

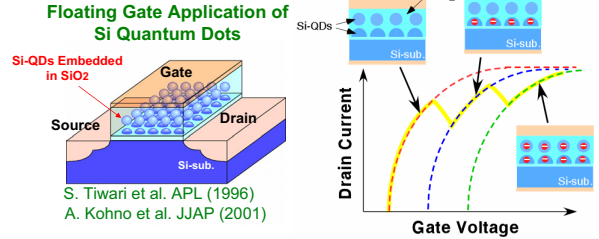
# Characterization Electronic Charged States of Si-based Quantum Dots for Multi-valued MOS Memories

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 Hiroshima University

- Motivation & Background
- Electron Injection to & Extraction from Single Si-QD with & without a Ge core
  - ➔ Surface Potential Change as Evaluated by an AFM Kelvin Probe Technique
- Floating Gate Application
  - ➔ C-V & I-V Characteristics of MOS Capacitors
  - ➔ Id-Vg & Id-t Characteristics n-MOSFETs
- Summary

Collaborators : K. Makihara, M. Ikeda, Y. Darma, T. Shibaguchi, K. Takeuchi, Y. Shimizu, R. Nishihara

# Si-QDs Floating-Gate MOS Memories — Multivalued & Low-Voltage Operations at Room Temp. —



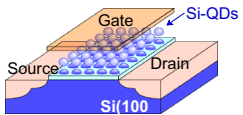
## ★ Control of Discrete Charged States in Si-QDs

↓  
 Electrical Interaction & Coupling among Electronic States in Neighboring QDs

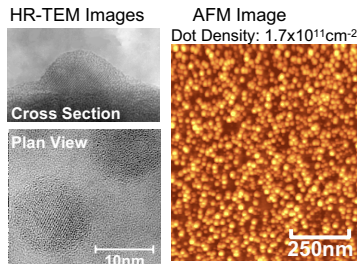
## Key Issues on Si-QDs Formation for Floating Gate Application

- The areal dot density comparable to the electron concentration in channel (higher than  $\sim 10^{11} \text{cm}^{-2}$ )

## ★ Uniformity in Size & Spatial Distribution

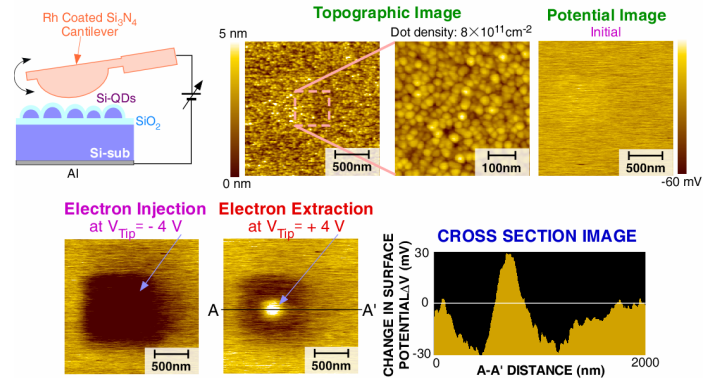


## Spontaneous Formation of nc-Si on SiO2 by LPCVD



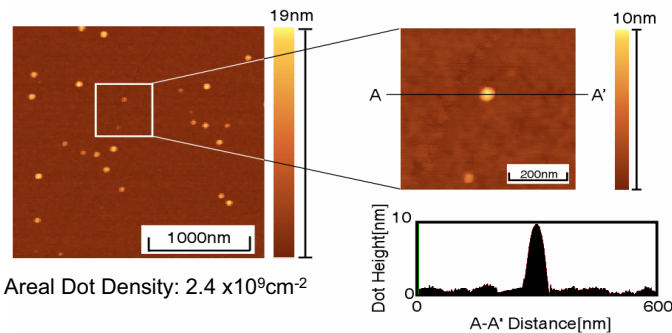
on as-grown SiO2 600°C, 0.2Torr, 36s  
 on HF-treated SiO2 560°C, 0.2Torr, 90s  
 S.Miyazaki et al. TSF (2000)

