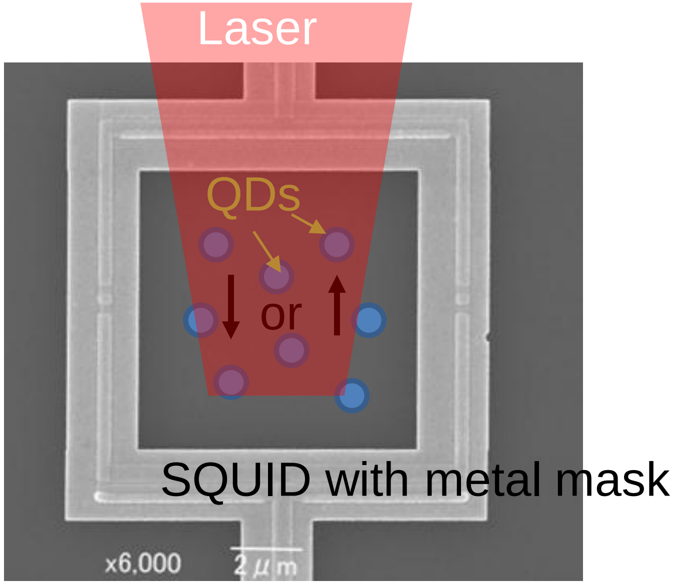
# Study for single spin/spin ensemble of electron(s) in InAs QD

## a. For single spin




QD-SQUID

## b. For spin ensemble




(SEM image from R. Ishiguro)

Al-SQUID

# II. QD-coupled to SQUID

Quantum dot (QD)


Highly controllable electron system

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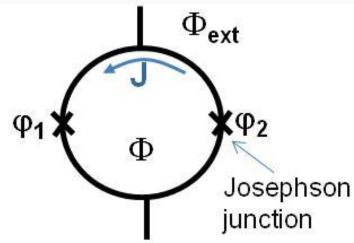
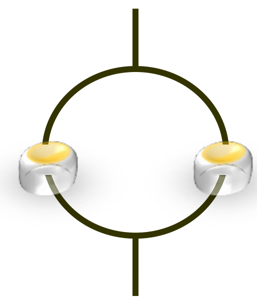
Superconducting quantum interference device (SQUID)




Most sensitive detector for magnetic flux

=

QD-SQUID



Applications for future quantum information device.

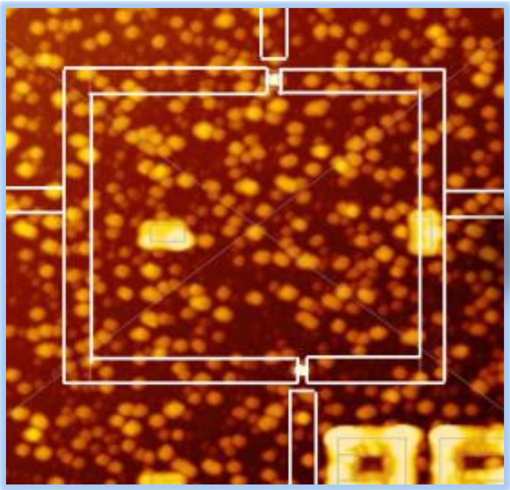
By employing InAs self-assembled quantum dot (SAQD) to QD-SQUID, we study the electrical transport properties of our device with two side-gates in order to study its potential for a quantum information device.

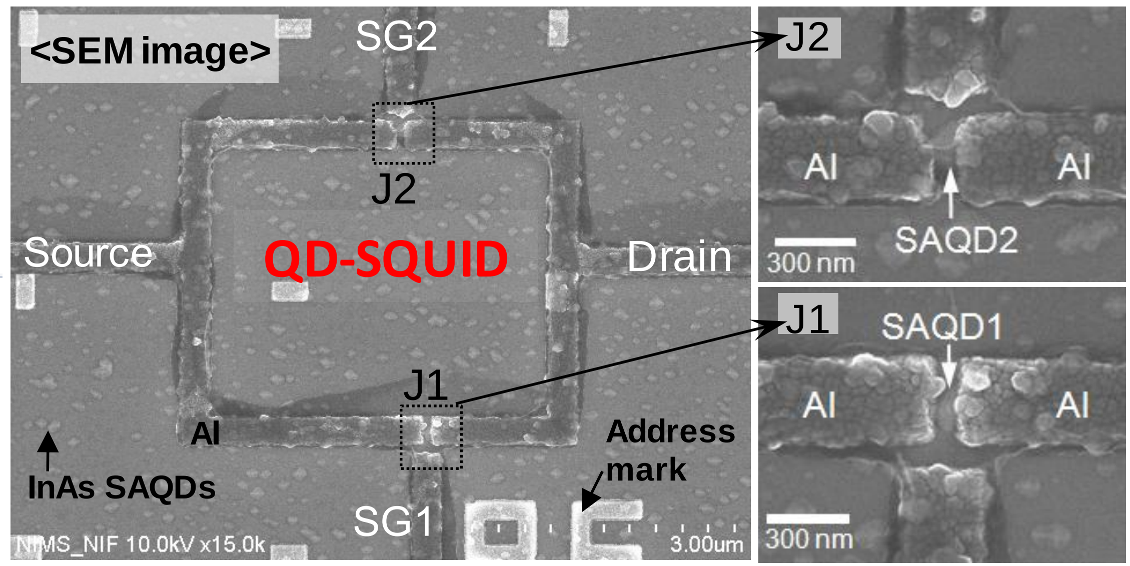
# QD-SQUID

InAs dot growth by Hirakawa group (Univ. of Tokyo)

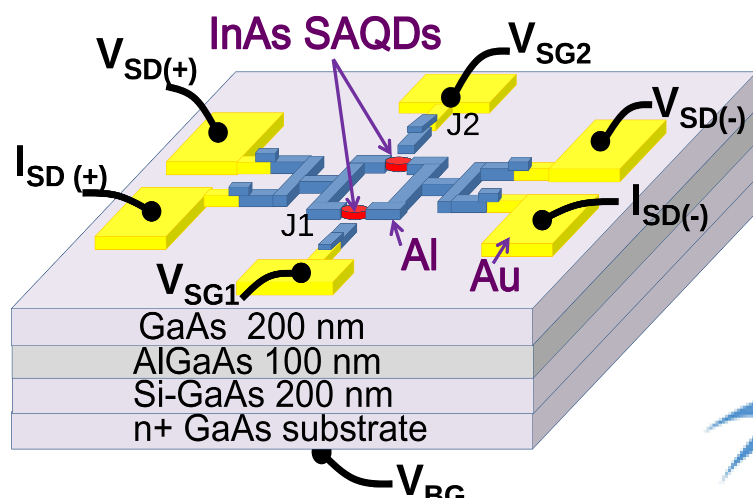
SQUID loop area: 4.02x3.23 $\mu m^2$ (Dot size: ~200 nm)

