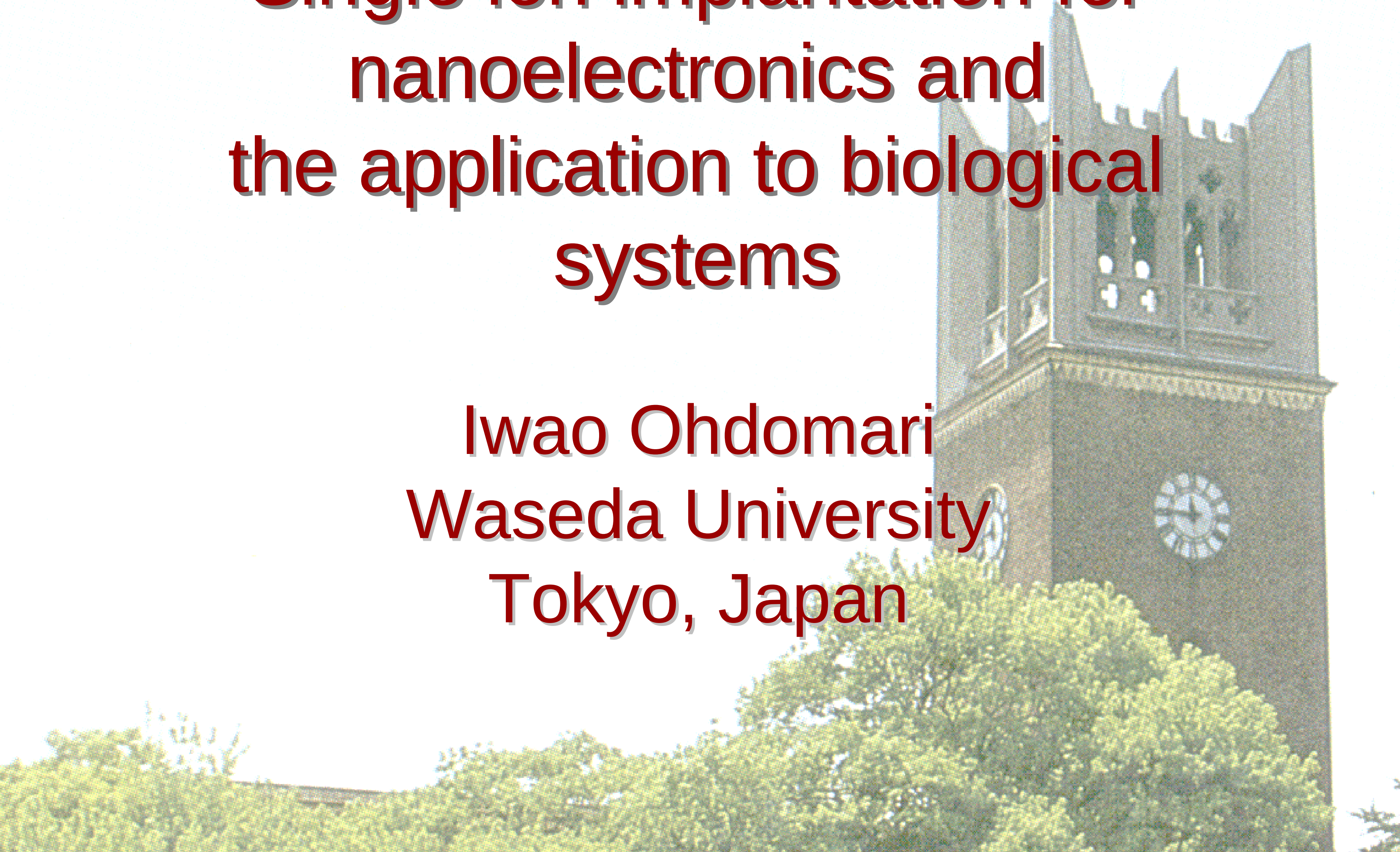


Single ion implantation for nanoelectronics and the application to biological systems

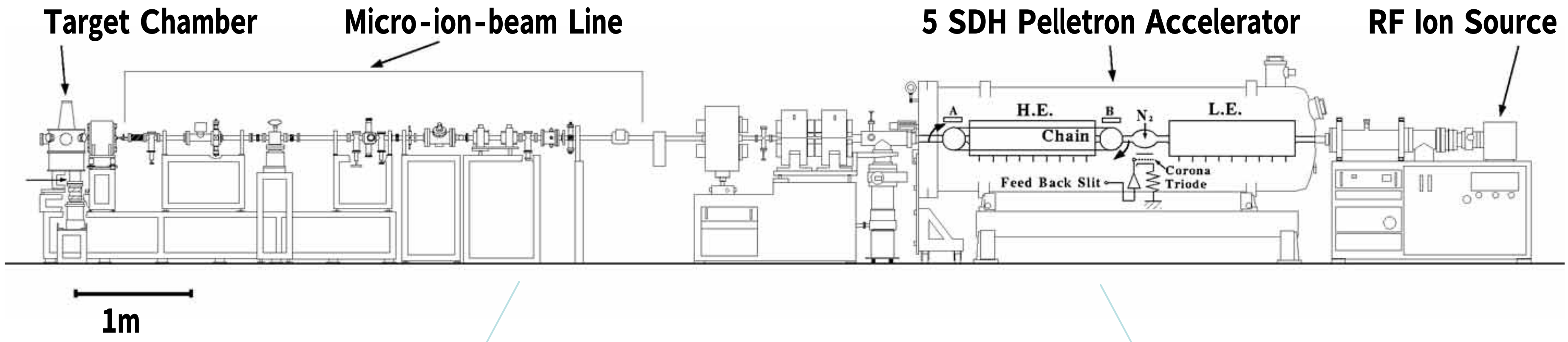
Iwao Ohdomari
Waseda University
Tokyo, Japan

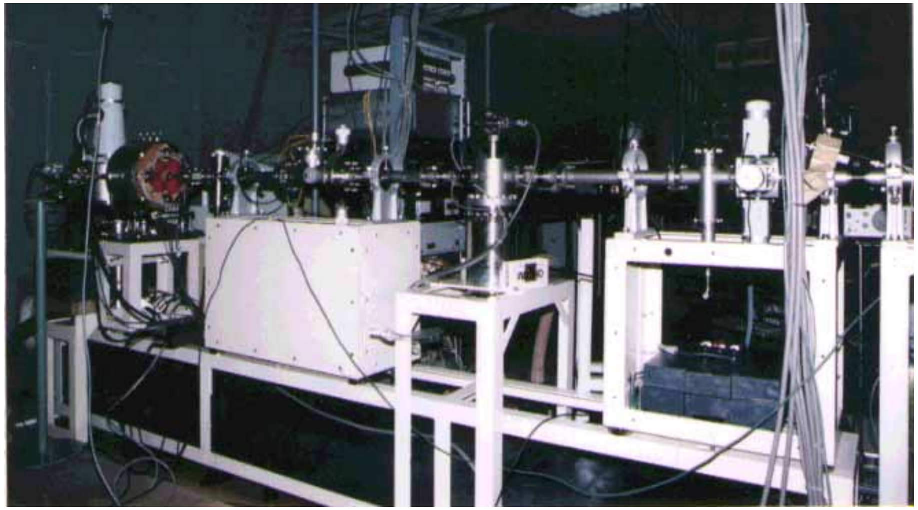
Contents

Chronology of the researches on single ion irradiation

1960s Advent of Rutherford backscattering spectroscopy(RBS). -
1980s Advent of ion micro-probe (IMP) technology. -
1992 Development of single-ion micro-probe(SIMP) at Waseda University. -
1992 Application of SIMP to mapping the site dependence of single event upset (SEU) or “soft error” hardness in semiconductor devices.
1994 Development of single ion induced charge (**SIBIC**) imaging using SIMP for high precision mapping of radiation immunity in fine semiconductor devices.
1994 Application of SIMP to testing total dose effects. -
1994 Proposal of the idea of single ion implantation (SII) by Ohdomari. -
1996 Application of SIMP to investigate influence of one-by-one ion irrdadiation on the functions of MOSFETs, pn junctions and Schottky diodes.
1996 Development of the first SII machine. a reasonable success
1996 - 2000 Application for COE program(MEXT)
1997 Analysis of radiation induced defects at SiO_2/Si interfaces using SIMP.
2000 Proposal for National Nanotechnology Initiative by U.S. President Klinton.
2000 Success in **‘trimming’ conductance value** of fine semiconductor resistors using SII for smaller fluctuation.
2001 Development of an ion-gun/high-temperature scanning-tunneling-microscope (STM) combined system (**IG/STM**) and success in in-situ observation of vacancy cluster behavior in Si.
2005 Creation of a novel semiconductor with an **ordered dopant array** using SII.
2005 Success in in-situ observation of Si interstitial behavior using IG/STM.
2005 Development of a liquid-metal-ion-source (LMIS) ion-gun/high-temperature STM combined system (**LMIS-IG/STM**). -