## Surface Potential Changes due to Electron Charging & Discharging of Si Dots on 3nm-thick SiO2/p-Si(100) as Evaluated by an AFM/Kelvin Probe Technique

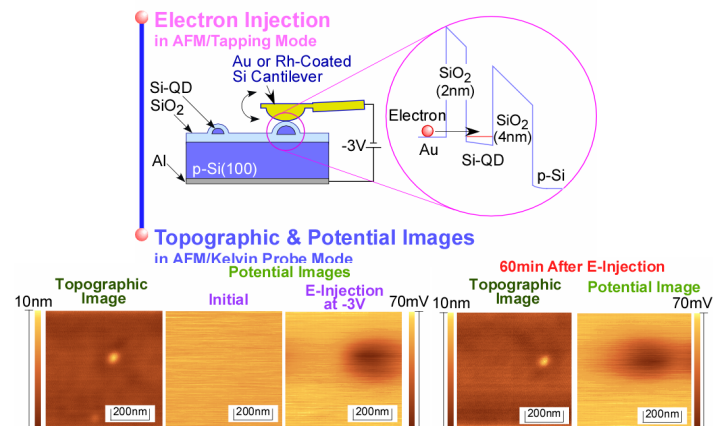


## AFM Images of an Isolated Si Quantum Dot

in AFM/Tapping Mode

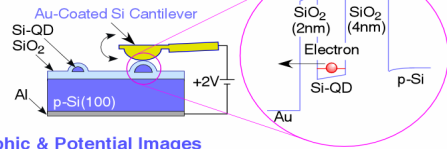


## Electron Injection to Single Si-QD



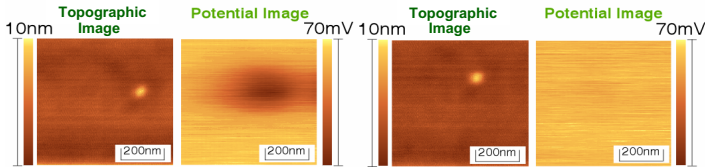
### Electron Emission from Charged Single Si-QD

Electron Emission  
In AFM/Tapping Mode



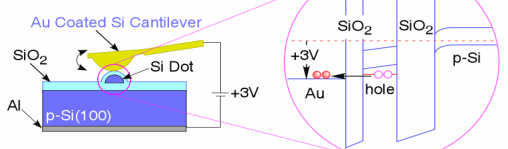
Topographic & Potential Images  
In AFM/Kelvin Probe Mode

60min After E-Injection in CR Air at RT

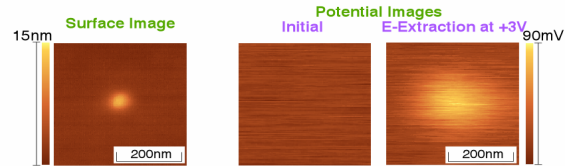


### Electron Extraction from Neutral Single Si-QD

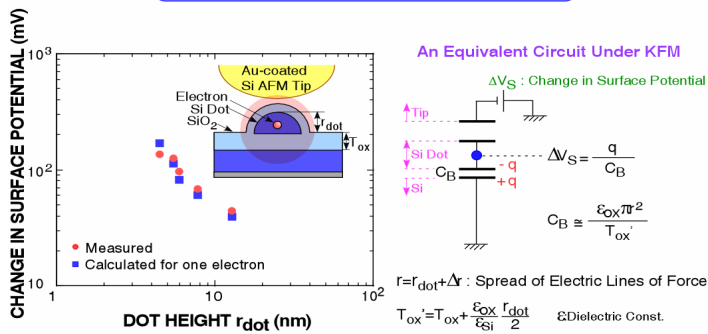
Electron Extraction  
In AFM/Tapping Mode