**<SQUID design on AFM image >**

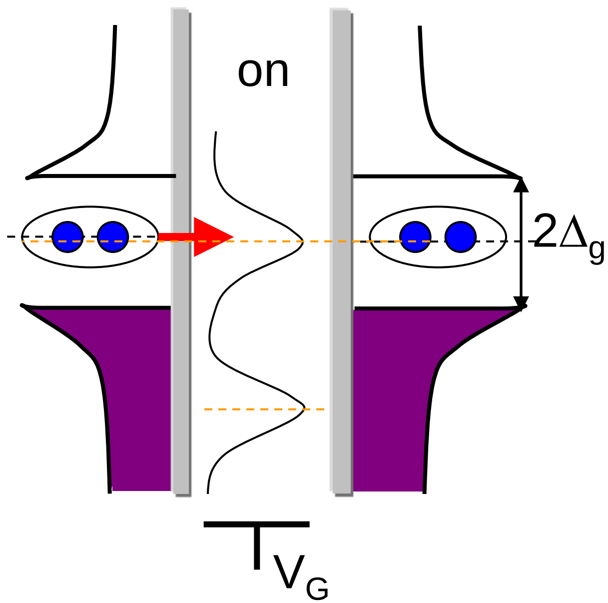





<Device configuration>

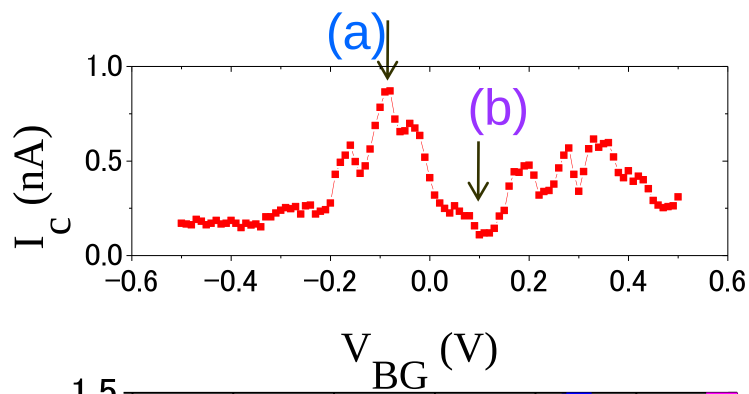


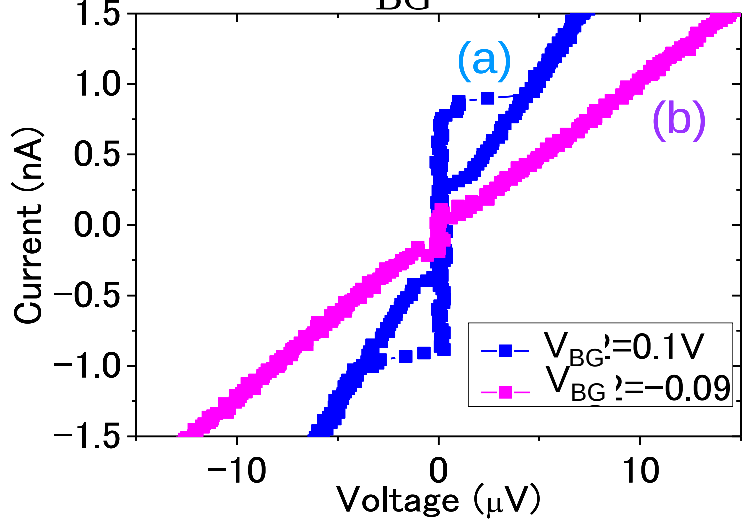
# Supercurrent flow


<on/off resonance tuned by gate voltage >

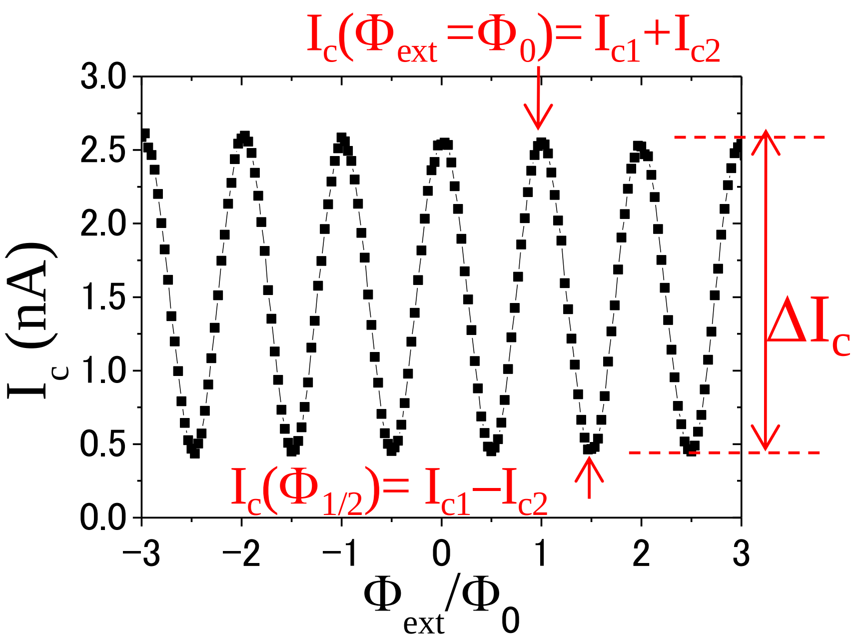
Tunable supercurrent



# SQUID operation

## Critical current ($I_c$) oscillation as a function of external magnetic fields



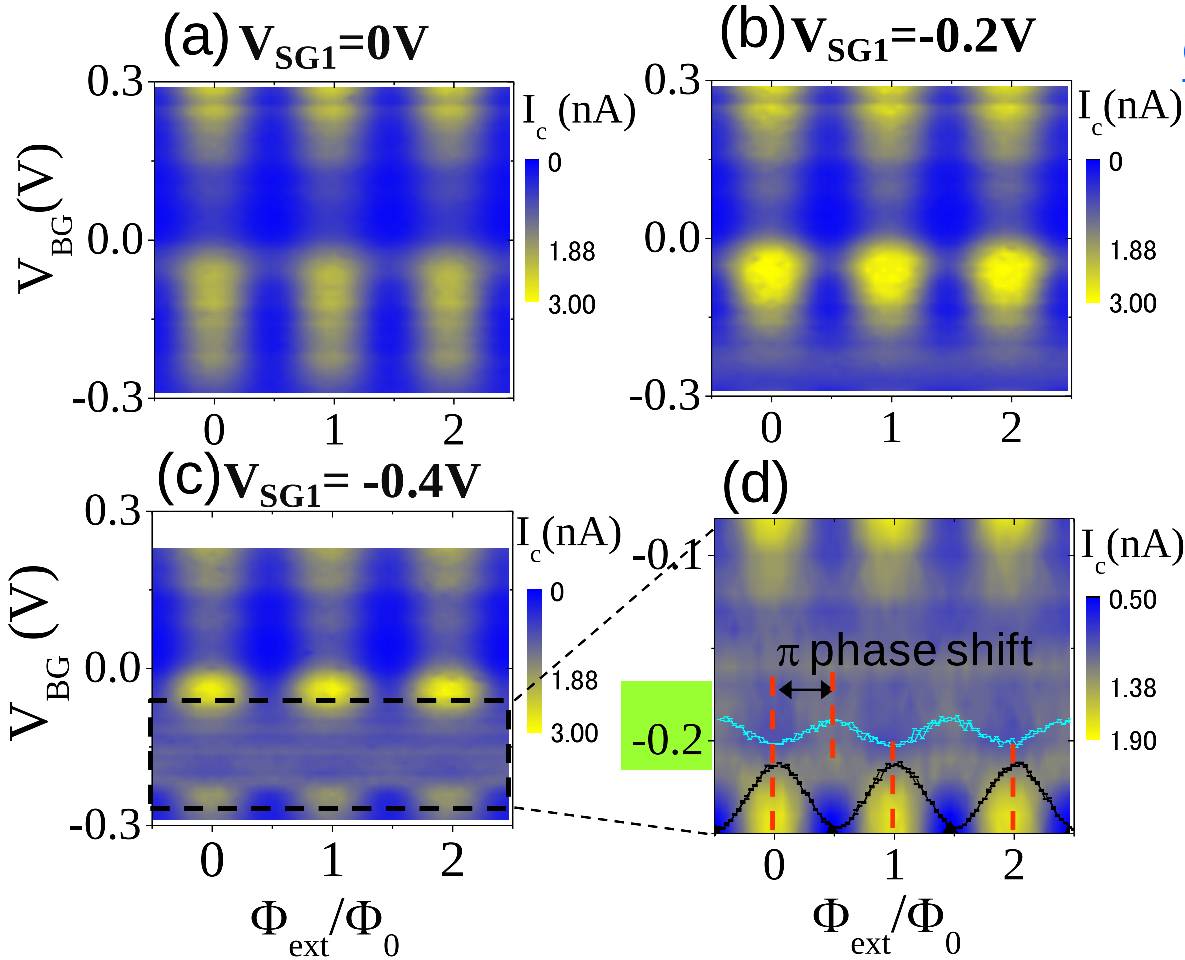

- Measured period: 1.500443 Gauss

$$\Phi_0 = \frac{\phi_0}{A} = \frac{2.07\times10^{-15}[Wb]}{4.02\times3.23[\mu m^2]} = 1.59[Gauss]$$

$H_0$: the field needed to add a flux quantum $\Phi_0$=h/2e to the effective SQUID area.

* Individual $I_c$ can be tuned by each side gate

# Side-gate controlled π junction behavior




## 0 Junction

- $I_c$ maximum at zero field
- Josephson relation:

$$I_s = I_c \sin(\varphi)$$

## π Junction

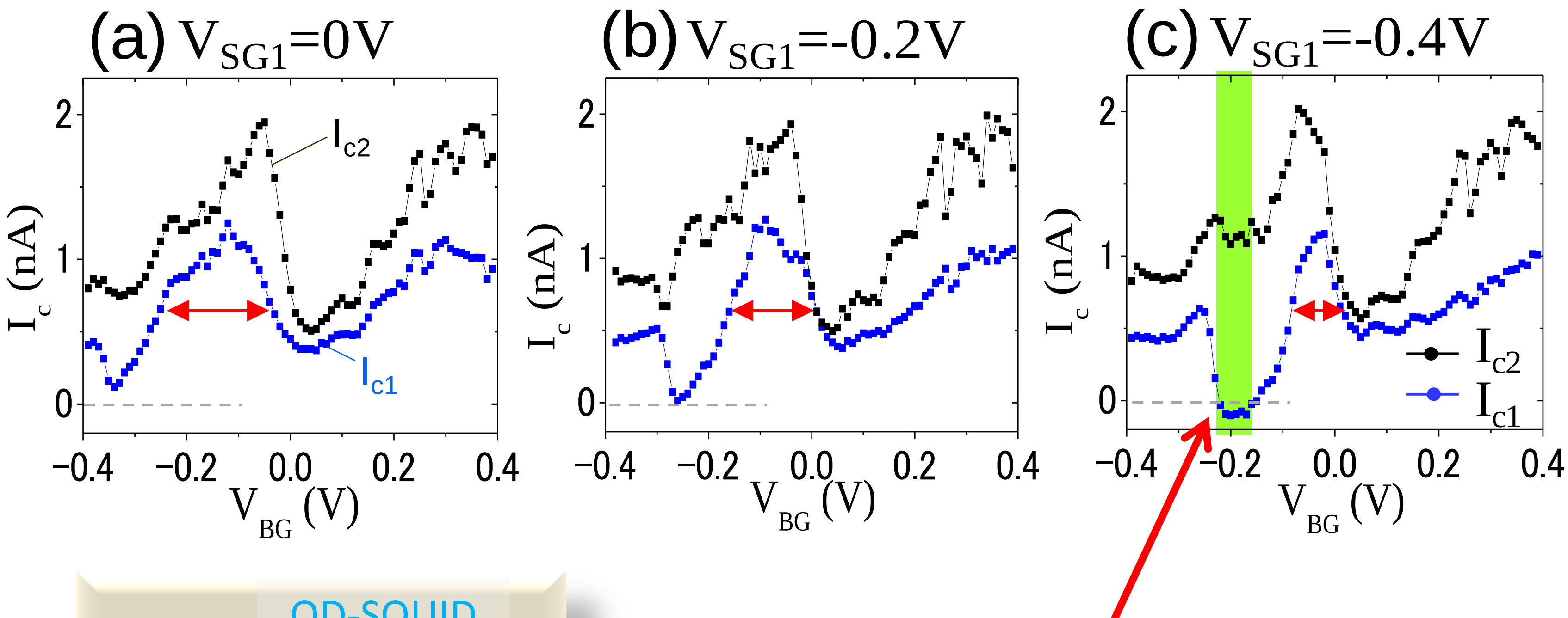
- π phase shift and a reversal of the sign of the supercurrent in a Josephson device

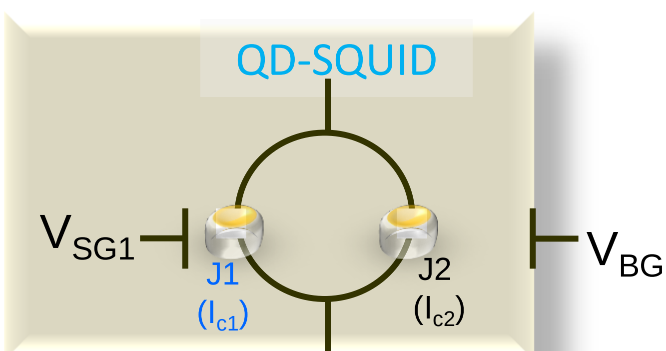
$$I_s = I_c \sin(\varphi + \pi) = -I_c \sin(\varphi)$$

# Which dot has pi junction transition?

- Individual $I_c$ profiles for each dot
→ distinguished by analyzing interference properties of SQUID

strong ← **$V_{SG1}$ : tune of the dot-lead coupling** → weak

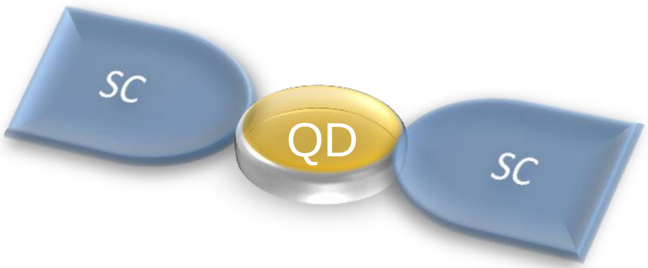



- Direct observation of negative supercurrent

# π junction behavior and spin state

- Spin flip tunneling in S-QD-S system




[I. Kulik, Sov. Phys. JETP, 22, 841 (1966)]

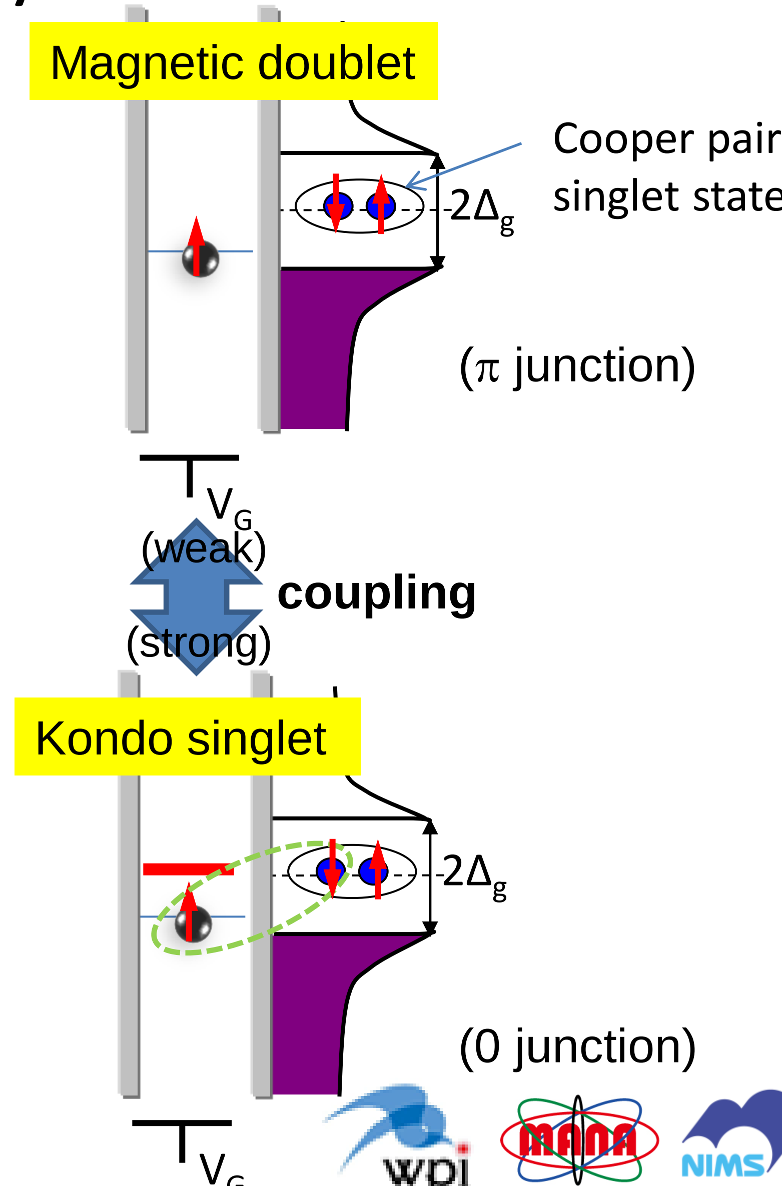
[L.N. Bulaevskii et al., JETP Lett. (1977) ]

[C. Benjamin et al., Eur. Phys. J. B, (2007)]

- During tunneling event, the spin-ordering of the Cooper pair is reversed.