Single Ion Micoprobe (SIMP) System





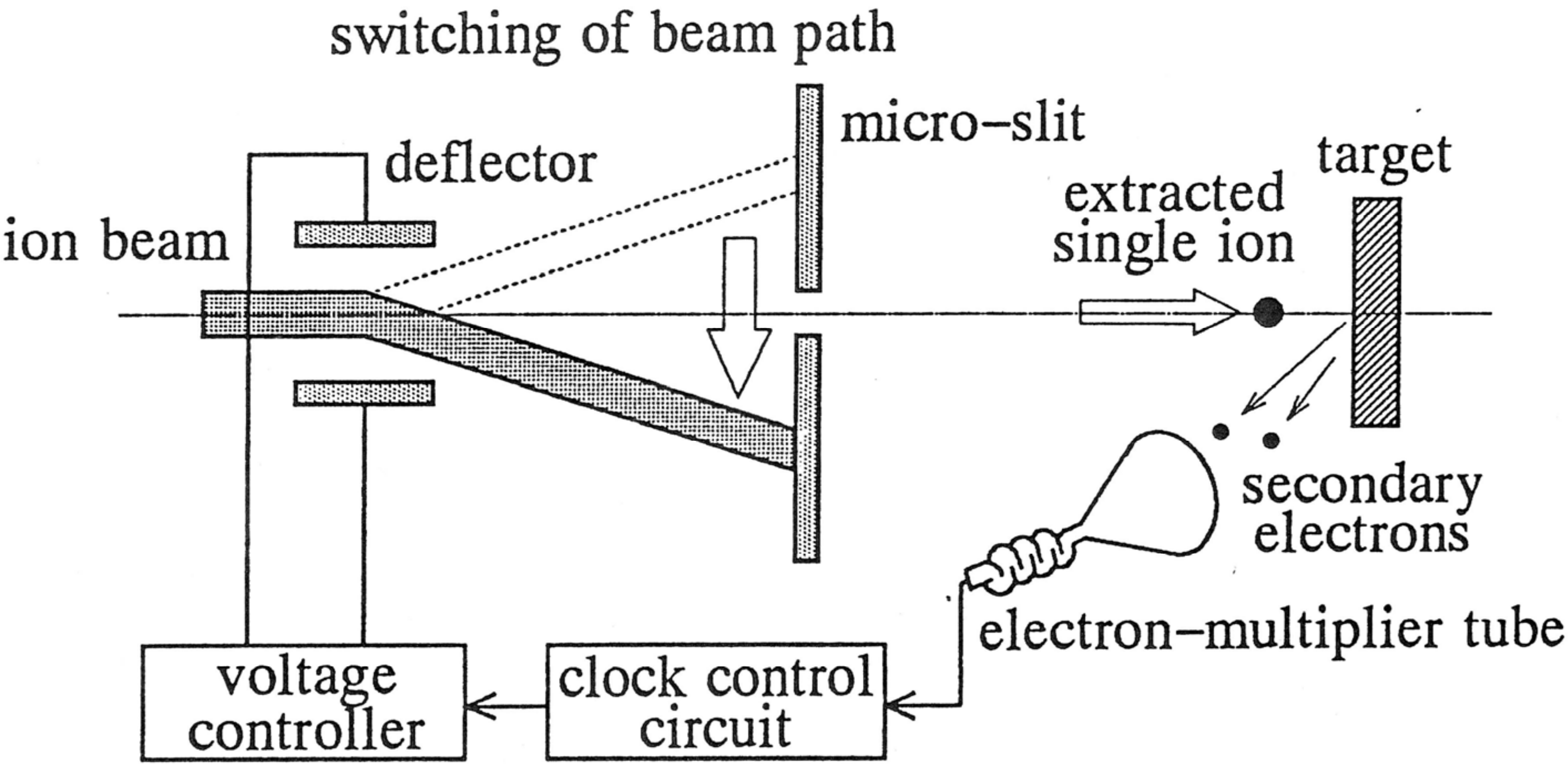
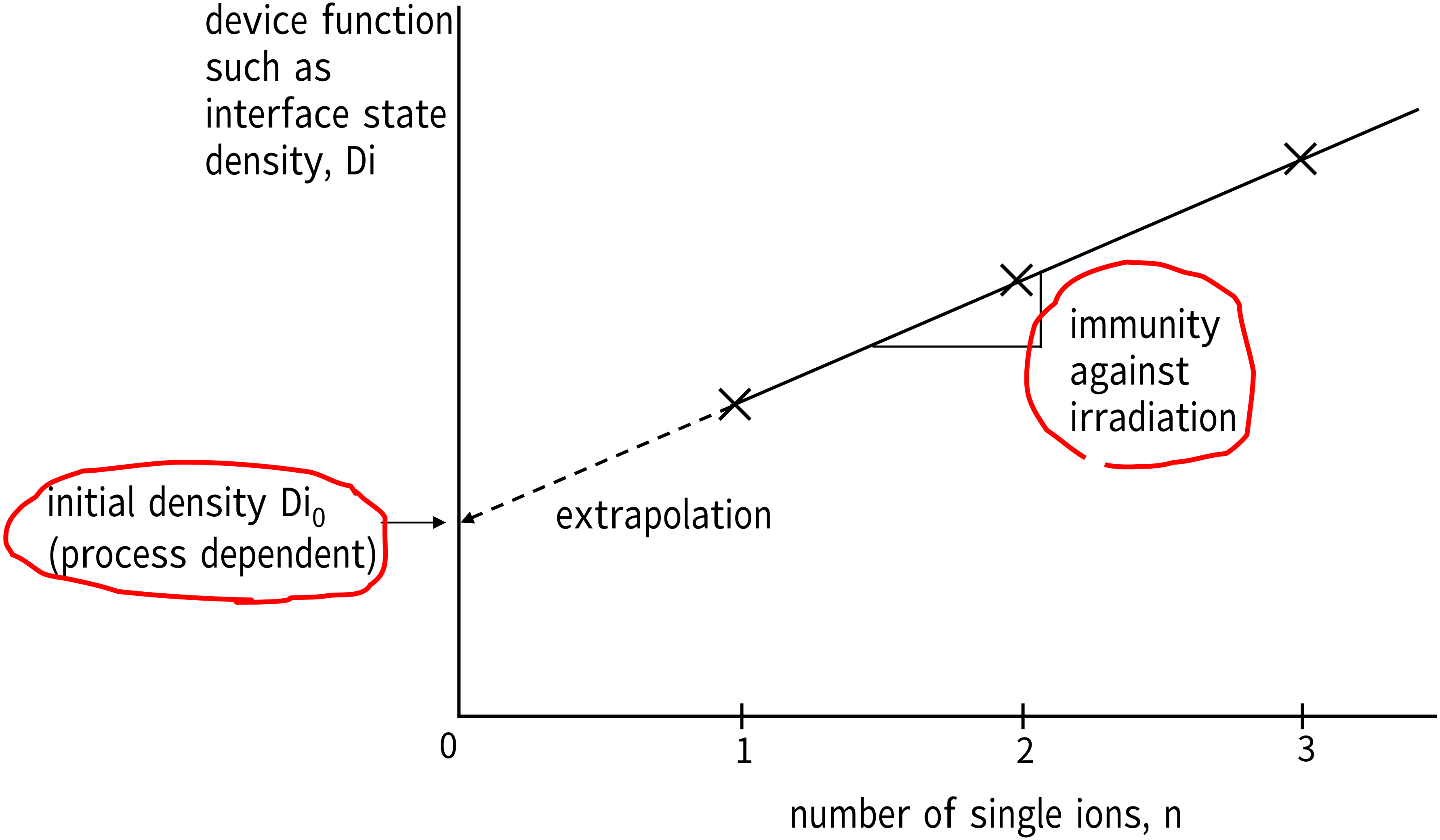

switching of beam path
micro–slit
deflector
target
extracted
single ion
ion beam
secondary
electrons
electron–multiplier tube
voltage
controller
clock control
circuit

Fig. 3

Advantage of SIMP

- **Device diagnosis**
- **Site dependence**



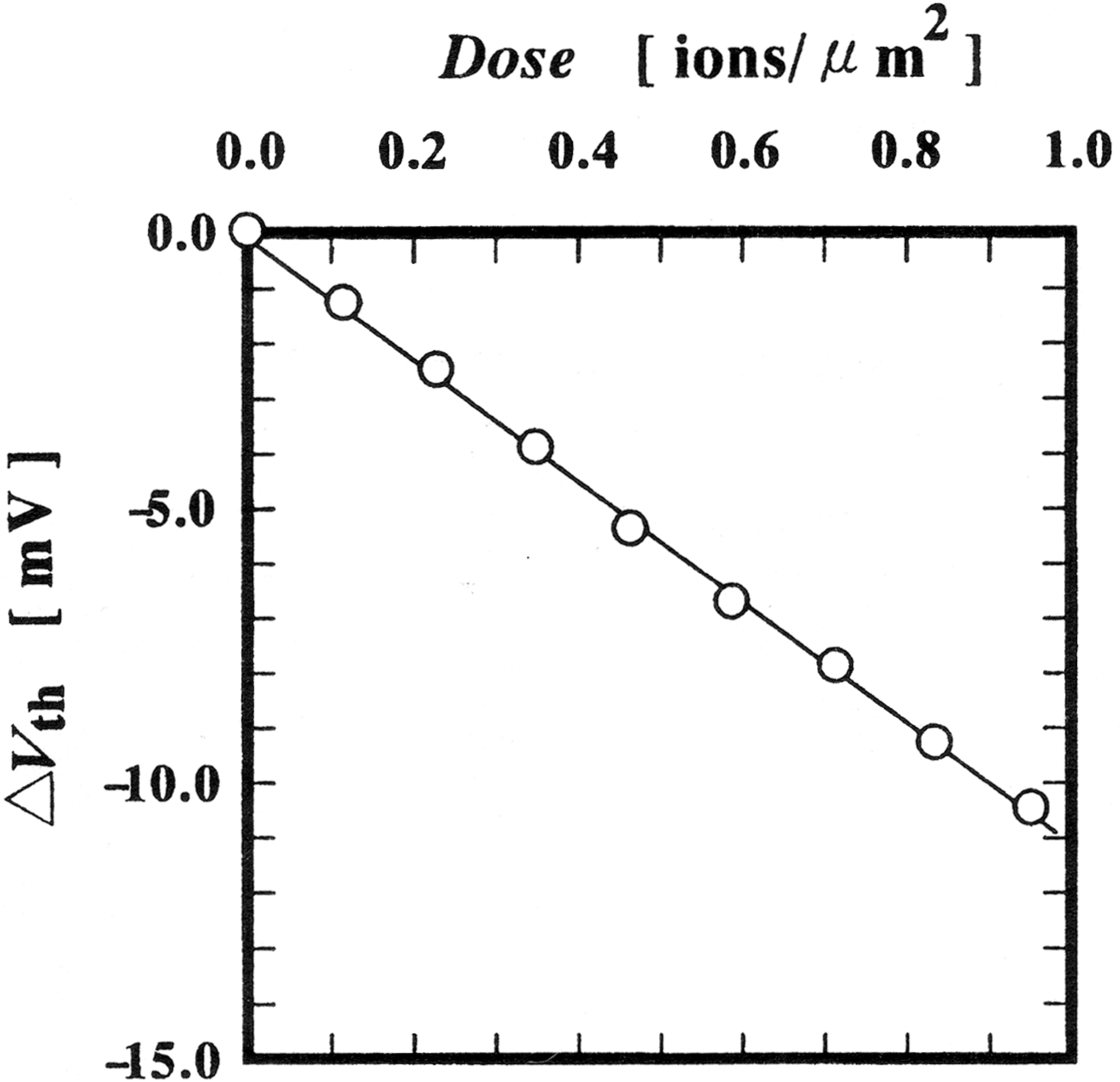
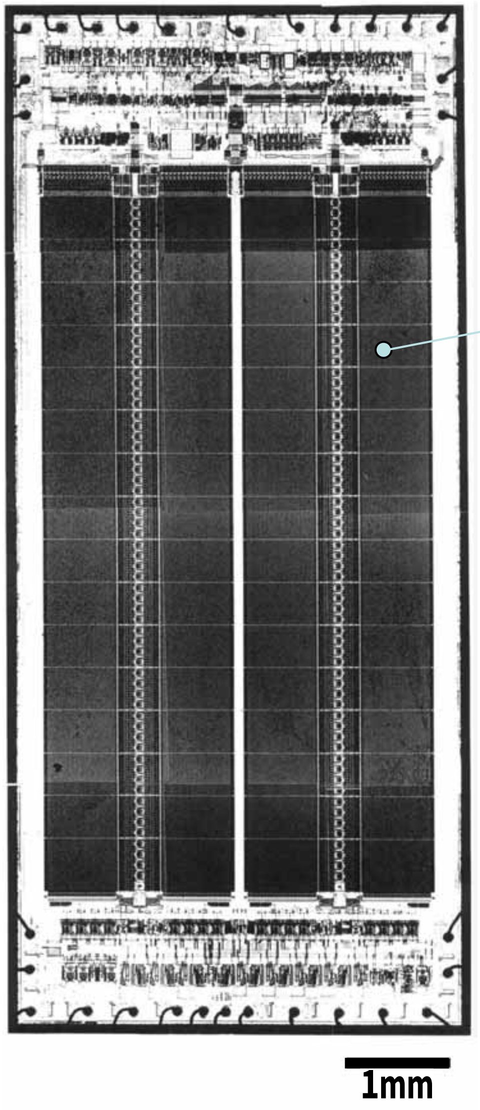
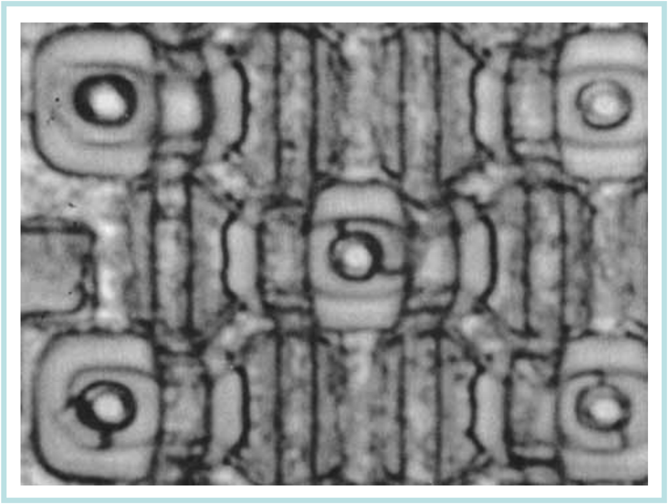