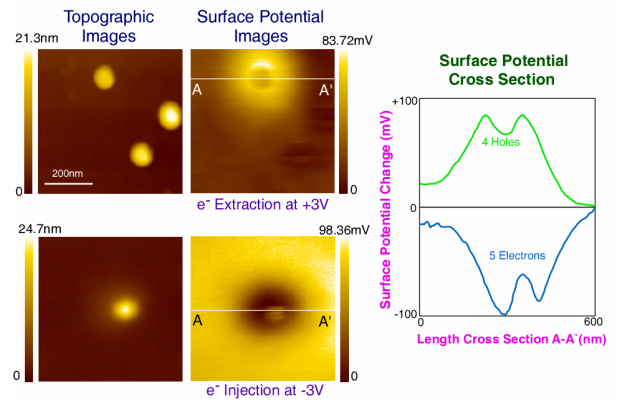
Topographic & Potential Images  
In AFM/Kelvin Probe Mode



### Dot Size Dependence of Surface Potential Changed by Electron Injection

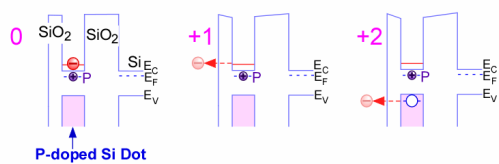


### Electron Injection and Extraction from Neutral Pure-Si Dot



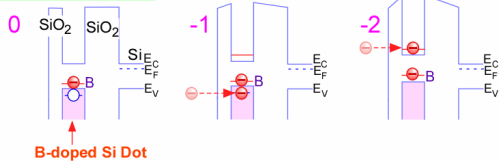
### Impact of Impurity Doping into Si-QDs on their Charged States

★ P-doped Si dots



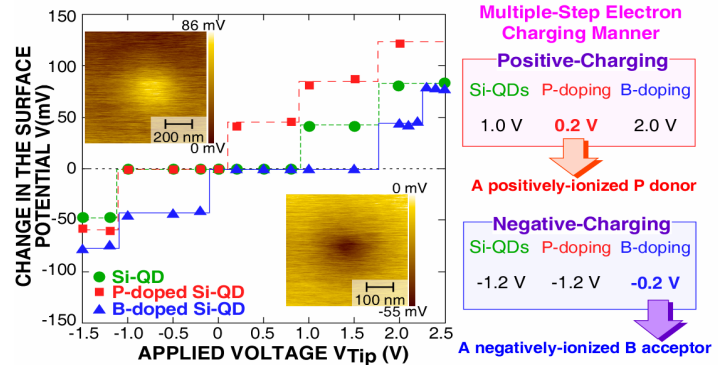
P-doped Si Dot

★ B-doped Si dots

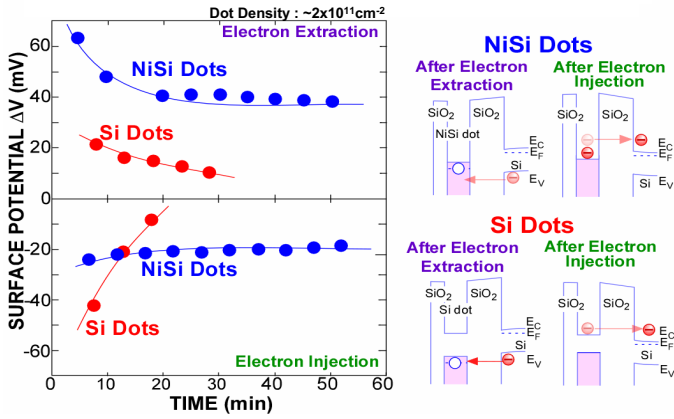


B-doped Si Dot

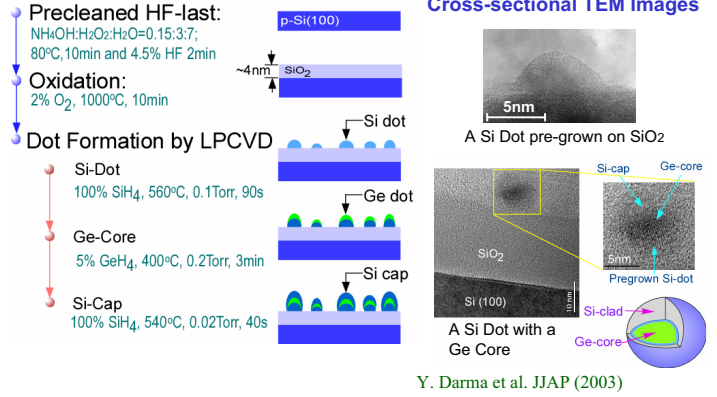
### Surface Potential Change for Undoped, P-doped & B-doped Si Quantum Dots / SiO2(4nm) / n+-Si(100) as a Function of Tip Bias