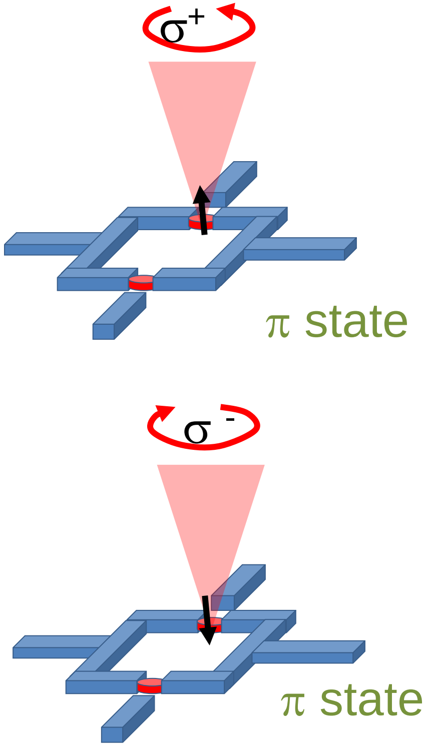
→A reversal of the sign of the supercurrent

- π junction transition by tuning coupling between QD and superconducting leads using side-gate
→due to transition from the Kondo singlet to magnetic doublet of the spin state of the InAs QD



# Limitation of directly coupled QD-SQUID

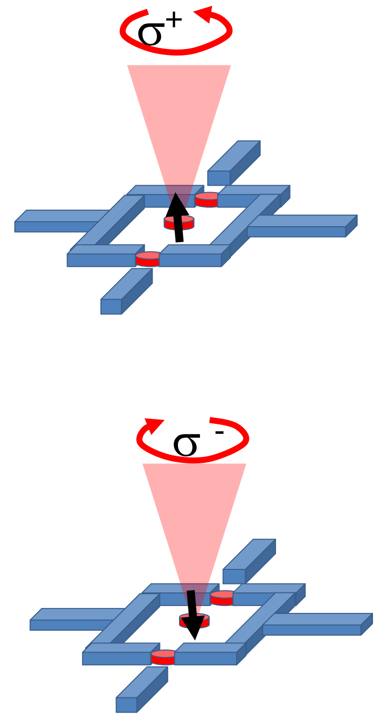
spin state ←→ superconducting state




**(a) π junction behavior**

→ not sensitive to the spin direction

→ results from the presence of electron spin.




**(b)The switching of magnetization by SQUID**

→find flux change in SQUID loop

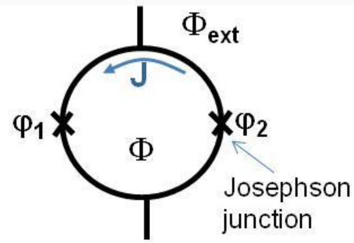
# III. SIS-SQUID

Quantum dot (QD)


Highly controllable electron system

+

Superconducting quantum interference device (SQUID)




Most sensitive detector for magnetic flux

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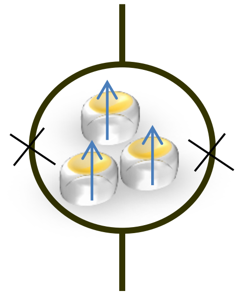


For spin ensemble measurement

→Magnetic flux variation induced by the spin >flux sensitivity of SQUID ( $\frac{\Delta\Phi}{\Phi_0} \cong 10^{-4}$ )

(R. Ishiguro et al. in Takayanagi lab)

(Slide from R. Ishiguro)

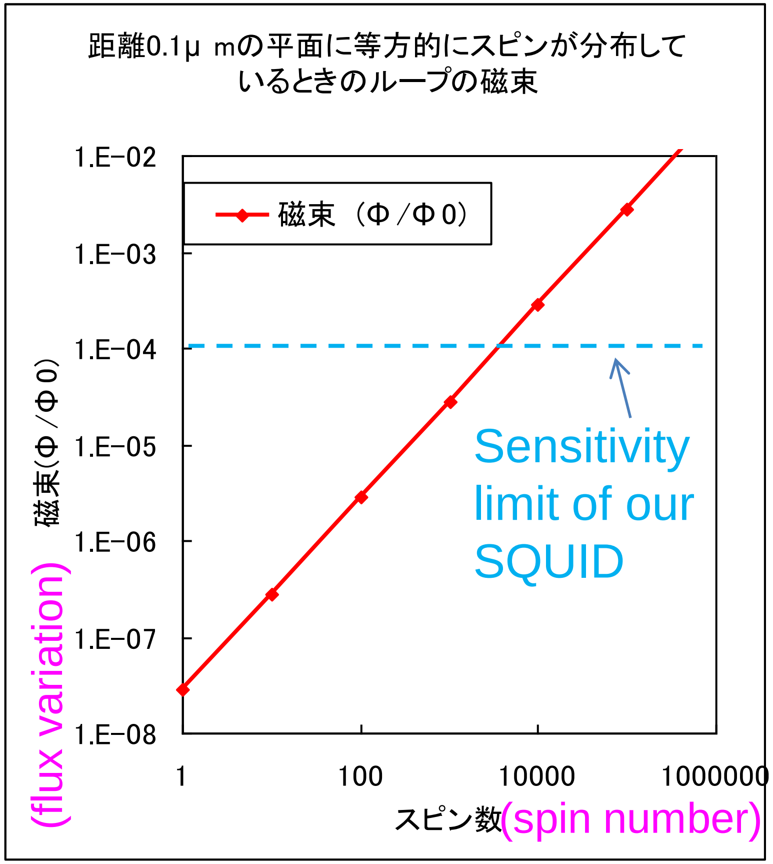
# スピンの数とループ磁束の変化の関係（臨界電流の変化の関係）

半径rの高さdの円筒内に等方的に磁気モーメントmが分布しているときの上面での磁束

$$\Phi = \frac{\mu_0 2\pi r^2 m}{2\pi r^2 d} = \frac{\mu_0 \mu_B N_{spin}}{d}$$

How many spins are necessary to detect with our SQUID ?
- About 10000 spins

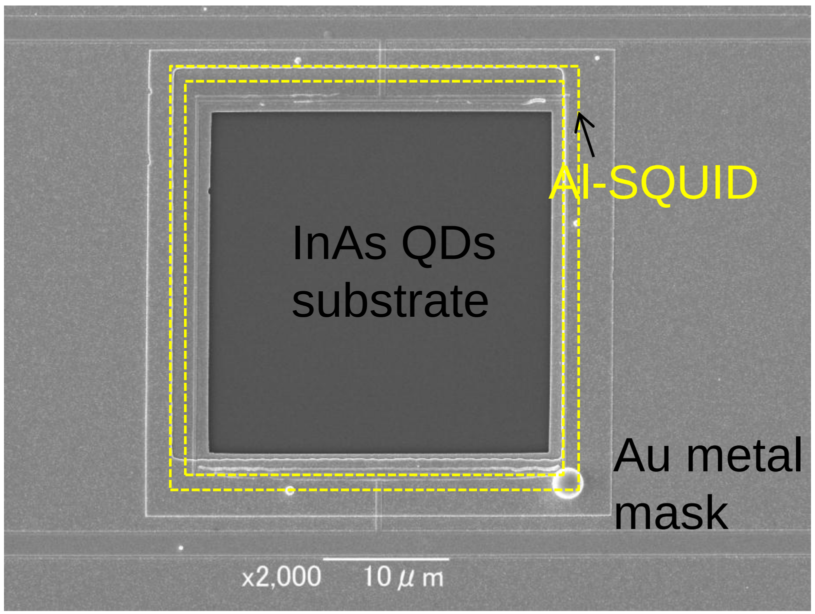
Considering QD density (25/μm$^2$), SQUID loop are should be more than 400 μm$^2$.(ex. 20x20 μm$^2$)

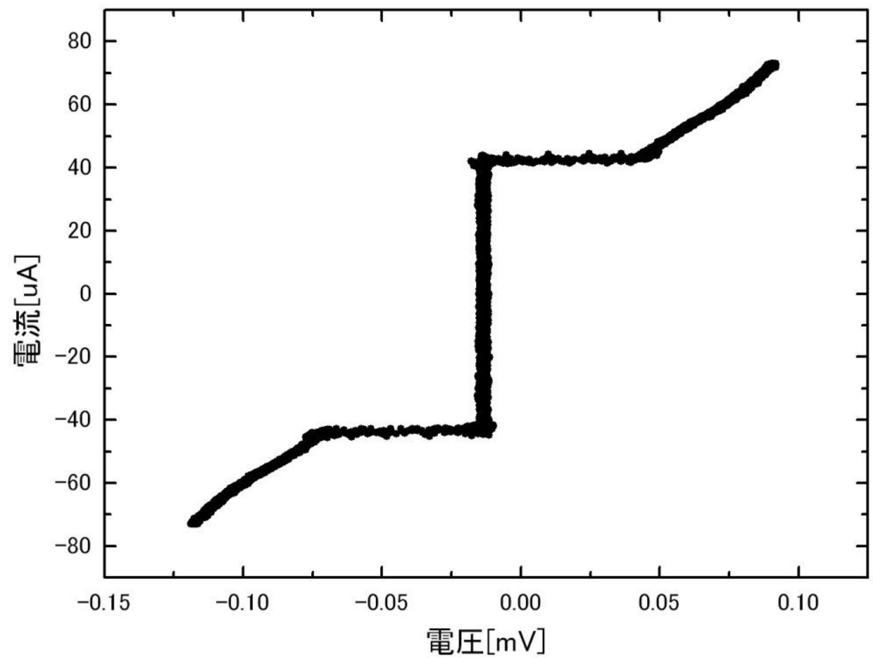


(Slide from R. Ishiguro group)