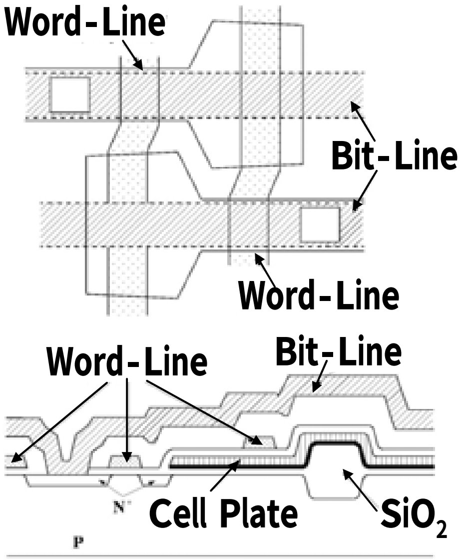
Fig. 18

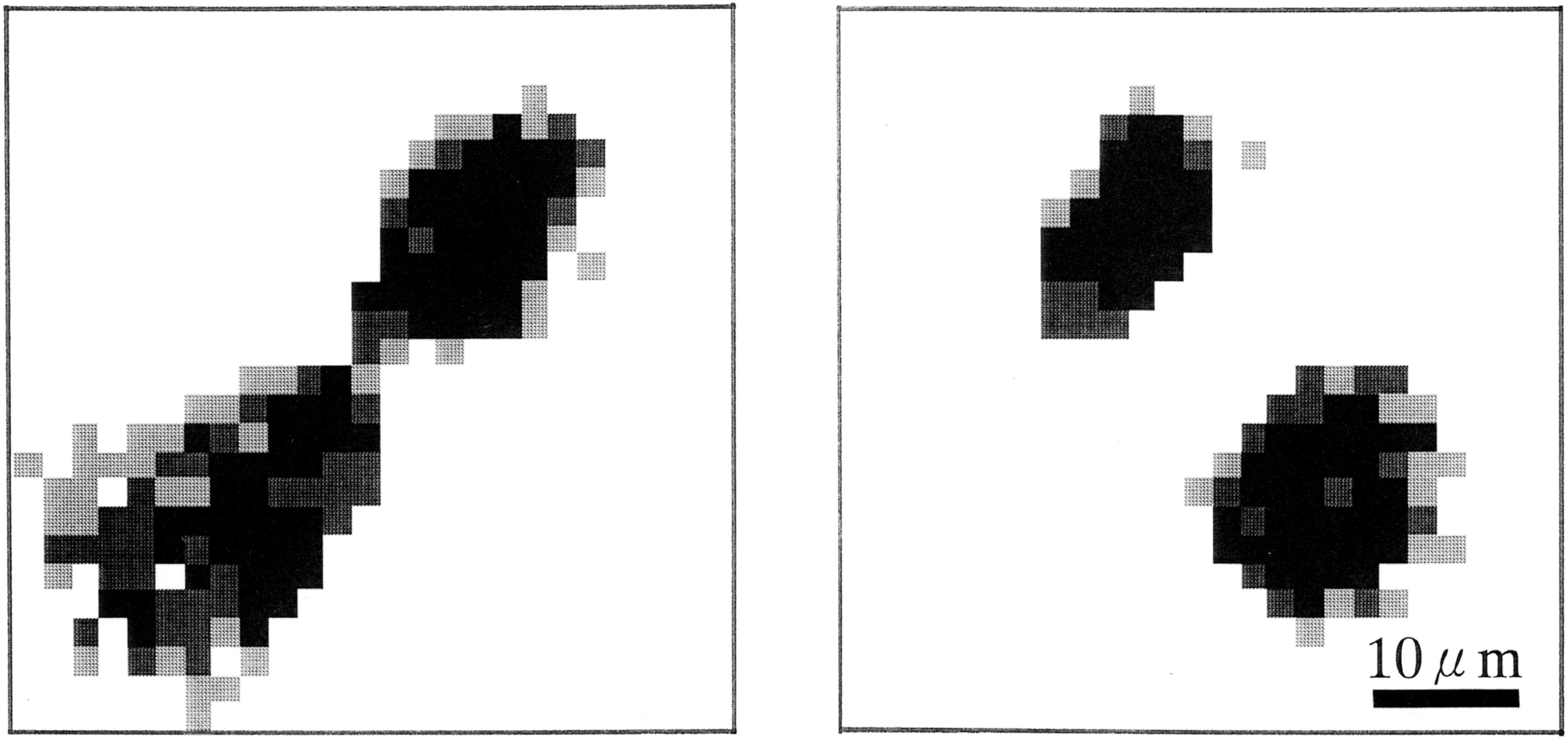
EVALUATION OF SOFT-ERROR HARDNESS OF DRAMS



256kbit DRAM TC51832P



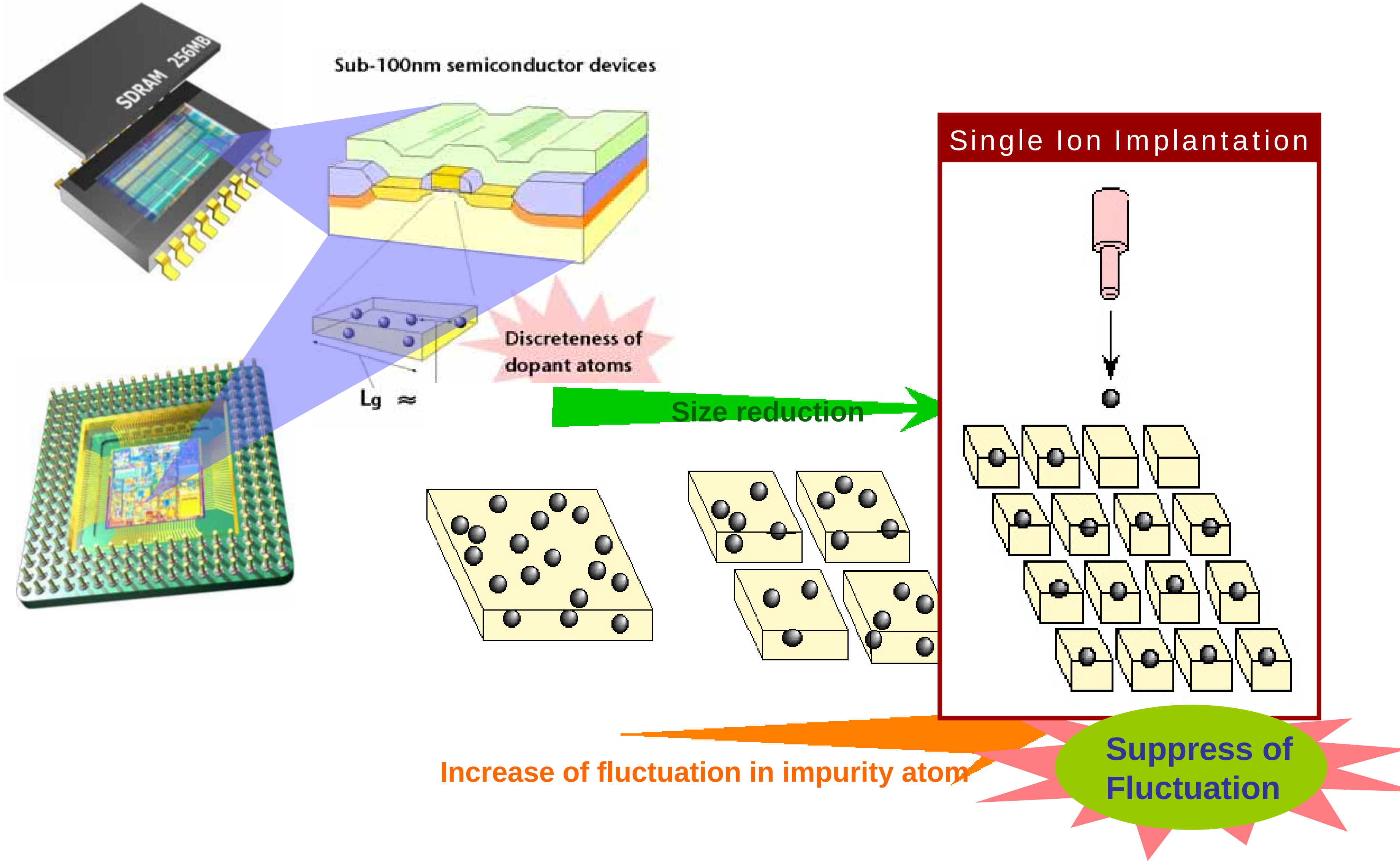




(a) "1"→"0" error (b) "0"→"1" error

Fig. 8

Motivation to develop SII



Size reduction

Single Ion Implantation

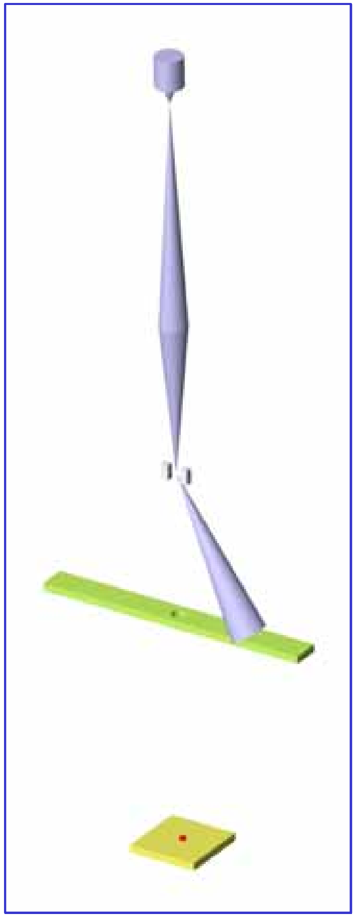
Increase of fluctuation in impurity atom

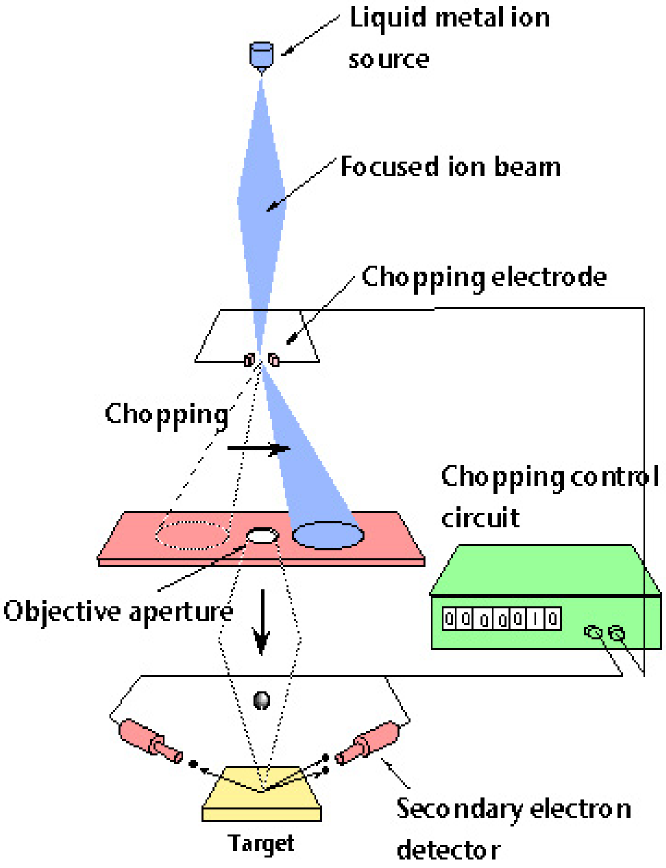
Suppress of Fluctuation

Single ion implantation

as novel tool for surface-modification

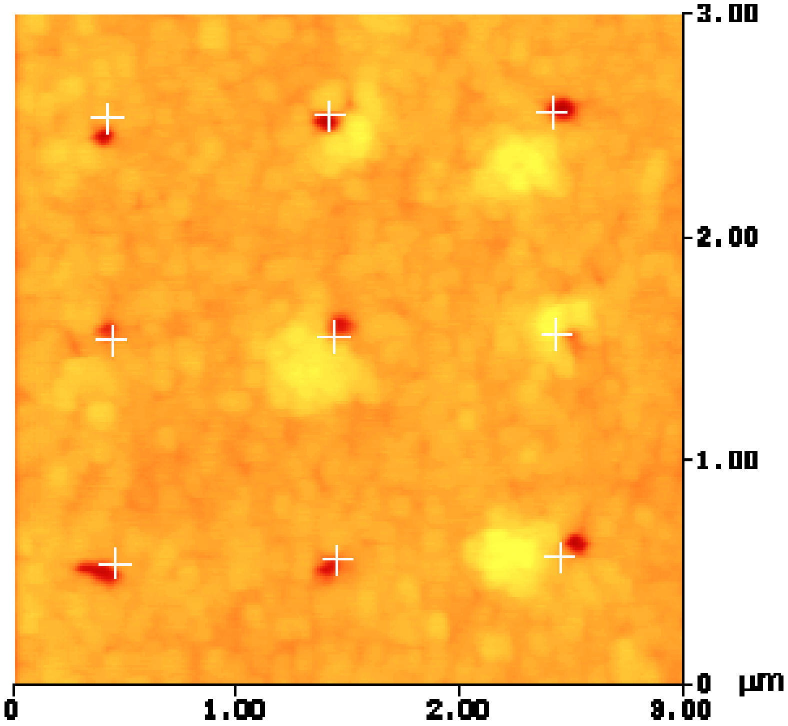
Manufactured by EIKO engineering, co. Ltd.