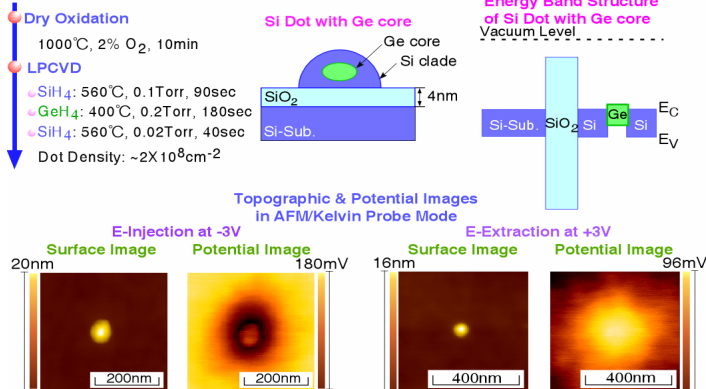
### Comparison between Charge Retention Characteristics of pure Si-QDs and NiSi QDs



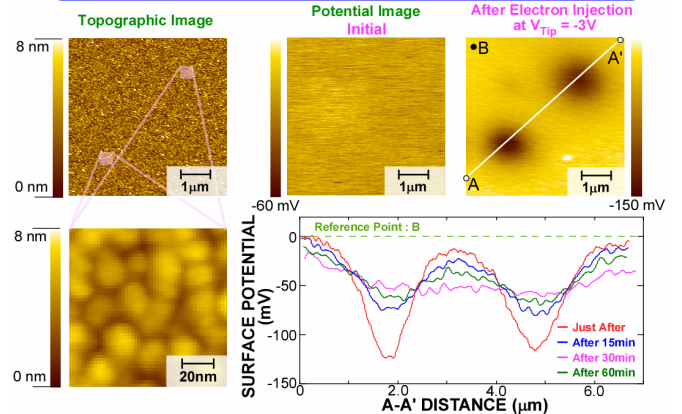
### Formation of Si Dots with a Ge Core



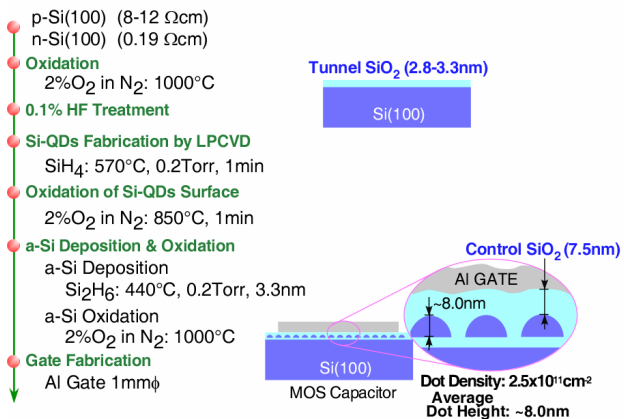
### Characterization of Electron Charging into an Isolated Si Dot with Ge core



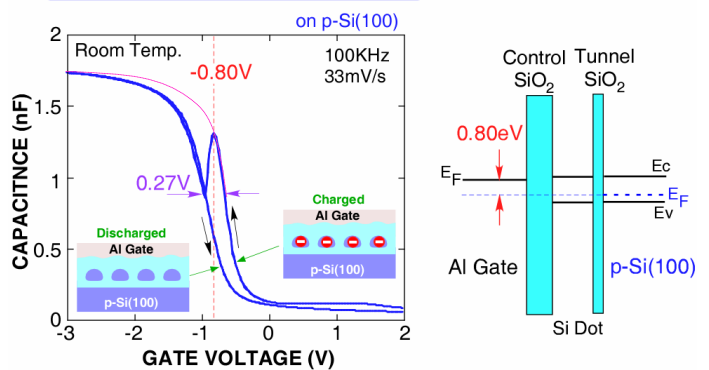
### Discharging & Spreading of Electrons Injected into 3-Stacked Si-QDs/ $\text{SiO}_2$ Formed on 4nm-thick $\text{SiO}_2$ /p-Si(100)