# QD基板上のSIS SQUID

## 金によるSQUIDのマスク




膜厚:300/500Å

酸化:0.5Pa 10min

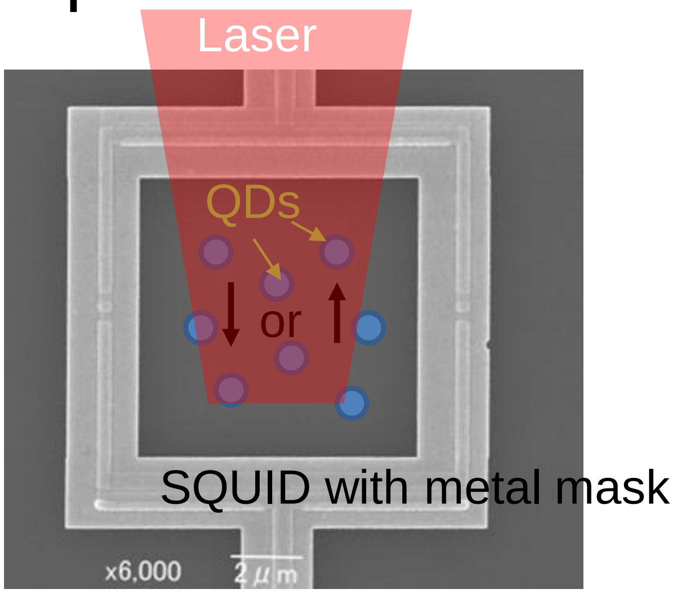
金マスク厚:2000+2500Å

実験後のPL測定より
ドットのギャップは
1430nm±10nm程度。

磁場応答あり。

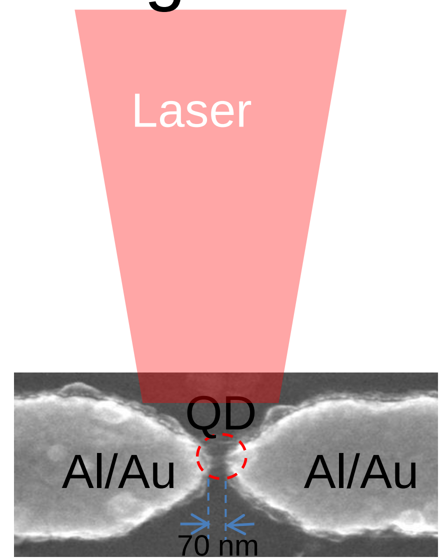
# IV. Preliminary experiment for optical excitation of QD spin

1. Photoluminescence measurement
2. Transport measurement under the light irradiation




(SEM image from R. Ishiguro)

Al-SQUID




QD-Josephson junction

<u>For spin ensemble</u>

<u>For single spin</u>

# Optically generated spin state

## <Spin selection rules for QD exciton state>

- Circularly polarized photon conveys one unit of angular momentum $+\hbar$ for $\sigma^{+}$ and $-\hbar$ for $\sigma^{-}$ → Produce excitons

- Total spin changes by $J_{e,z} + J_{h,z} = \pm\hbar$

$$J_{e,z} = \pm\frac{1}{2}\hbar \Rightarrow (e\uparrow, e\downarrow) \qquad J_{h,z} = \pm\frac{3}{2}\hbar \Rightarrow (h\uparrow, h\downarrow)$$

$$\sigma^{+} \Rightarrow +\hbar = -\frac{1}{2}\hbar + \frac{3}{2}\hbar \Rightarrow e\downarrow + h\uparrow$$

$$\sigma^{-} \Rightarrow -\hbar = +\frac{1}{2}\hbar - \frac{3}{2}\hbar \Rightarrow e\uparrow + h\downarrow$$

Only the transitions with (e↓, h↑) for $\sigma^{+}$ and (e↑, h↓) for $\sigma^{-}$ are optically active.



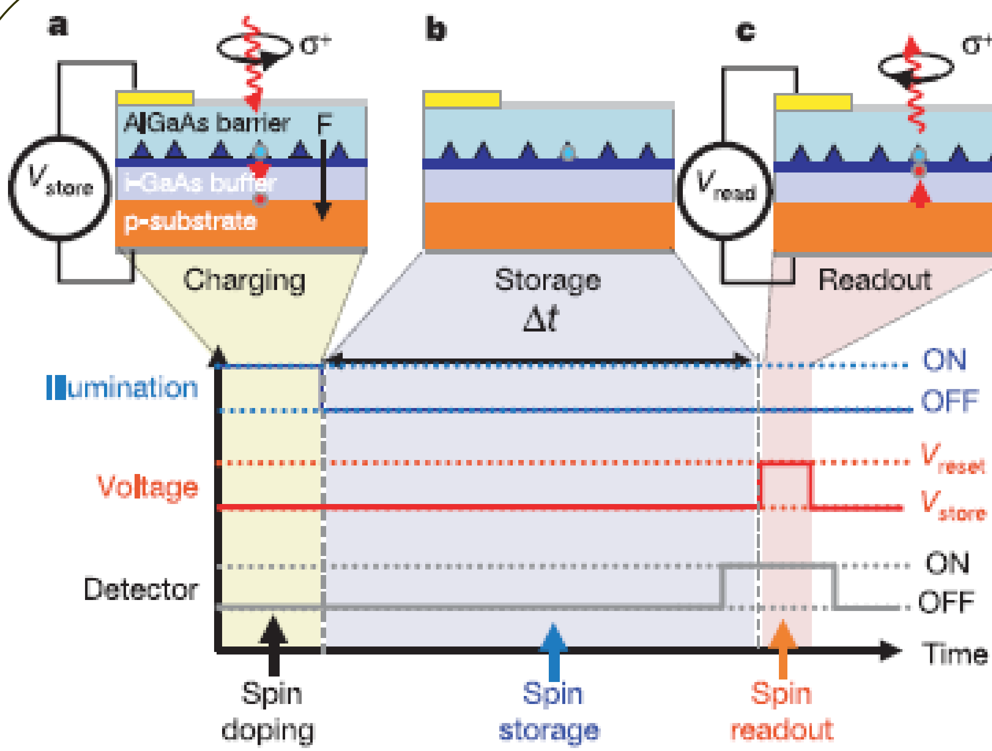
[Heiss, et.al., PRB2007 ]

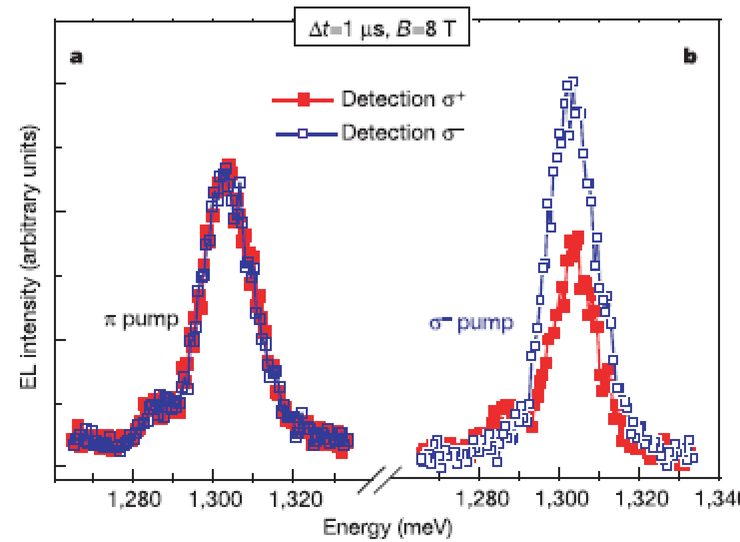
# Optically programmable electron spin memory using semiconductor quantum dots

**Miro Kroutvar, Yann Ducommun, Dominik Heiss, Max Bichler, Dieter Schuh, Gerhard Abstreiter & Jonathan J. Finley**

*Walter Schottky Institut, Technische Universität München, Am Coulombwall 3, D-85748 Garching, Germany*

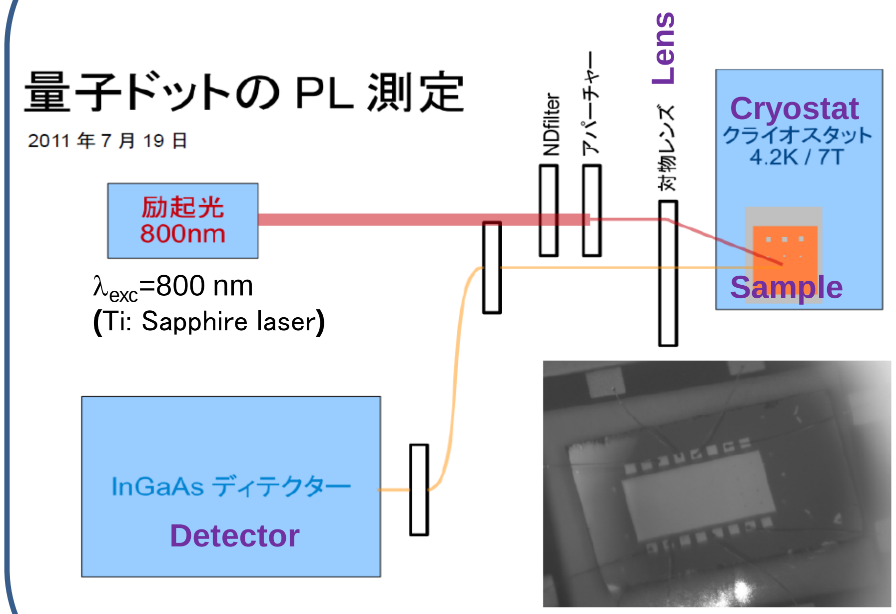
[M. Kroutvar et. al., *Nature*, 432, 81, 2004]

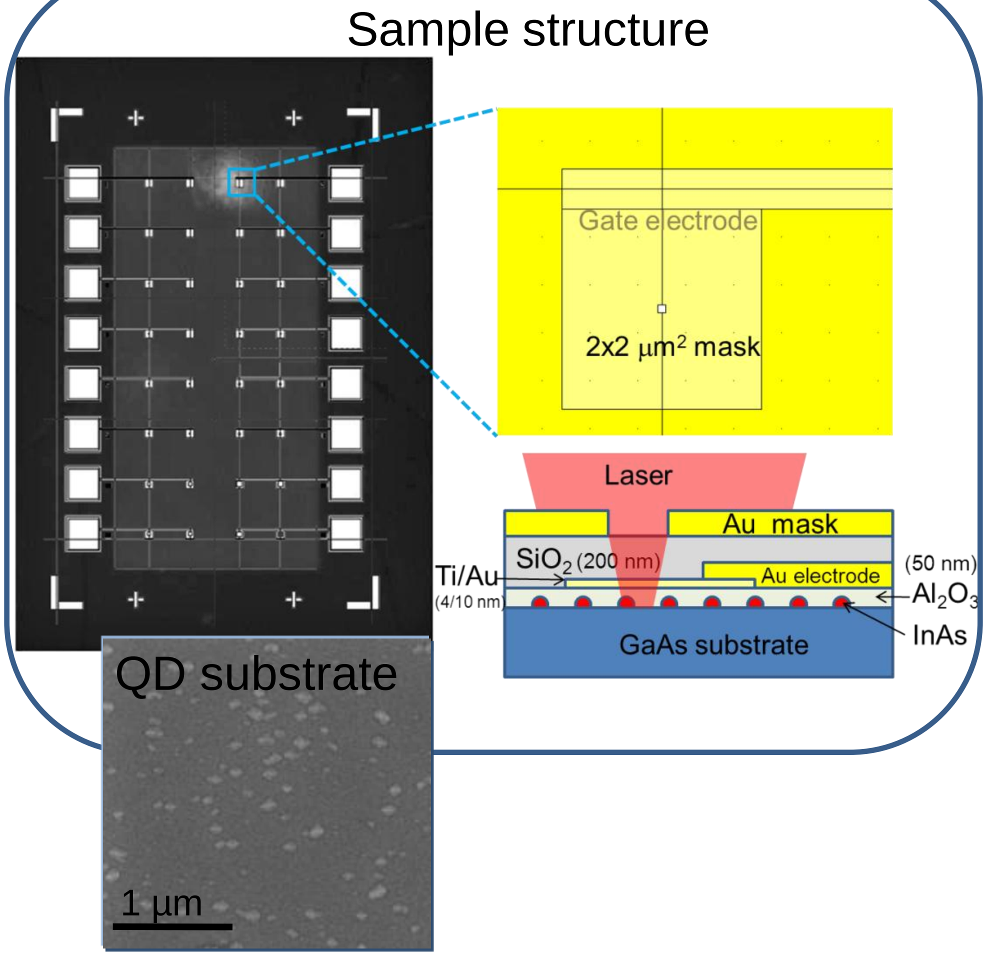


# Which wavelength is sensitive to create exciton in QD?

➔ Check with Photoluminescence(PL) spectrum
for Initial characterization of optically excited QD spin