SPECIFICATIONS

T. Shinada, et al., : Jpn. J. Appl. Phys., 41, L287-289 (2002)

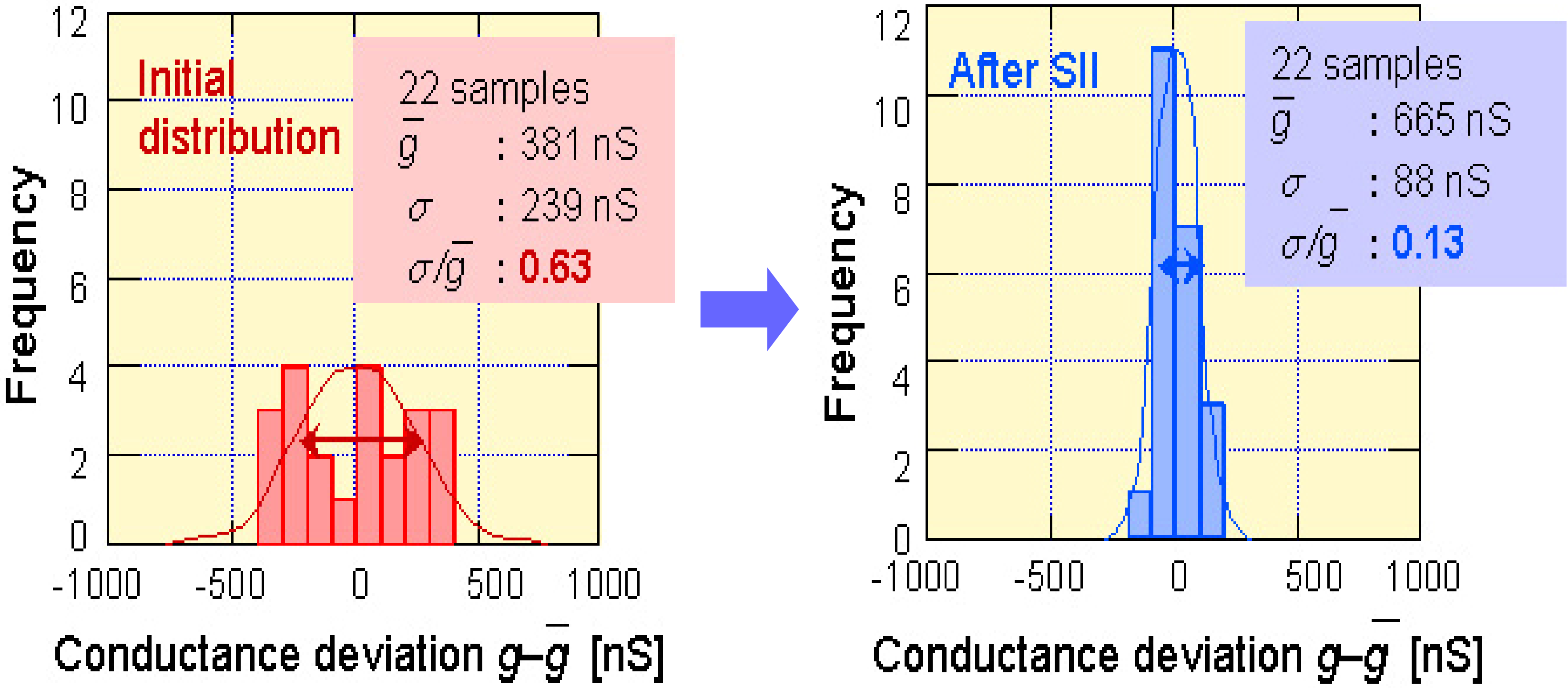


AFM image of etch-pits created by single ion incidence

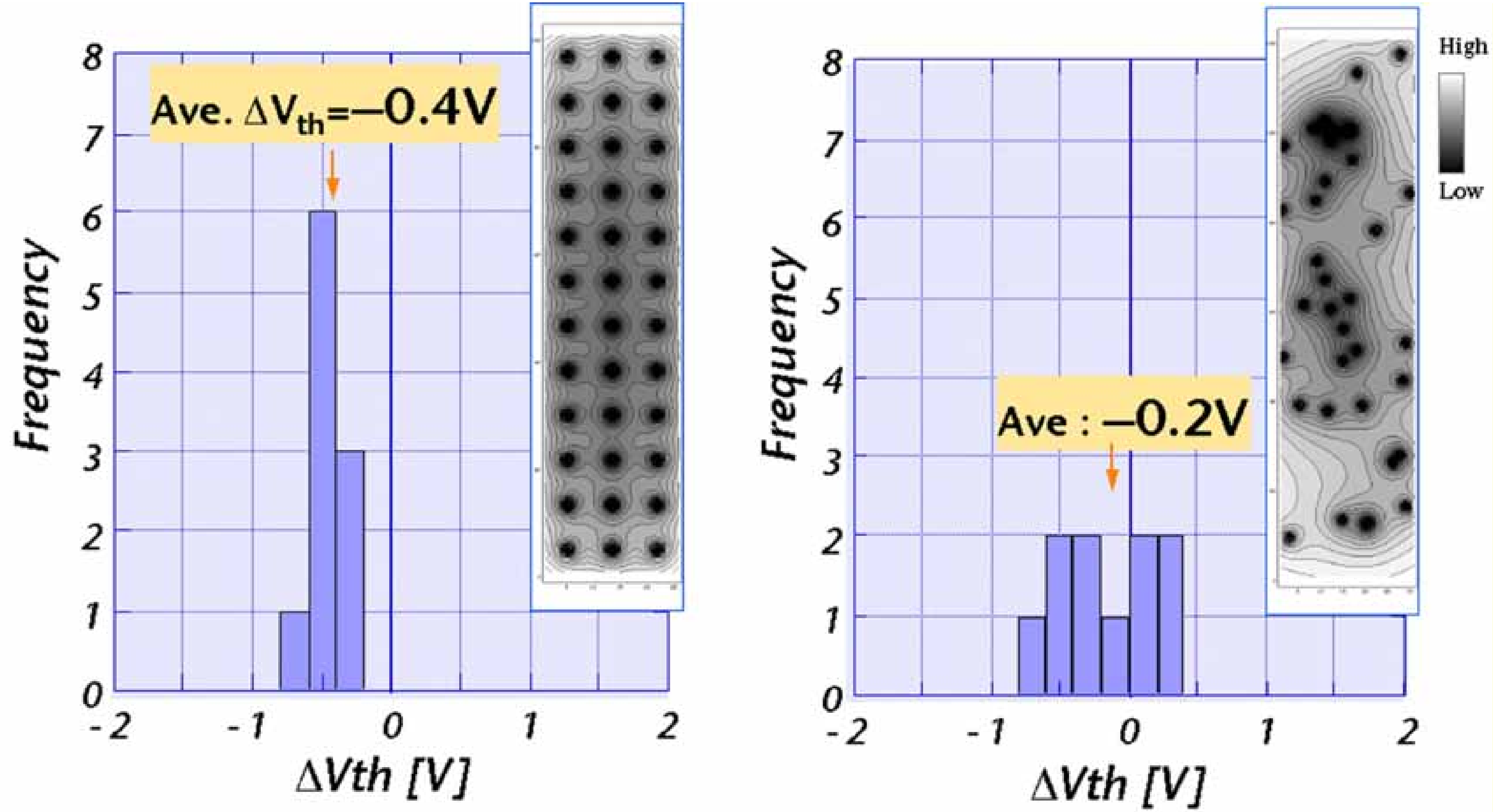
Ion species	**B, Si, P, Fe, Co, Ni, Cu, Ga Ge, As, Pd, In, Sb, Pt, Au**
Ion source type	**Liquid metal ion source**
Energy	**30keV (single charge) 60keV (double charge)**
Beam diameter	**20nm**
Aiming precision	**60nm**
Controllability of dopant atom number	**90% for SiO_2 95% for GaAs**

REDUCTION OF FLUCTUATION

T. Shinada, et al., Jpn. J. Appl. Phys. 39, L265 (2000).



Creation of novel semiconductor with periodic dopant distribution by SII (Ohdomari's group) －Threshold voltage control of MOSFET－



(a) Ordered distribution

(b) Random distribution

（注） SII ：シングルイオン注入法

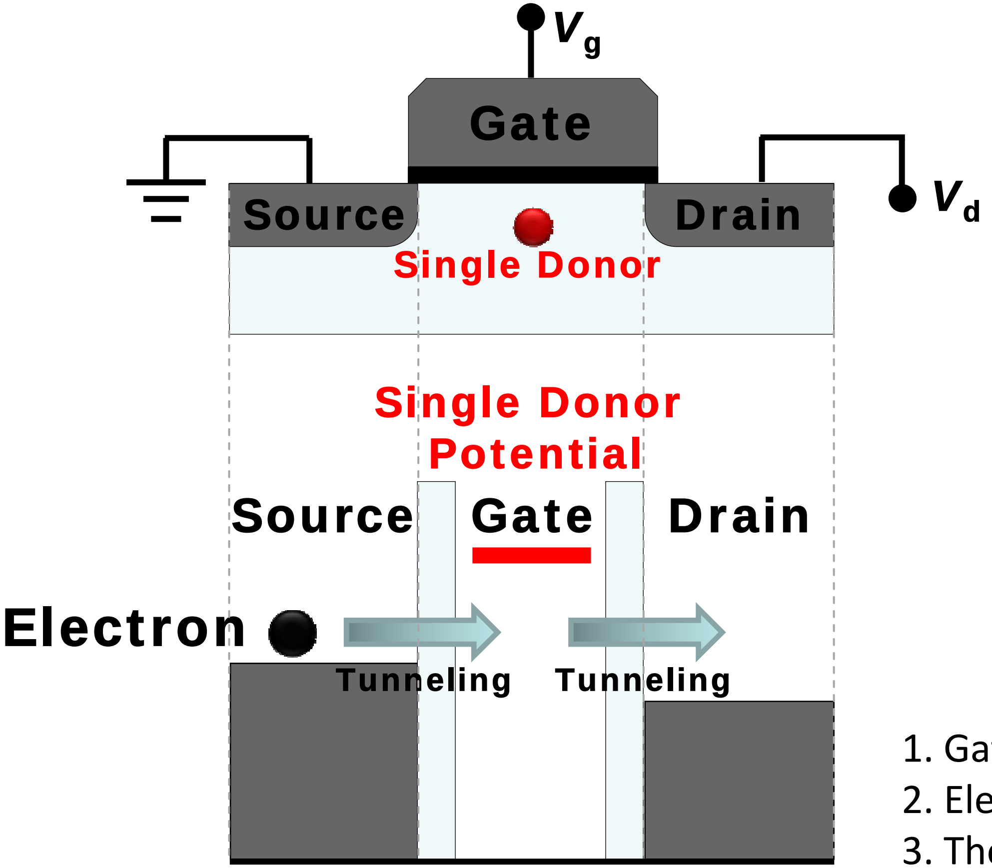
Nature, 2005

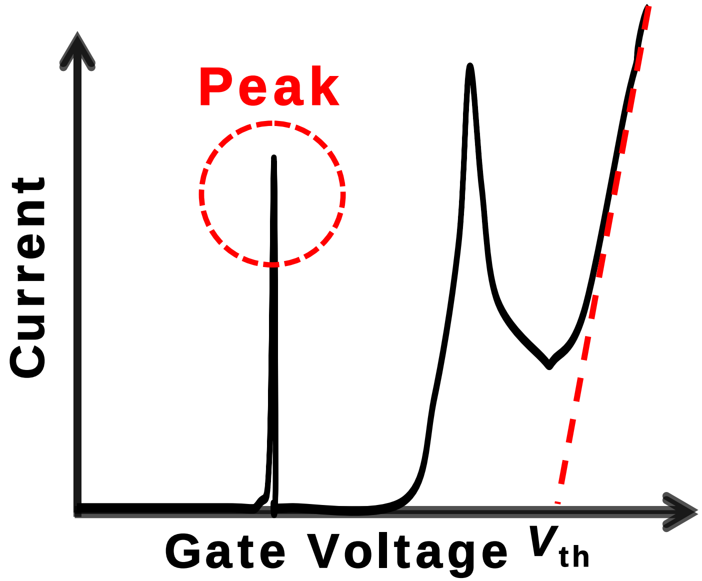
Quantum Transport in Si FETs with Deterministically Implanted Single-Arsenic Ions

Masahiro Hori, Waseda Univ., Univ. Toyama(present)
Takahiro Shinada, Waseda Univ., AIST(present)
Enrico Prati, Laboratorio MDM, IMM-CNR
Filippo Guagliardo, Politecnico di Milano
Giorgio Ferrari, Politecnico di Milano

Single-dopant device

One positive outcome has been demonstrated using a few dopant atoms in channel.