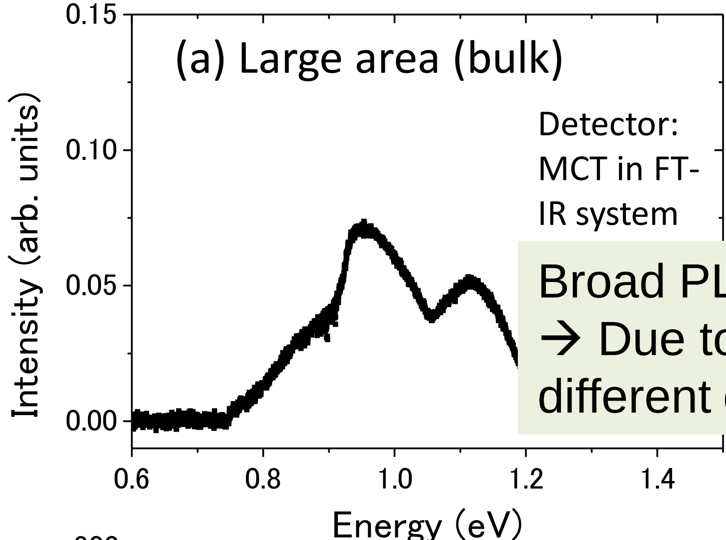



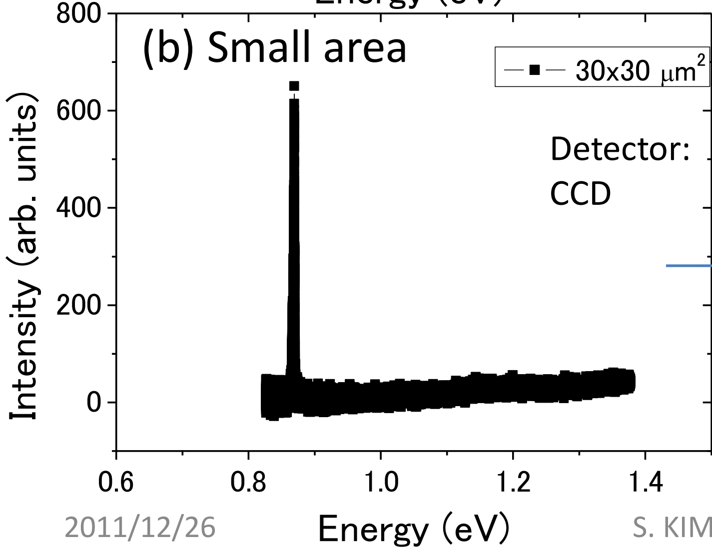

(in collaboration with Nomura-lab
in Tsukuba Univ.)

# Photoluminescence

$\lambda_{exc}$=800 nm
**(**Ti: Sapphire laser**)**

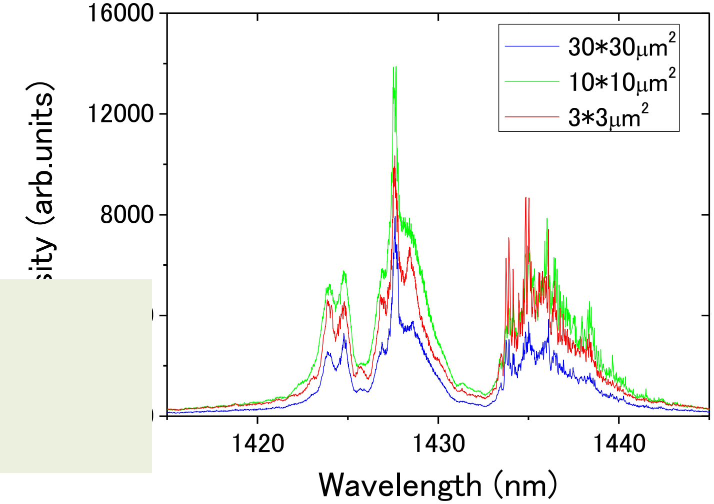
$$\hbar\omega_{exc} = 1.54 eV$$

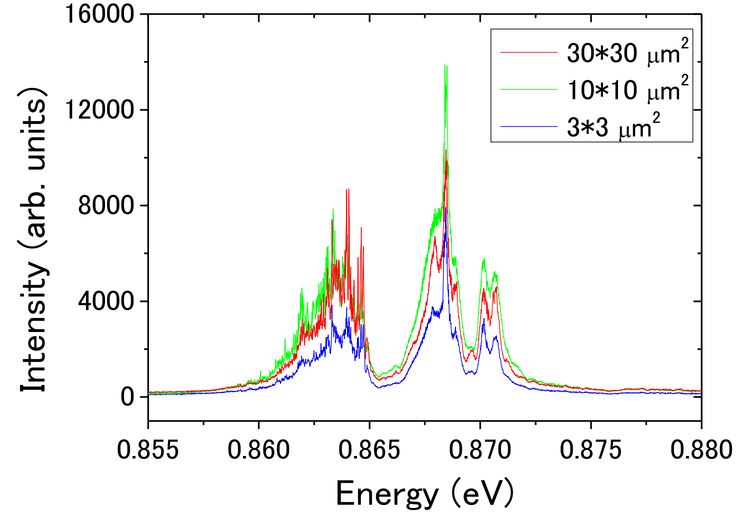


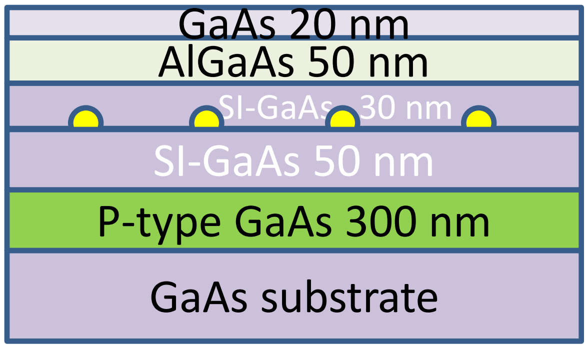

Broad PL spectrum
→ Due to mixing of different dot size

PL data from Ishiguro-san

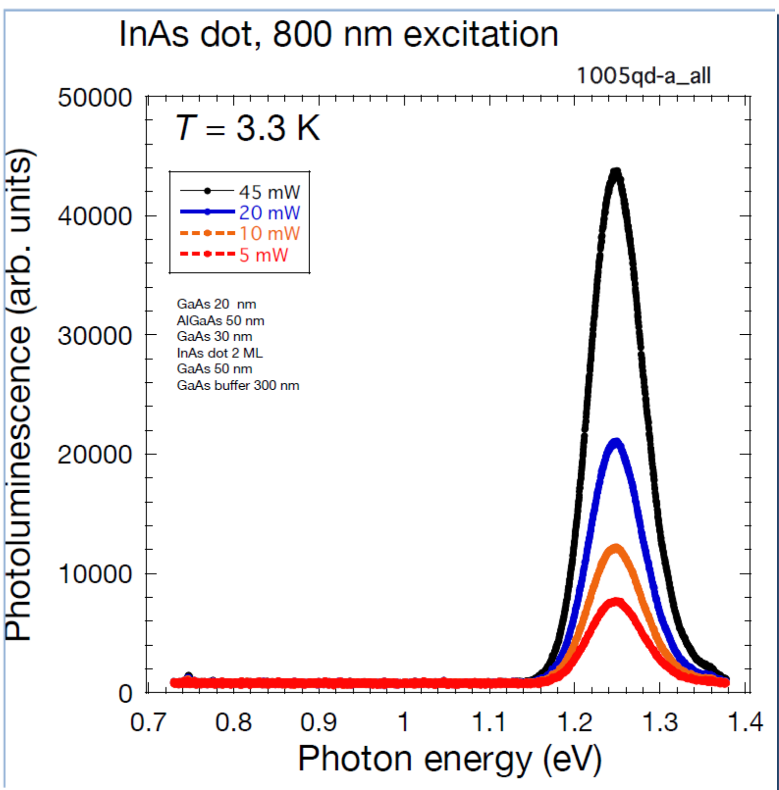


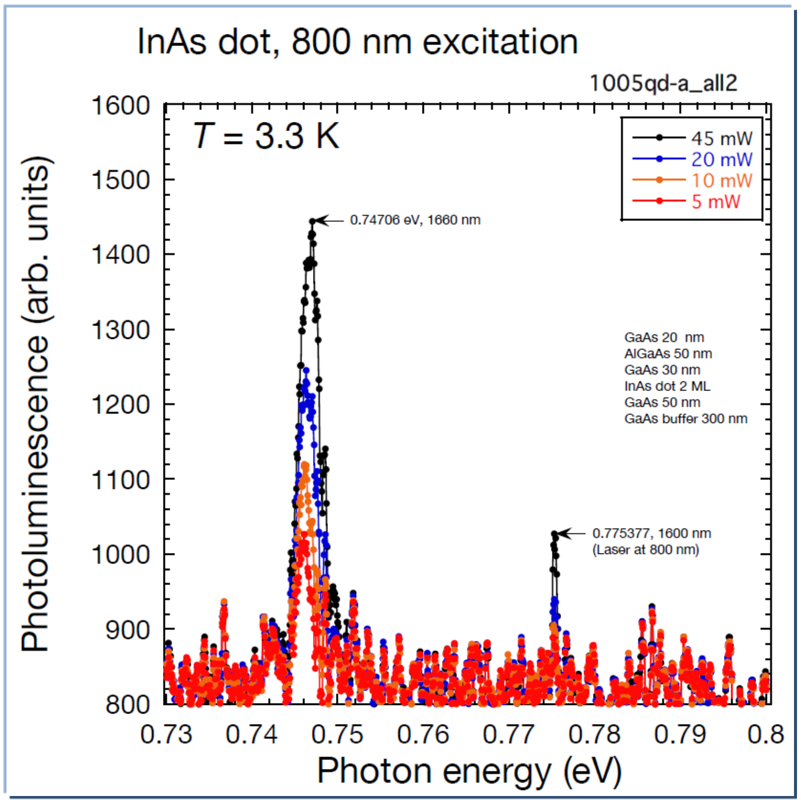



# <New QD substrate >

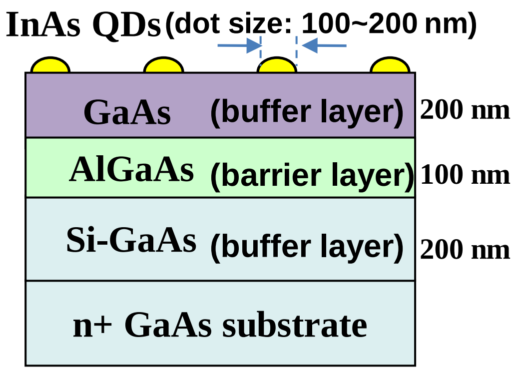



-Capping layer
-Uniform small dots (~40 nm)
-p-type GaAs

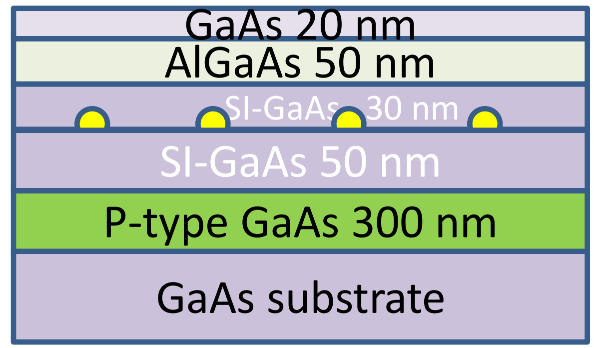


## <QD from Hirakawa group>

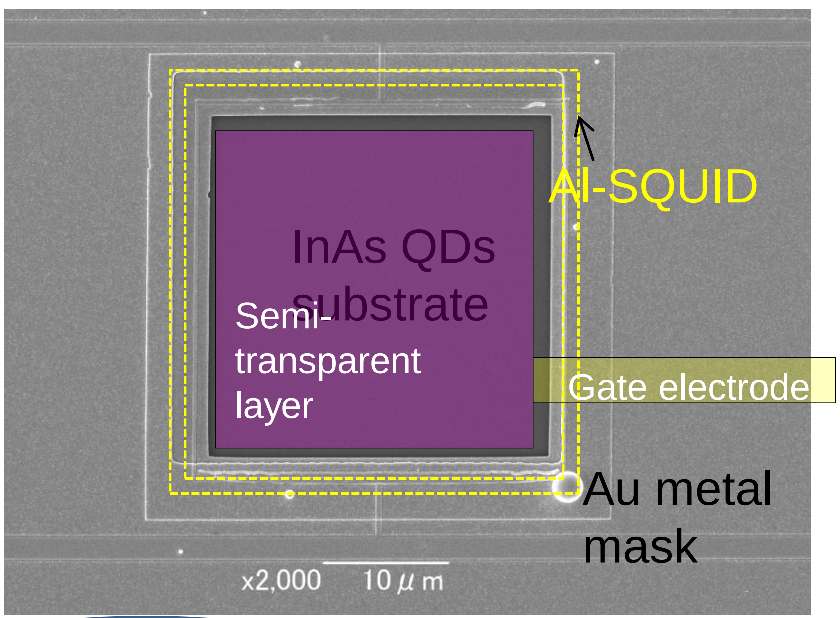


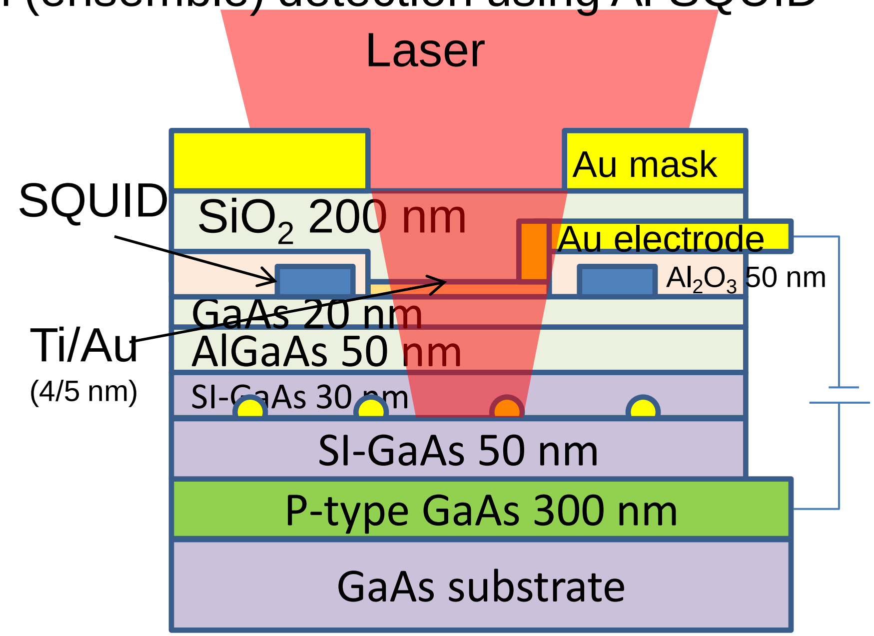

## <New QD substrate >




- Capping layer
- Uniform small dots (~40 nm)
- p-type GaAs

Configuration of our device for the spin (ensemble) detection using Al-SQUID



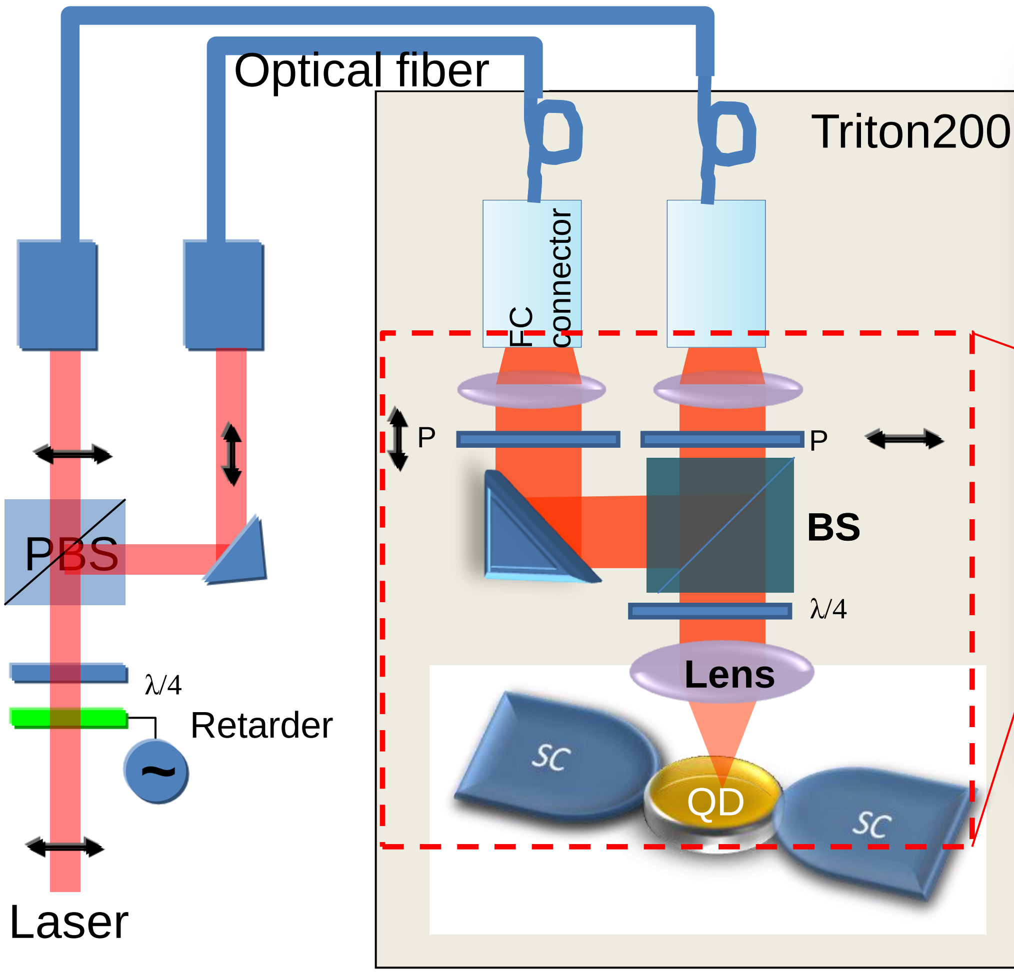

Schematic view of our device

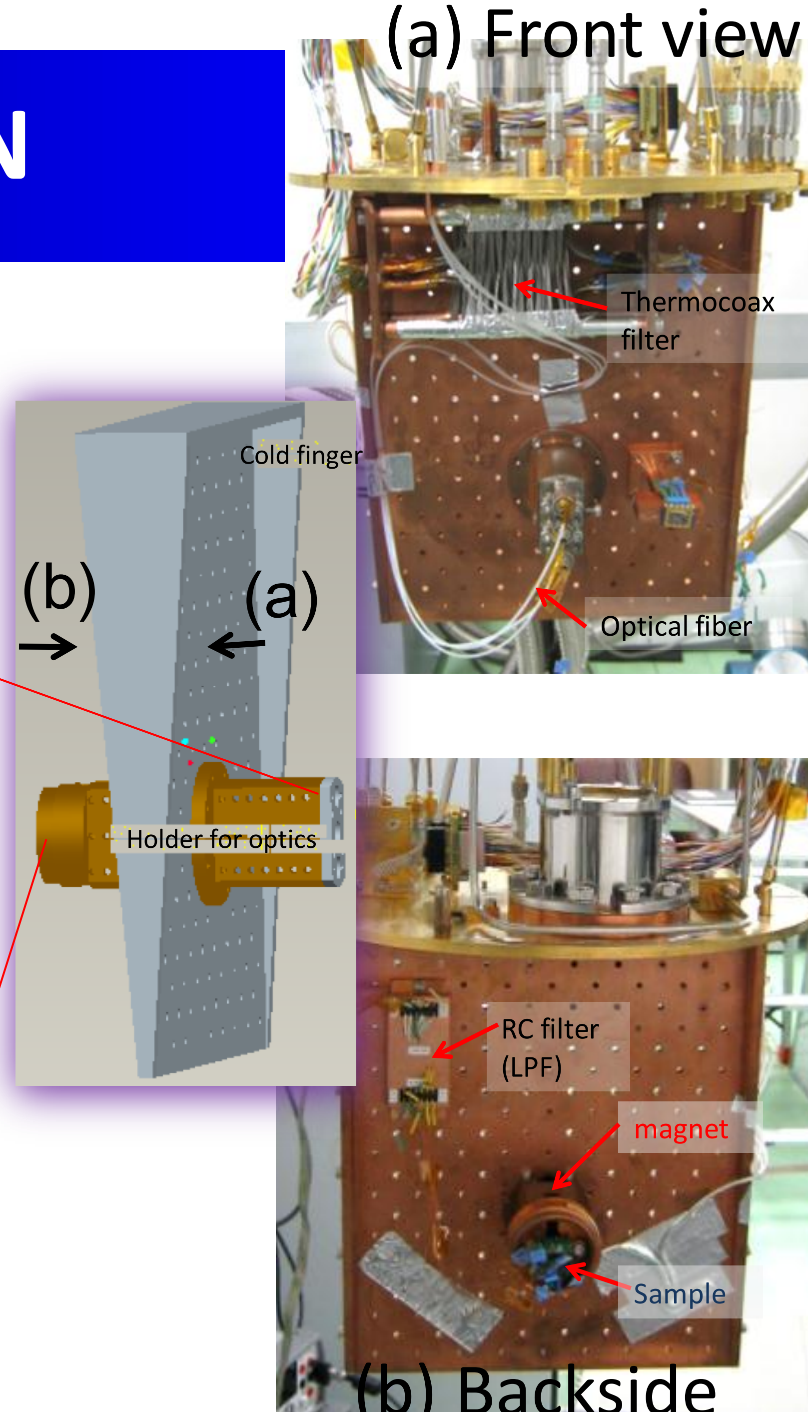
plan

1. We will do PL measurement with new substrate in order to determine the gate-voltage range for each charging state, along with the associated optical transition frequencies.
2. . Fabrication with new scheme of our SQUID device