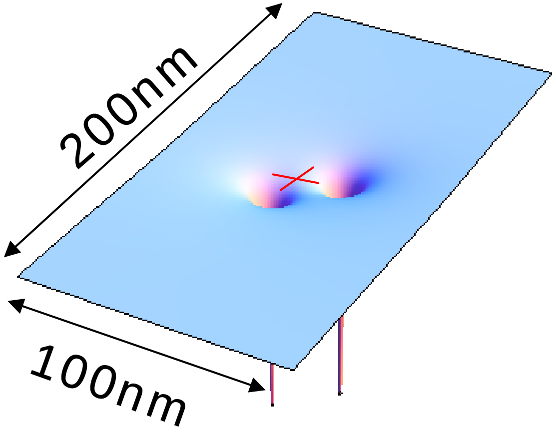
1. Gate voltage is applied to align the donor level
2. Electrons tunnel from source to drain
3. The electron tunneling is revealed as a current peak

Using the conventional ion implantation, however, only a few devices showed the single dopant operation due to the random dopant fluctuation.

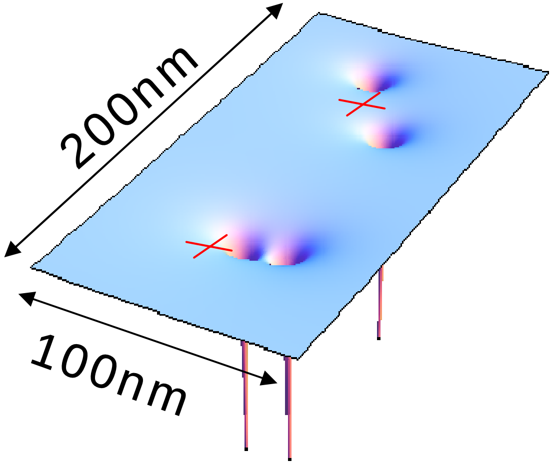
This work

- ■Fabrication of three types of devices with controlled dopant distribution
- ■Investigating the electron transport property at low temperature

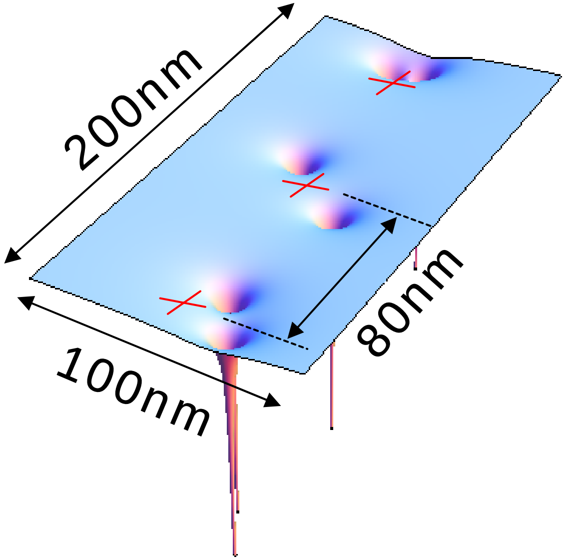
Sample A
Single-site device



Sample B
Double-site device



Sample C
Triple-site device



Total no. of donors:

2 donors **4 donors** **6 donors**

We can discuss the electron transport around the **“critical density”** which causes the transition from the **isolated donor regime** to the **continuous impurity band regime**.

Fabrication process flow

○ **Fabrication of transistor**

P-doped n-type (100) silicon-on-insulator (SOI) substrate

Initial doping concentration: 1×10^{15} cm^{-3}

Channel size: L = 200 nm, W = 100 nm, t_{SOI} = 90 nm

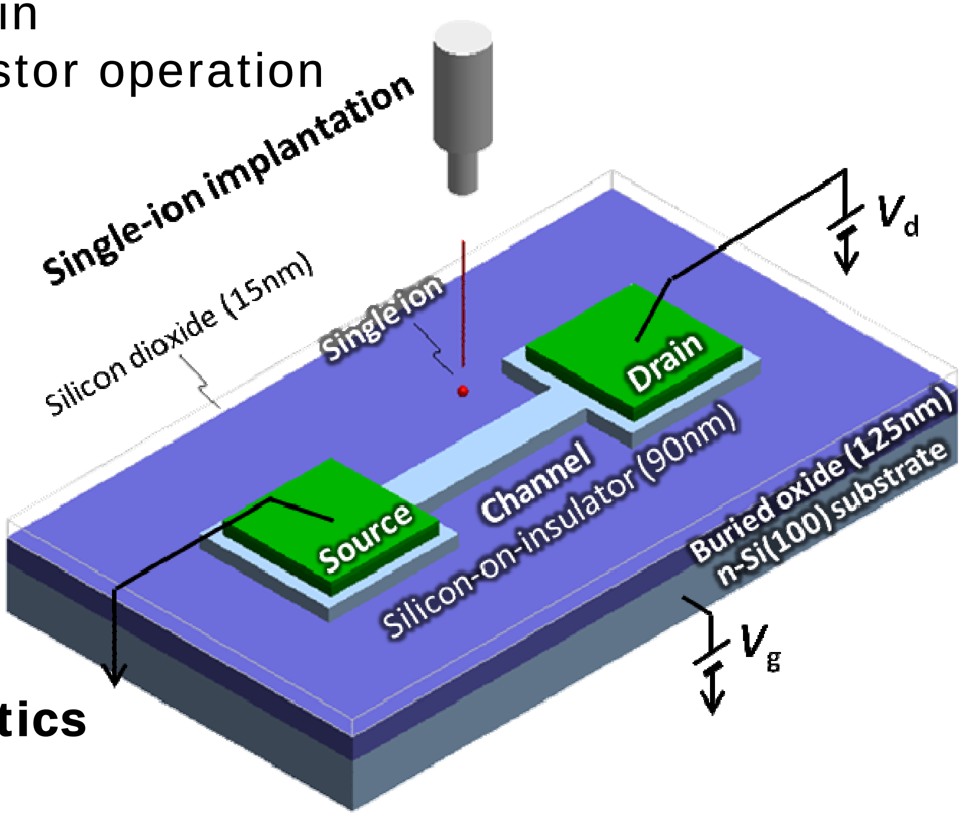
Highly P-doped n-type source/drain

Accumulation-mode n-type transistor operation

○ **Single-ion implantation**

Arsenic, 60 keV

Dopant number: 2per dot



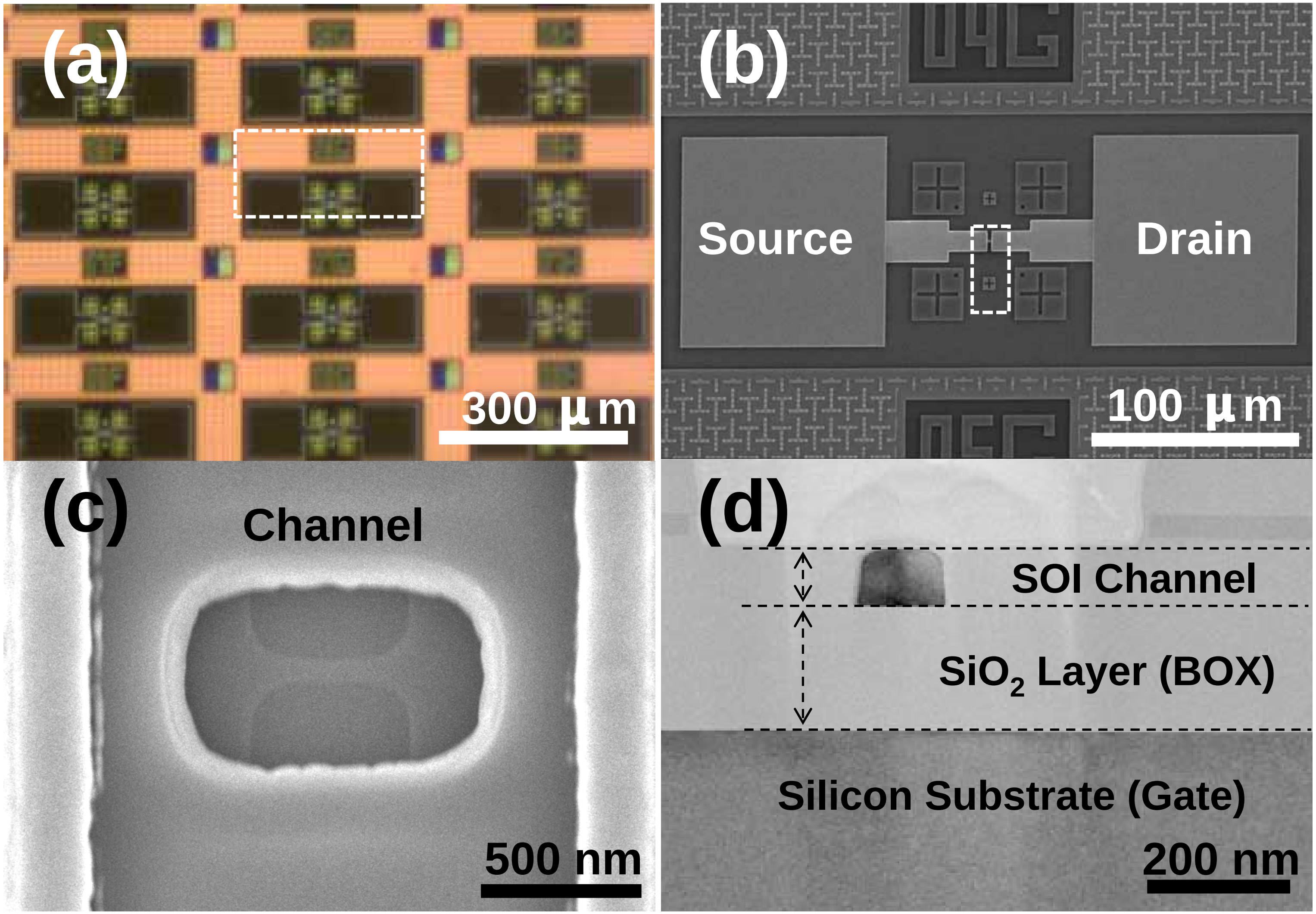
○ **Rapid thermal annealing**

at 900℃, 1 min in N_2

○ **Evaluation of V_g-I_d characteristics**

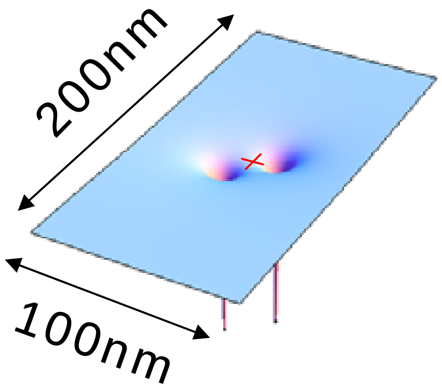
at V_d=5 mV at 4 K

Microscope images

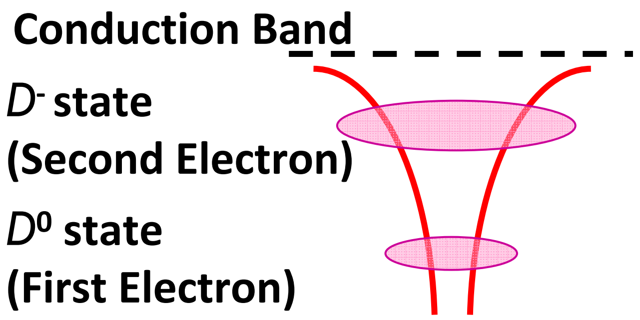


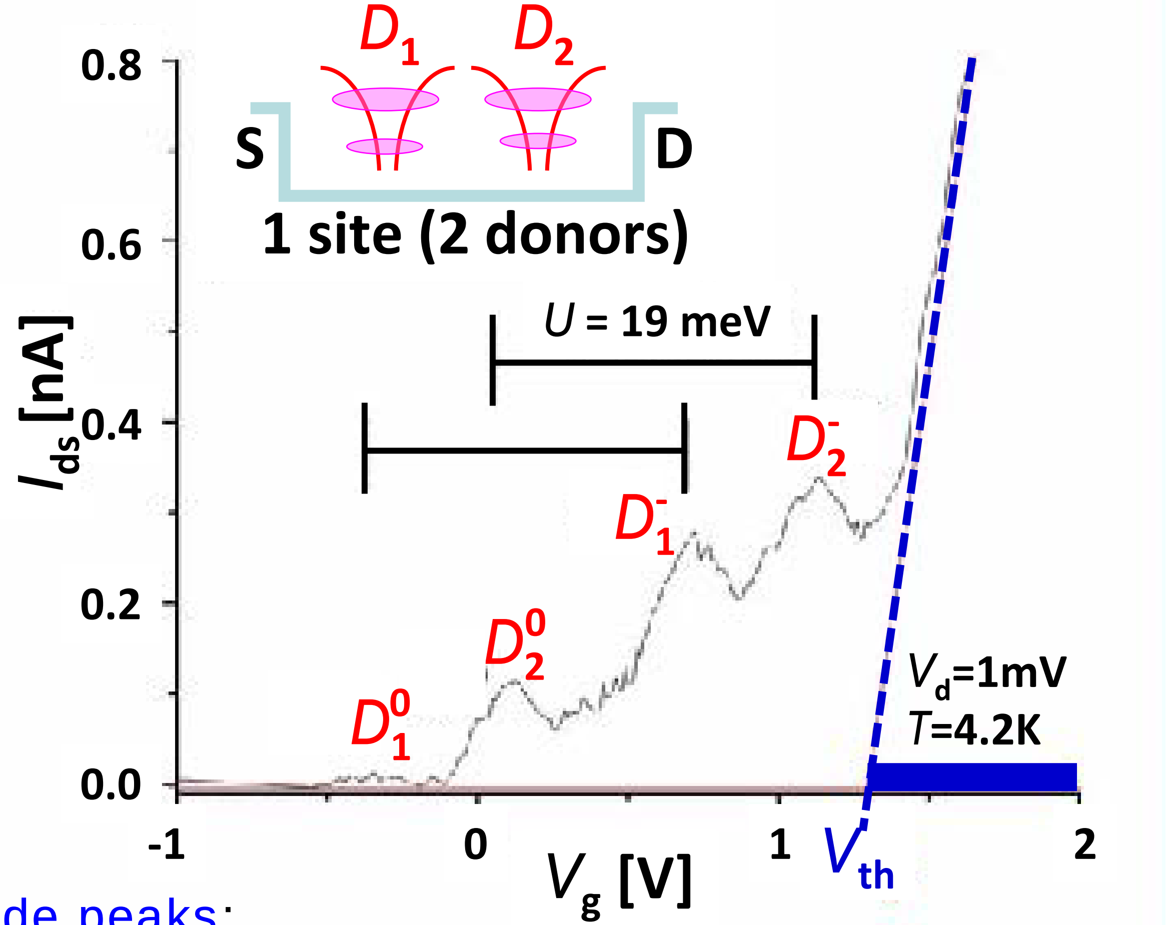
Experimental result Sample A

Sample A Single-site device



Donor level in Silicon



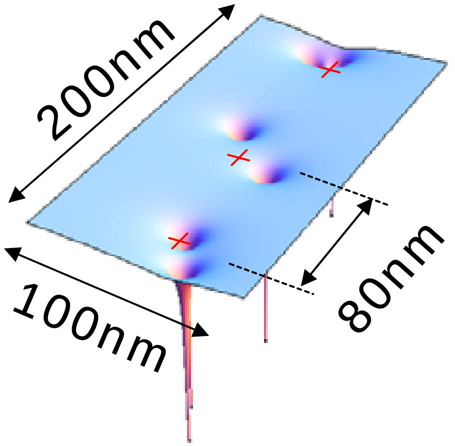


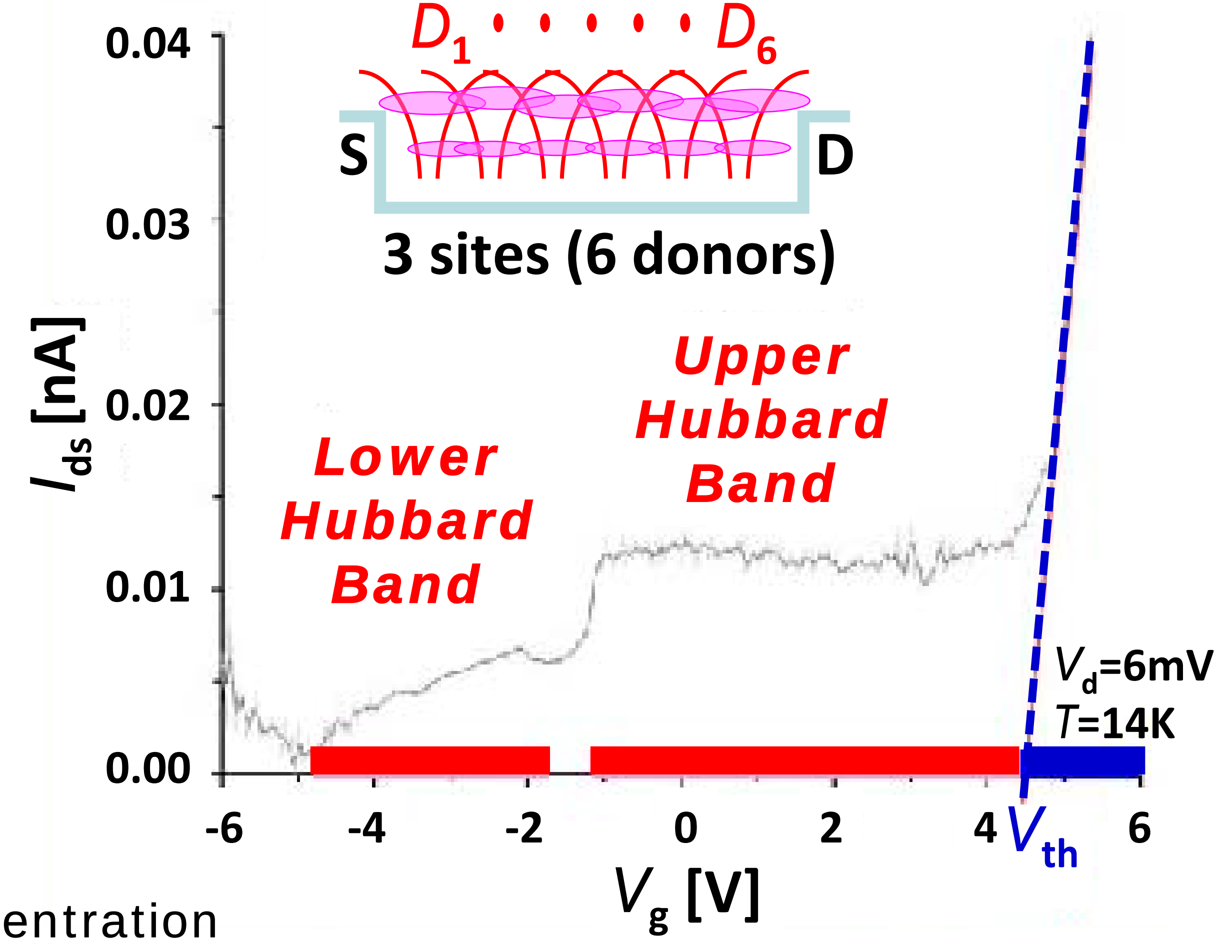
- Isolated Coulomb blockade peaks;
- No other peaks above the fourth
- Number of the peaks coincides with double of the number of dopants.

Nature Nanotechnology **7**, 443-447 (2012)

Experimental result:Sample C

Sample C Triple-site device



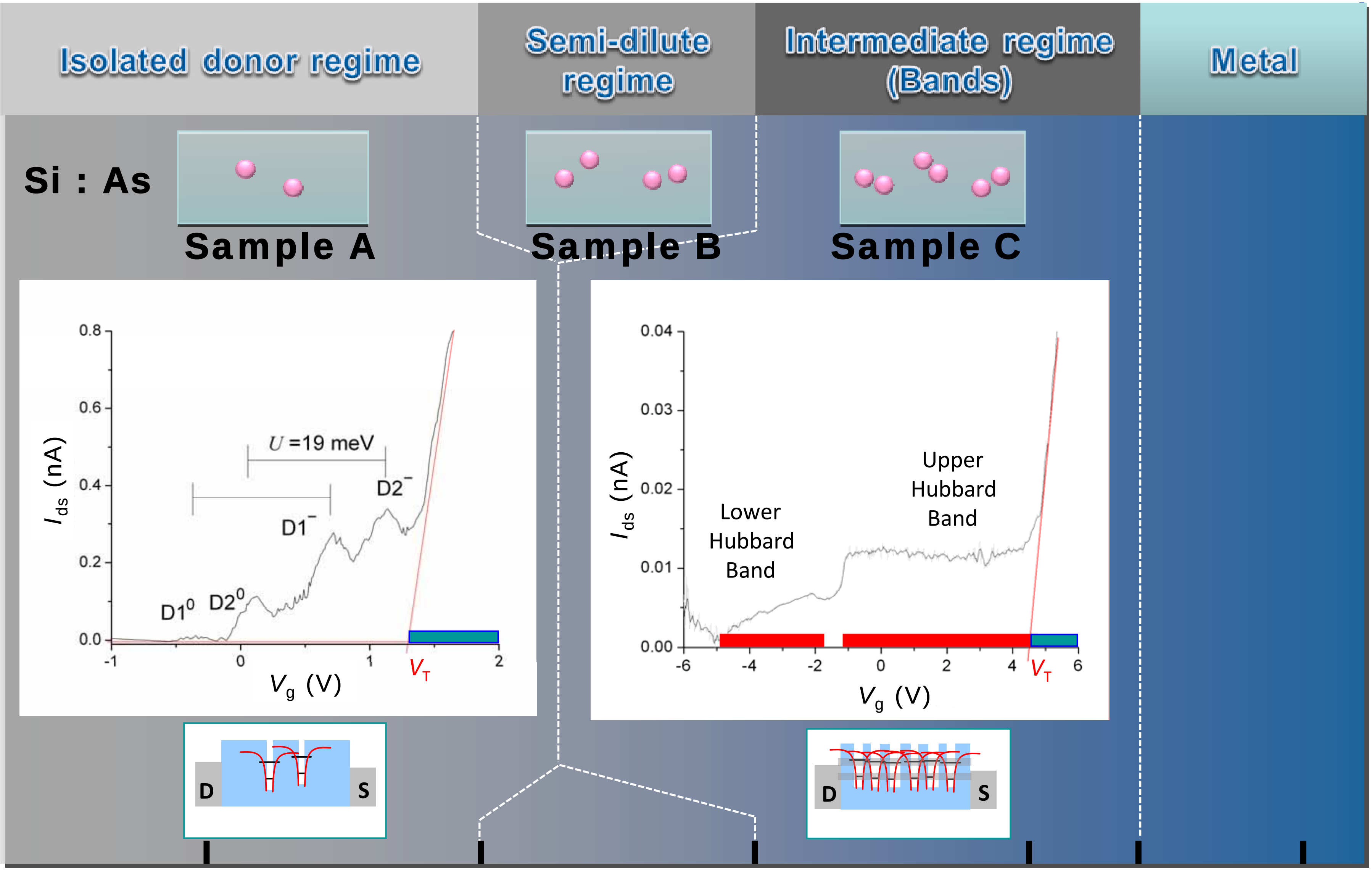


- Higher donor concentration
- Broad characteristic in which Coulomb blockade peaks merge;
- Overlap of the wave functions.

Nature Nanotechnology **7**, 443-447 (2012)

Conclusion of quantum transport

ce



Isolated donor regime

Semi-dilute regime

Intermediate regime (Bands)

Metal

Si : As

Sample A

Sample B

Sample C

r_c [nm]	100	46.4	21.5	10	4.6	4.6
n [cm^{-3}]	10^{15}	10^{16}	10^{17}	10^{18}	3.7×10^{18}	10^{19}

Nature Nanotechnology **7**, 443-447 (2012)

Summary

- For investigating the quantum transport at low temperature, deterministically doped silicon transistors have been fabricated containing 2, 4, and 6 donor ions in an array along the channel.

- The quantum transport was measured through the D^0 and D^- states of deterministically doped donors.

- Two different transport mechanisms contributed to the deterministically doped device;
  the isolated donor regime and the Hubbard band regime.

- These results pave the way towards single atom electronics for extended CMOS applications.

Modulation of viability of live cells by focused ion-beam implantation

Takahiro Shinada, Waseda Univ., AIST(present)
Masahiro Hori, Waseda Univ., Univ. Toyama(present)
Takayuki Akimoto, Waseda Univ., Univ.Tokyo(present)
Takashi Tanii, Waseda Univ.
Yanwei Zhu, Waseda Univ.
Hisa Goke, Waseda Univ.
Iwao Ohdomari, Waseda Univ.