# Optical setup of TRITON

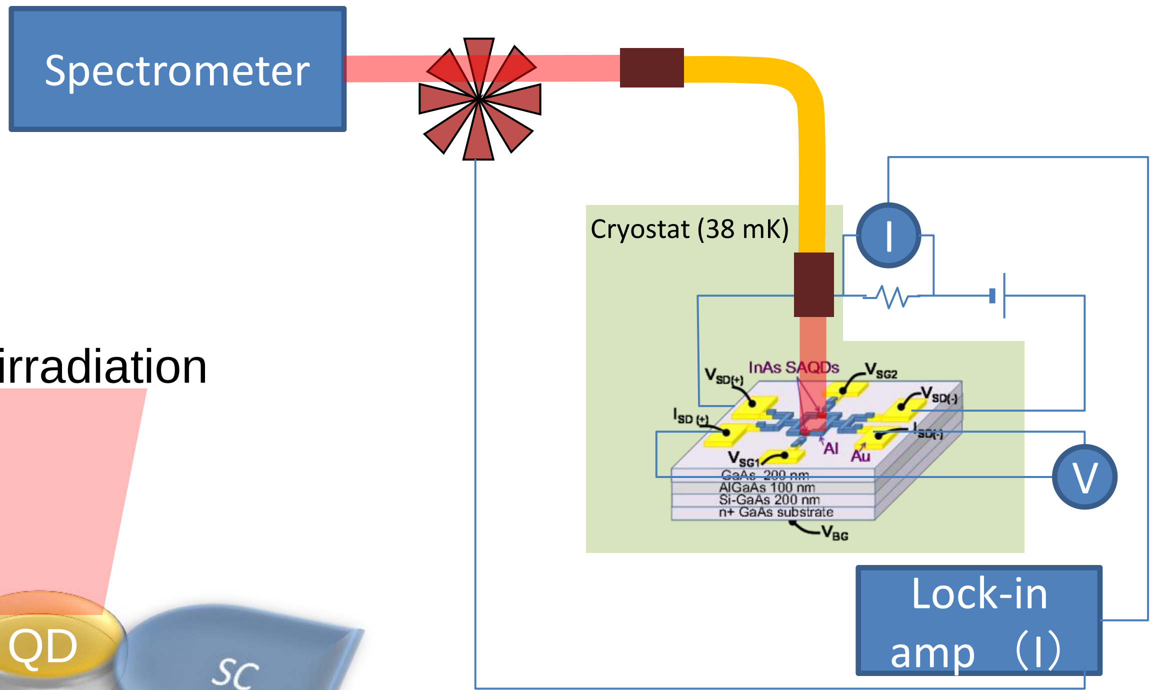
<With Inoue-san and Tusumu-gun>

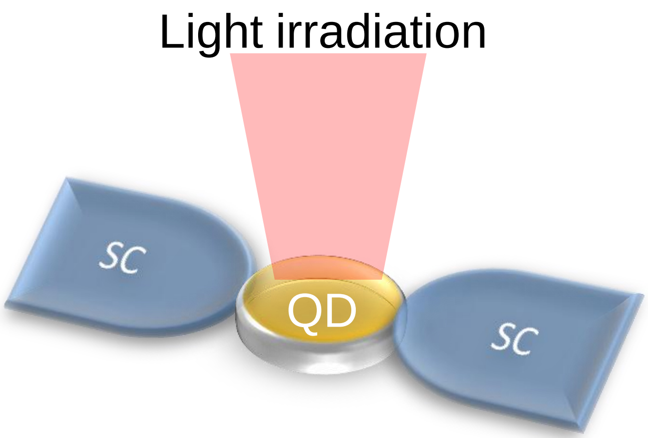


# Photocurrent measurement

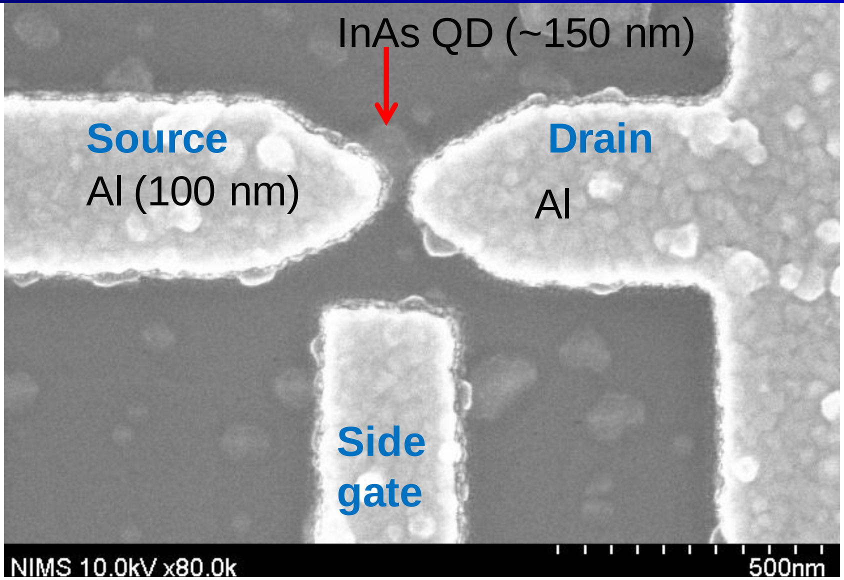
For the characterization of single dot,  we tried photocurrent measurement of QD-Josephson junction.

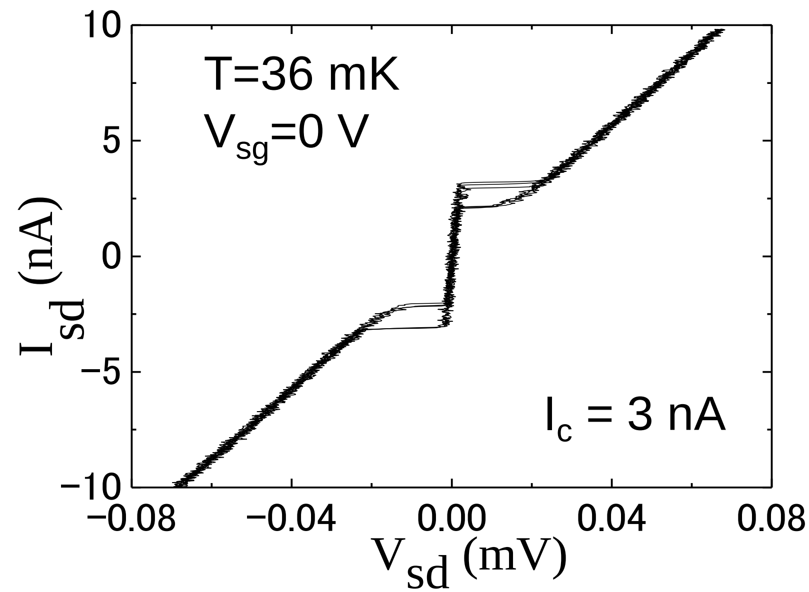


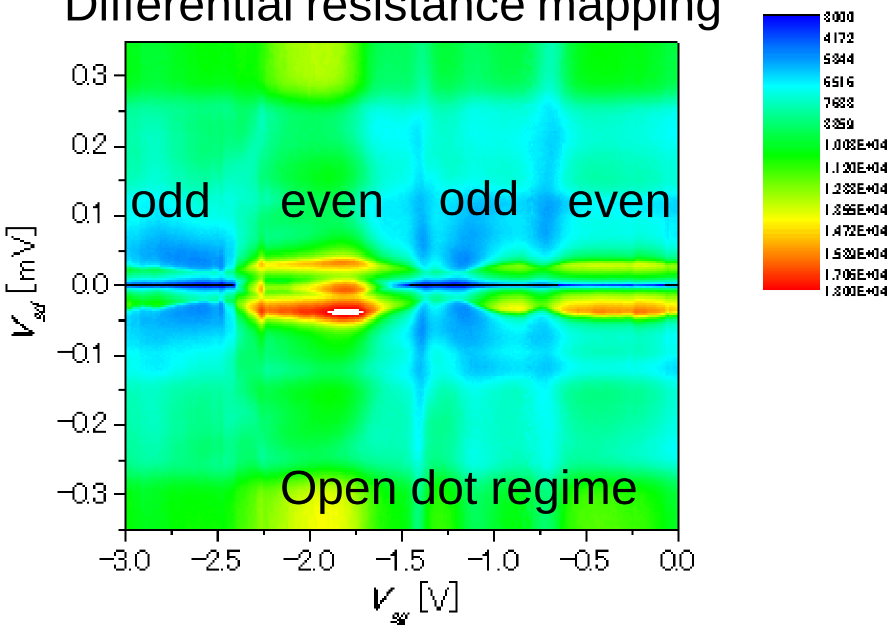

To determine effective wavelength

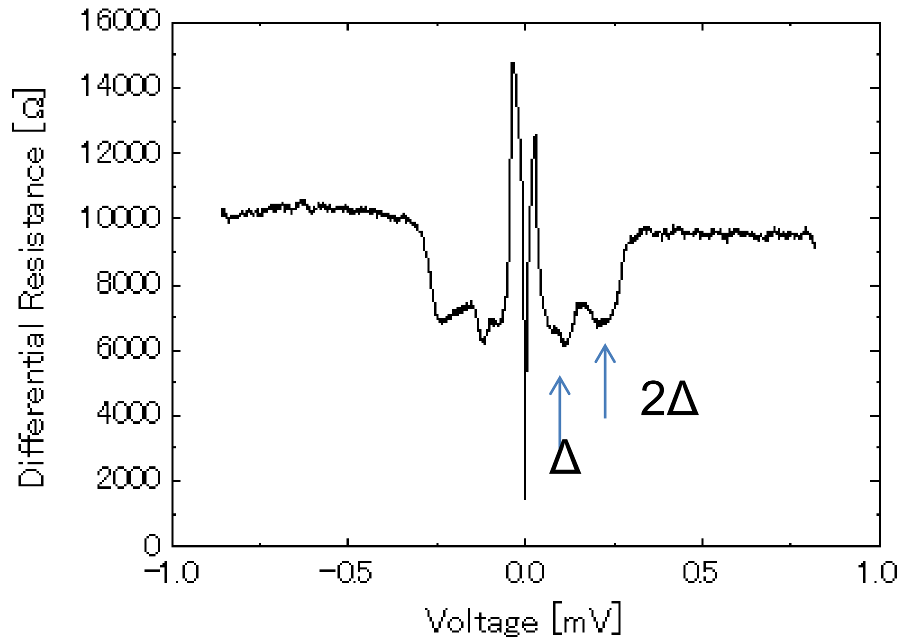
# Transport properties of QD Josephson junction