Background

Introduction of membrane-impermeant substances into living cells

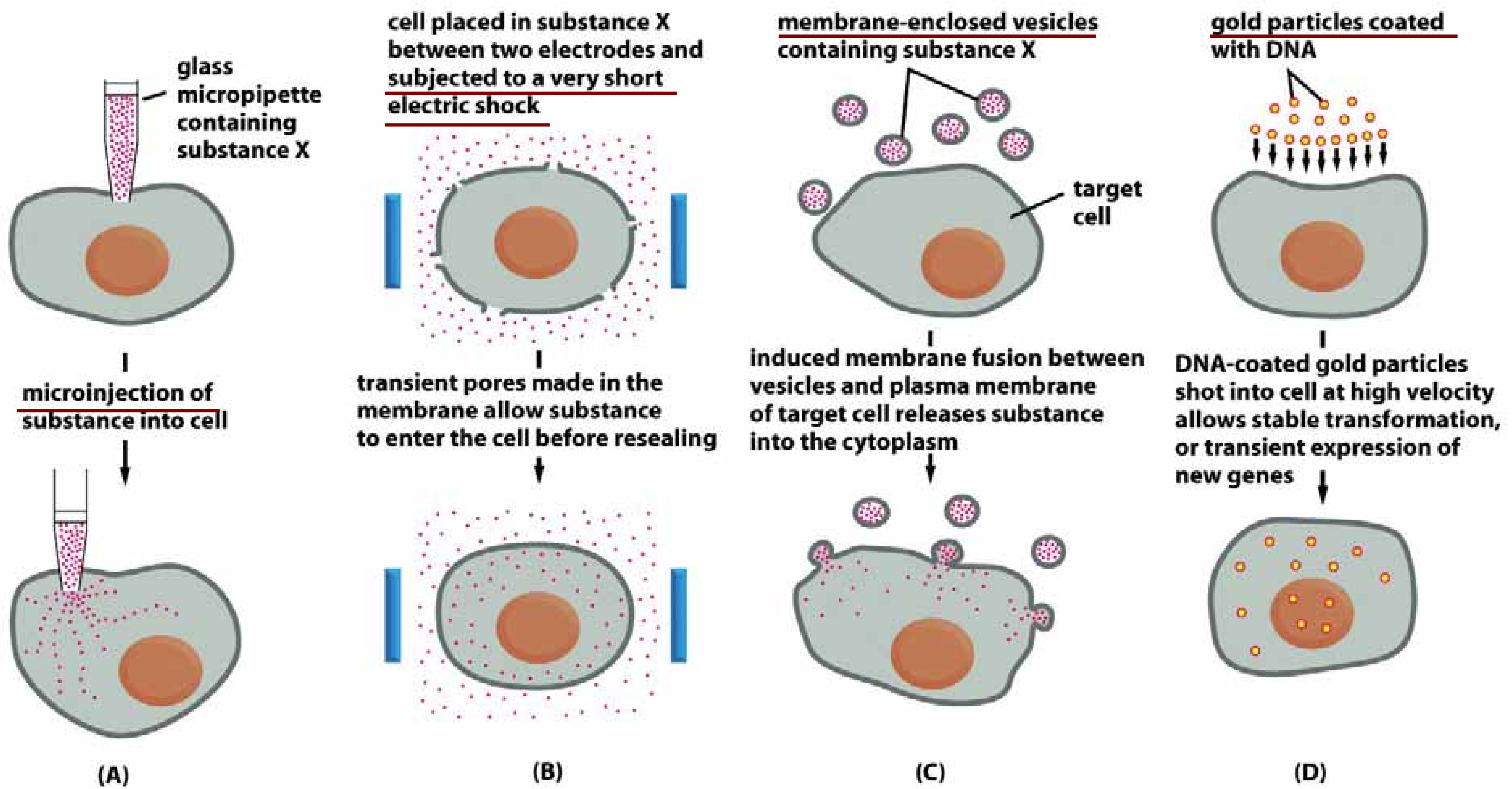


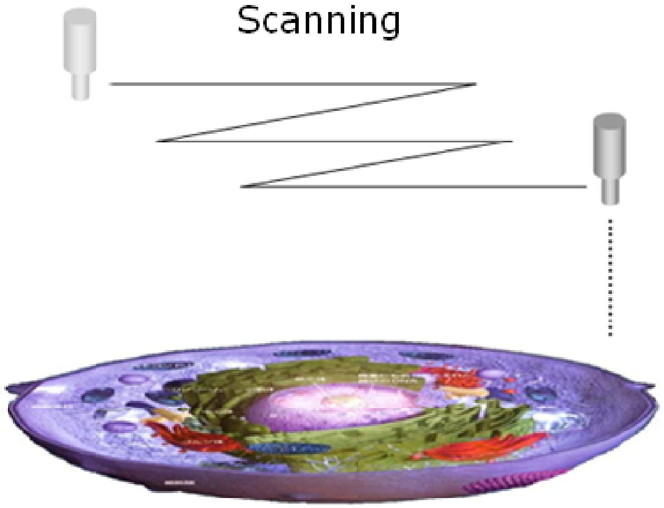
Figure 9-34 Molecular Biology of the Cell 5/e (© Garland Science 2008)

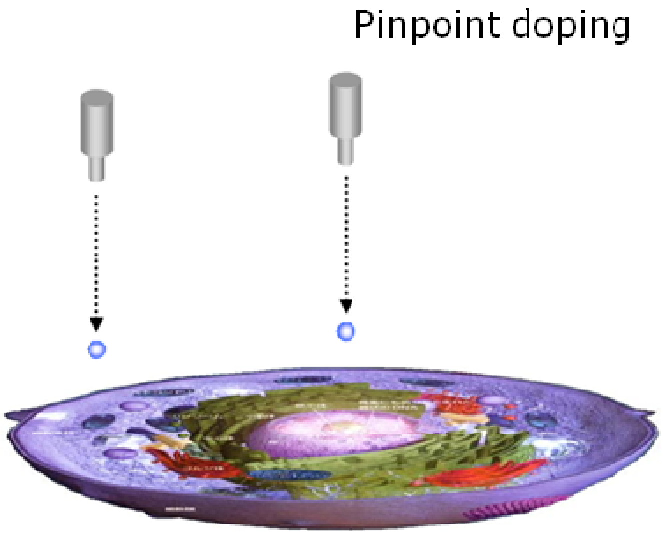
Source: Molecular Biology of THE CELL, 5th ed.

Purpose of this study

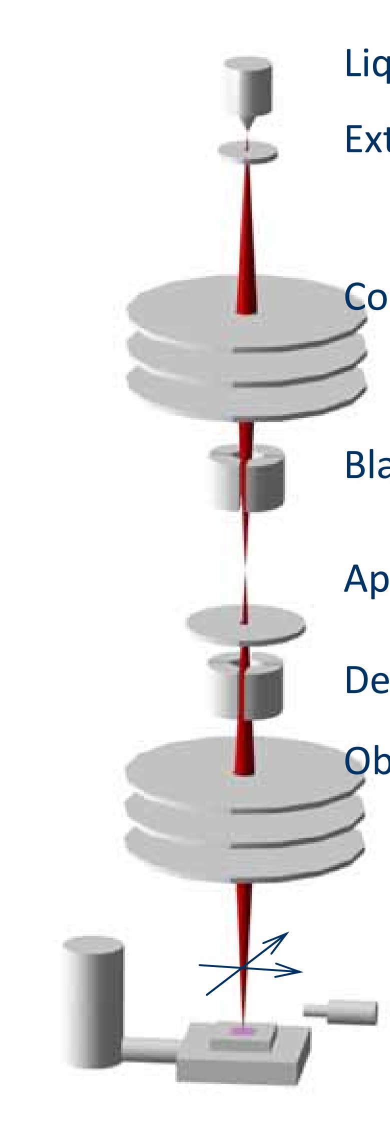
The purpose of this study is to develop the ion implantation method for modifying the function of living cells and explore for an element that is effective for therapy and diagnosis.

In this study, we focus on gold ions, as gold has historically been believed to have therapeutic effects and verify the effects of implanted gold ions on cell function.





Ion implanter for live cells



Liquid metal ion source

Extractor

Condenser lens

Blanker

Aperture

Deflector

Objective lens

Secondary electron detector

Ion species	Be, B, Si, P, Fe, Co, Ni, Cu, Ga, Ge, As, Pd, In, Sb, Pt, Au
Ion source type	Liquid metal ion source
Acceleration voltage	10kV (Currently fixed)
Energy	10keV (single charge) 20keV (double charge)
Beam diameter	100nm

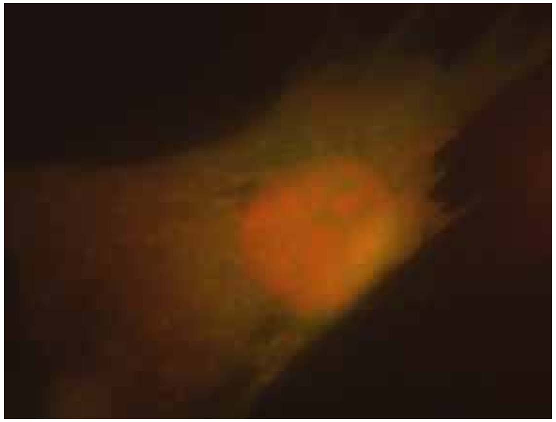
Experimental

Mouse skeletal muscle cell

○ **Cell culture**

Myoblasts(C2C12) **筋芽細胞**

Cell concentration 25,000cm^{-2}



Fluorescent image of single-cell

○ **Cell freezing** at -80 **°C**

○ **Control**

at -150**°C**
in Vacuum

○ **Ion implantation**

Au^{2+} , 10kV
1,000~50,000 ions/cell
at -150**°C** in Vacuum
(for 30 min.)

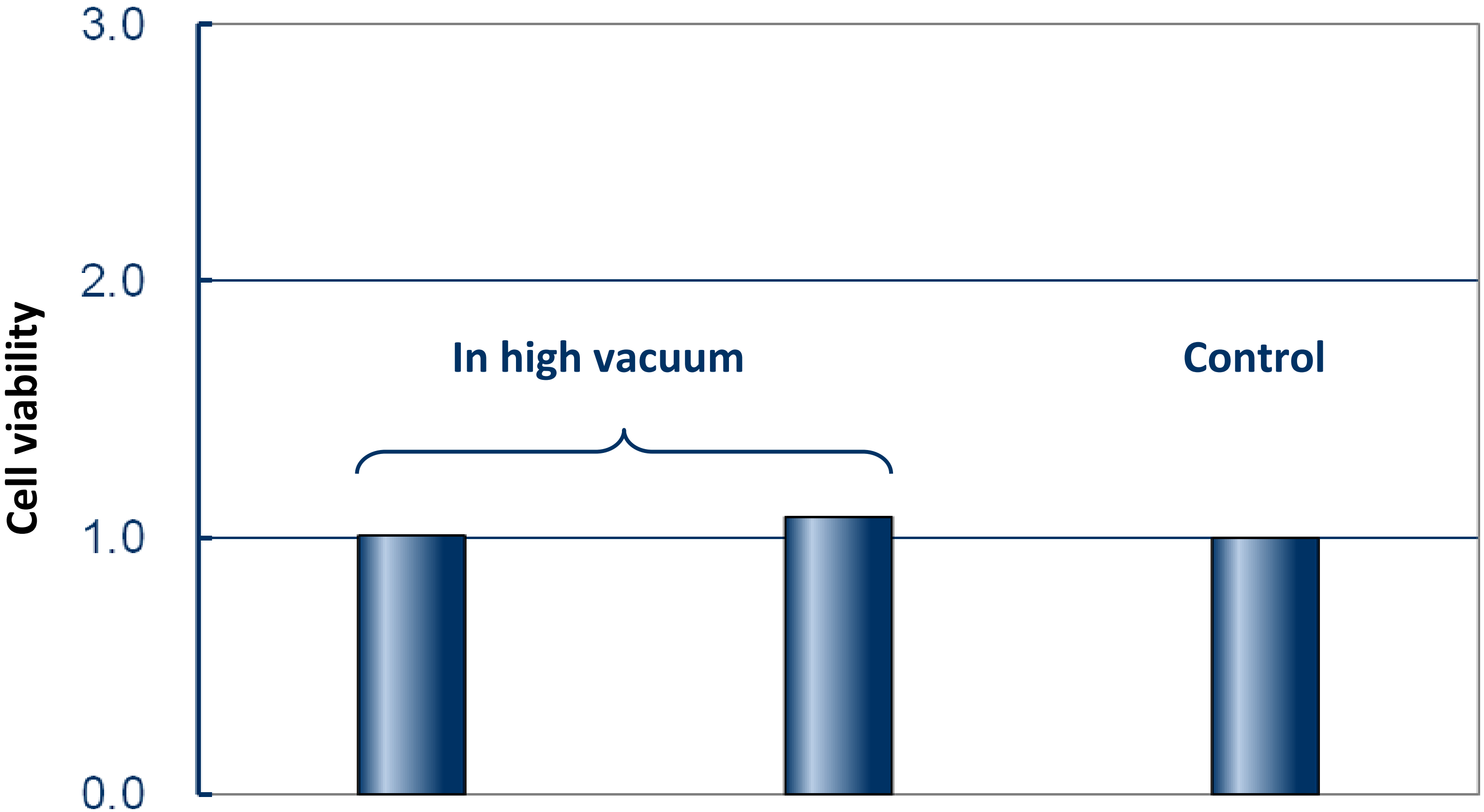
○ **Ion implantation**

As^{2+} ,10kV
1,000~2,000 ions/cell
at -150**°C** in Vacuum
(for 30 min.)

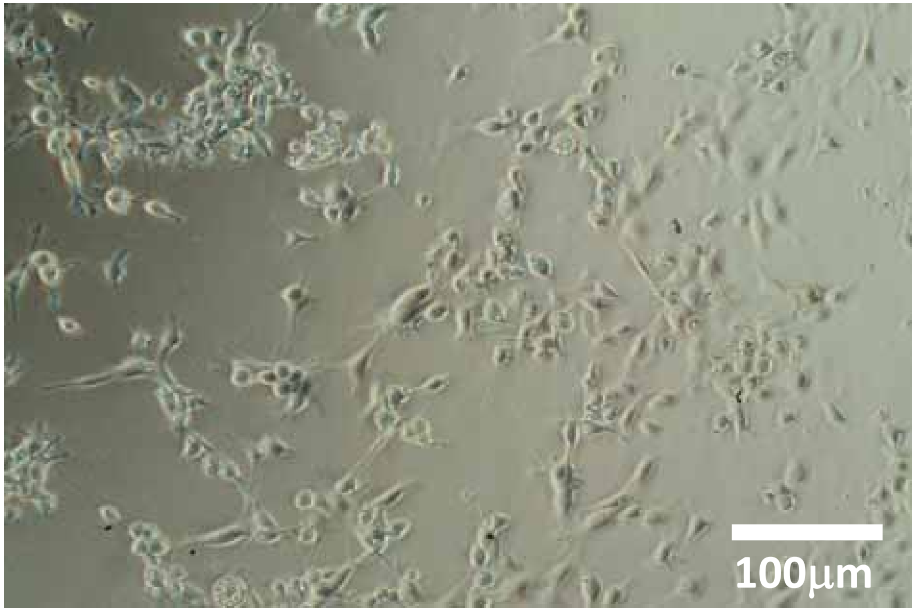
○ ○ ○ **Cell viability evaluation**

Comparison

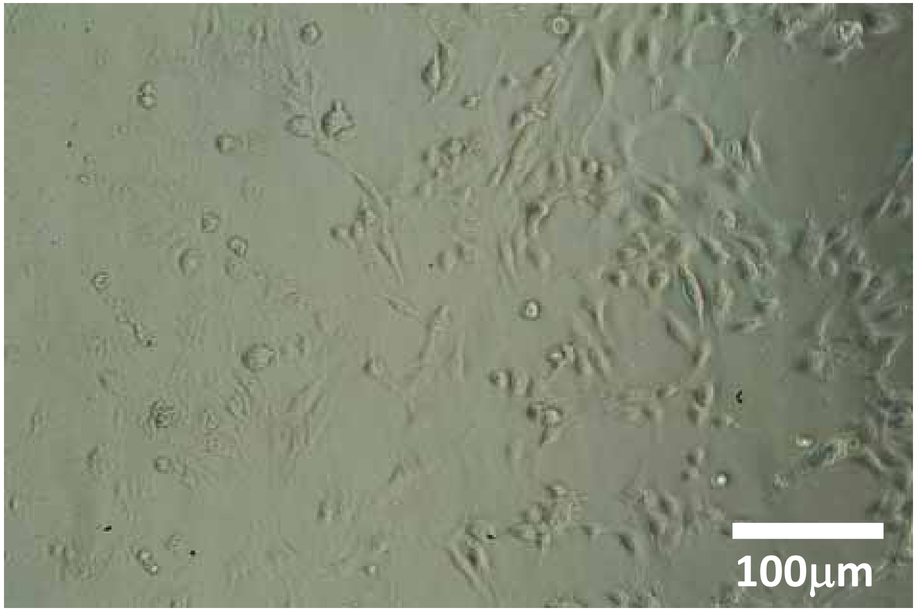
Viability of cells exposed in high vacuum environment



Optical Microscope Observation of cell morphology

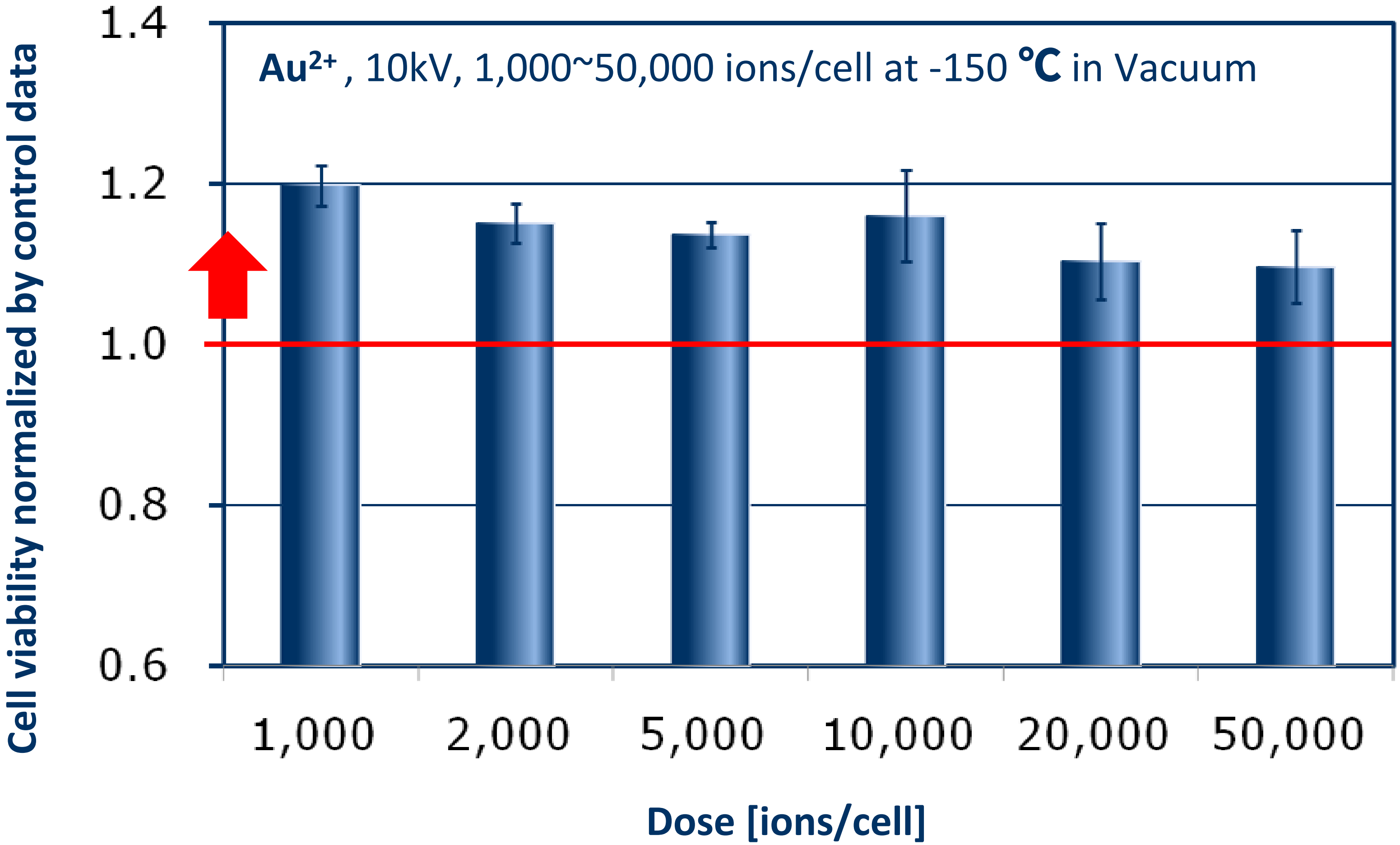


Before Au ion implantation



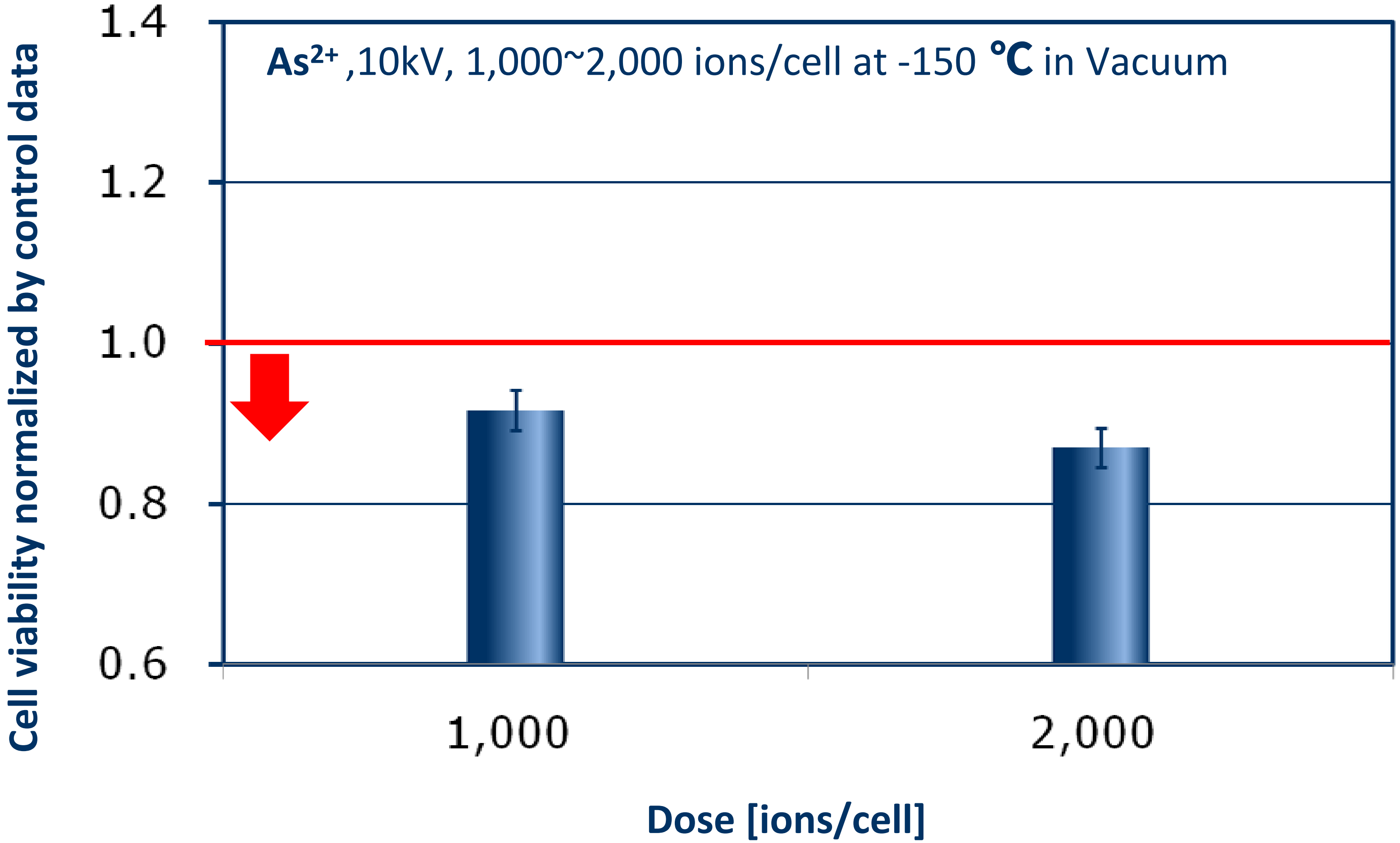
After Au ion implantation

Viability evaluation of Au-ion implanted cells



Au^{2+}, 10kV, 1,000~50,000 ions/cell at -150 **℃** in Vacuum

Viability evaluation of As-ion implanted cells



Summary

-The functional modification of cells has been tried by employing ion implantation.

-We investigate the influence of Au and As-ion implantation into living cells and evaluate the viability of the ion implanted cells by measuring the concentration of adenosine triphosphate (ATP).

-10～20% enhancement of viability has been observed in the gold ion implanted cells, while the viability of the arsenic ion irradiated cells decreased by about 10% compared with that of control.

-The results are still preliminary and the collaboration with physiologists is inevitable.

Thank you very much for your attention !