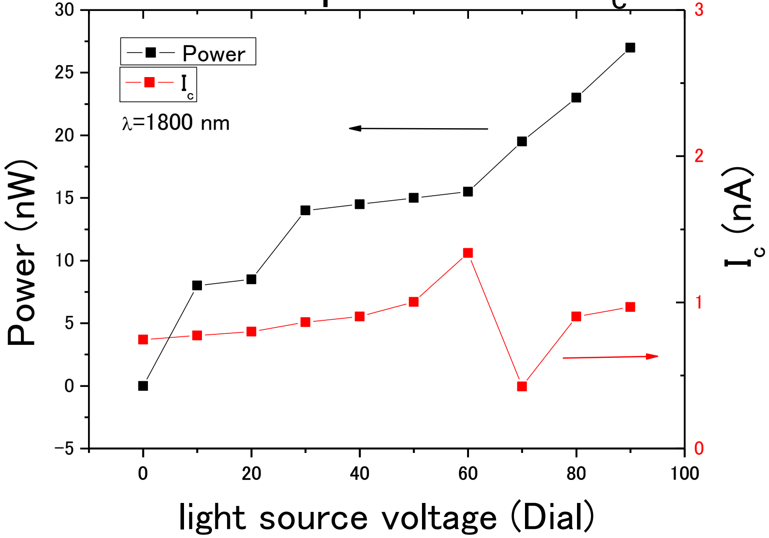

Differential resistance mapping

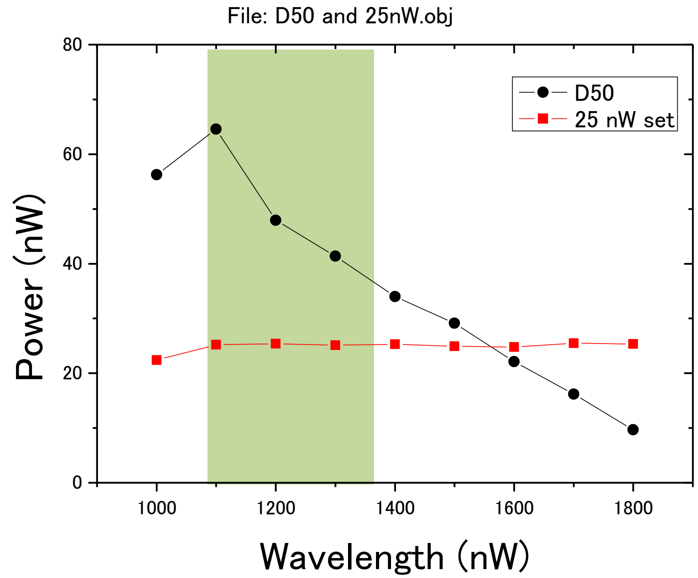


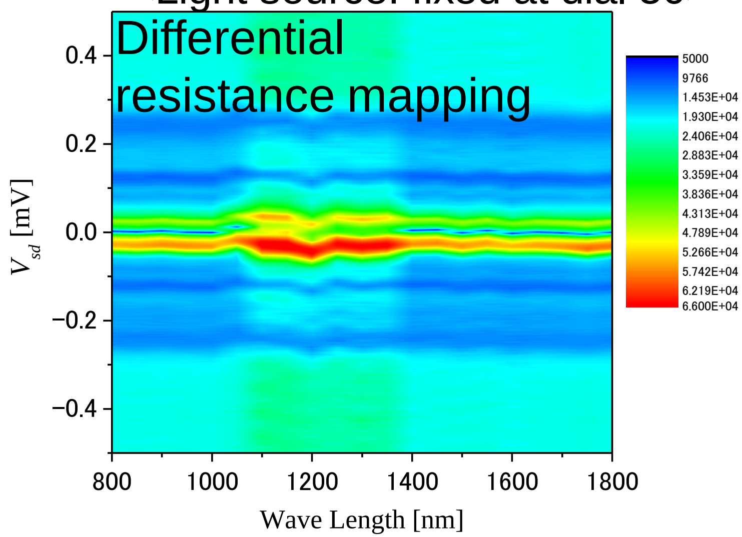
# Under the light irradiation

Power dependence of $I_c$

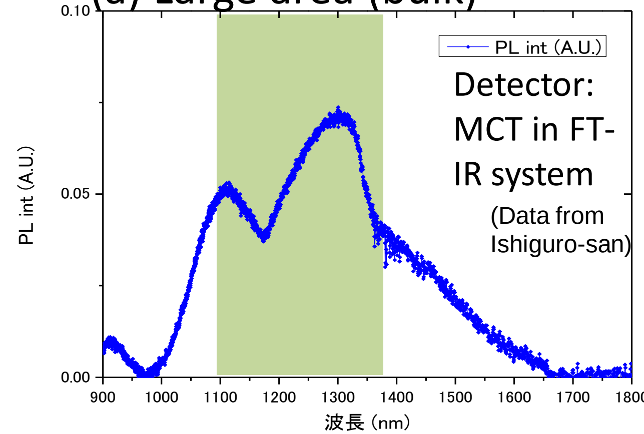



<Light source: fixed at dial 50>



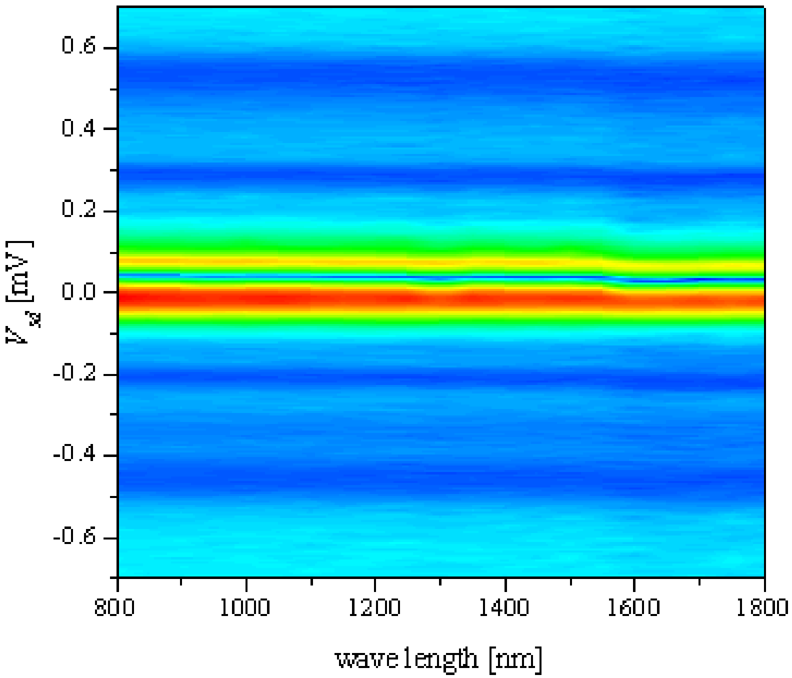

(a) Large area (bulk)



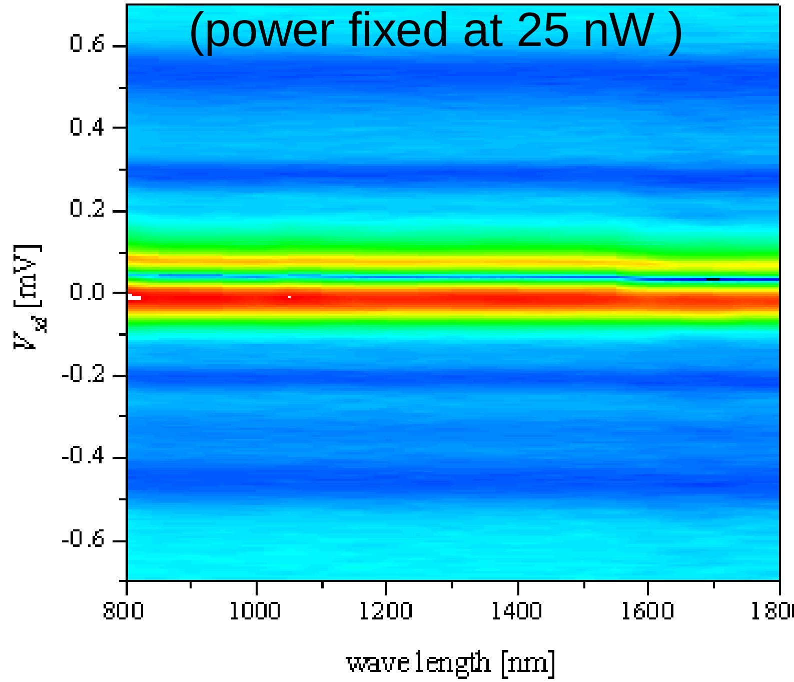

Sample characteristics is change during irradiation →Charge variation due to surface level?

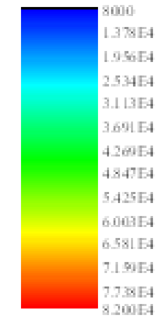
# Differential resistance at same power

a. Dark




b. Under the irradiation
(power fixed at 25 nW )




Left : dial 0

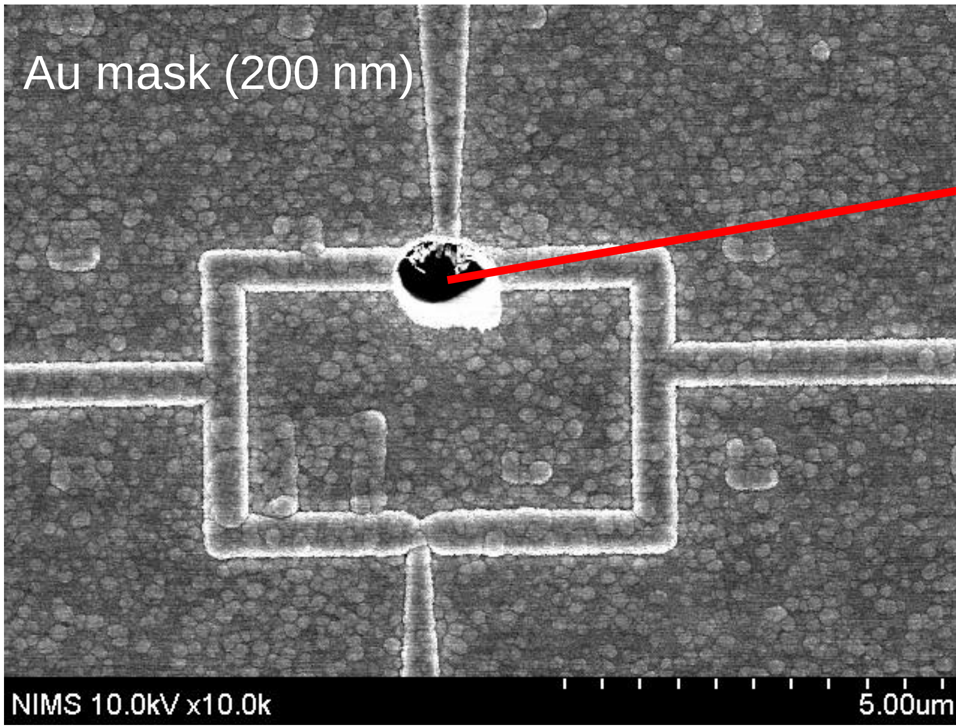
Right : Power = 25 nW

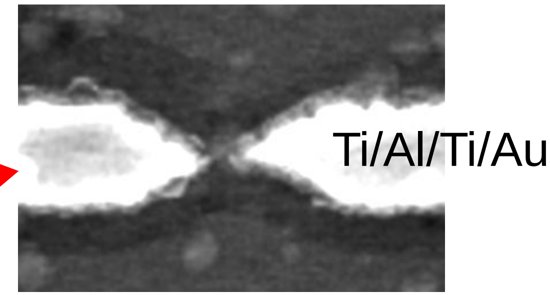
Laserを当てている場合、当てていない場合で変化が見られない。

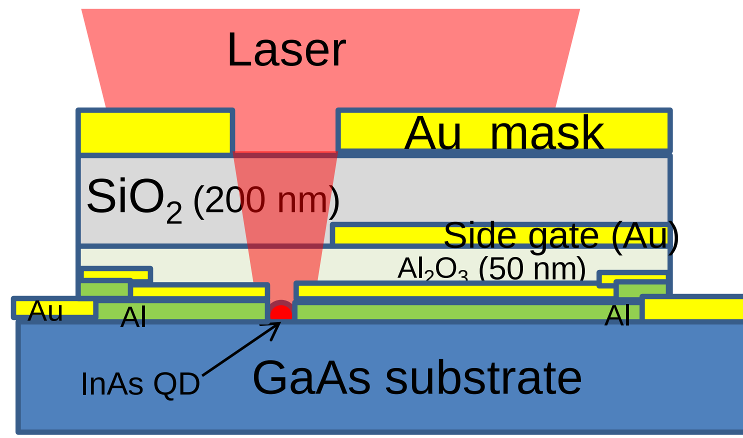
Next experiment

- -Power is not enough? → Try with higher power.
- -Use of lock-in amp
- - Use small dot and weak coupling (few electron )

# QD-SQUID with metal mask




Schematic diagram of our sample

Thank you for your attention!