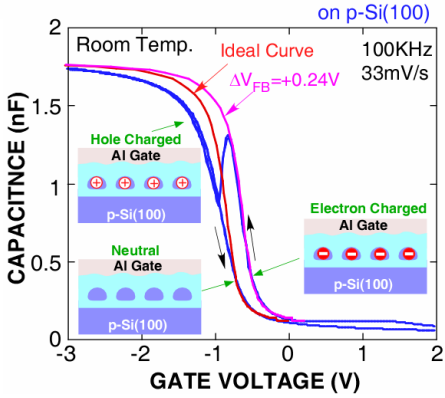
### Fabrication of Si-QDs Floating Gate MOS Capacitors



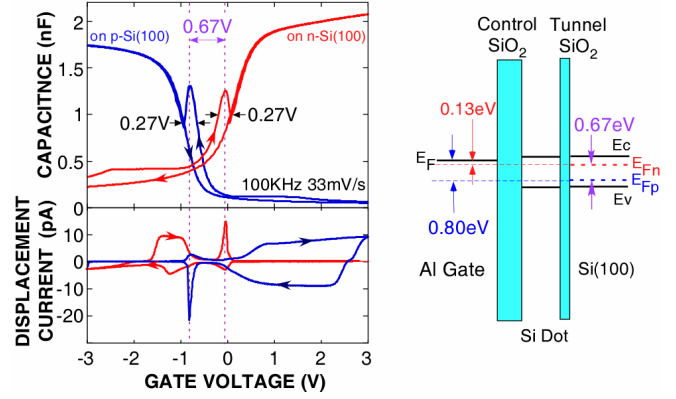
### C-V Characteristics of a MOS Capacitor with Si-QDs Floating Gate



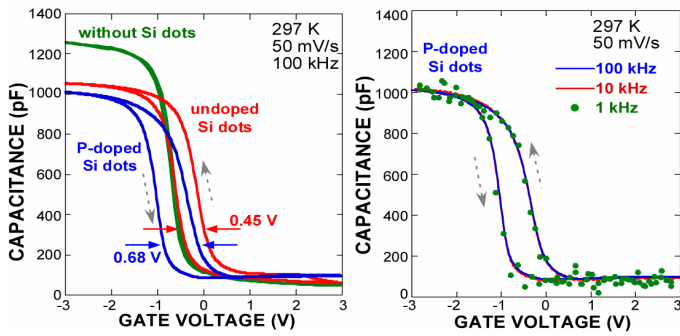
**Comparison between Measured and Simulated C-V Curves for Si-QDs Floating Gate MOS Capacitor**



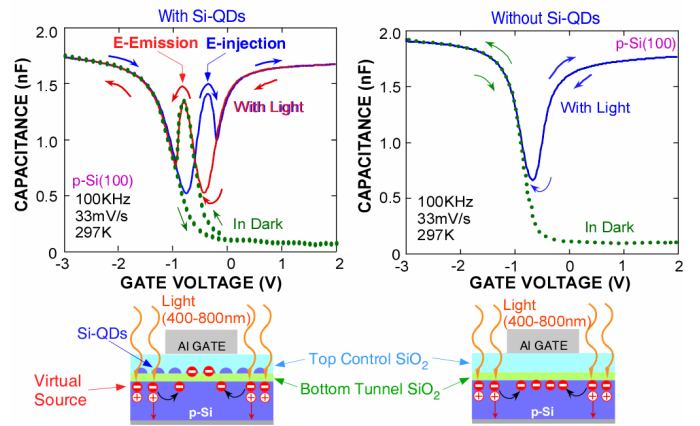
**C-V & I-V Characteristics of Si-QDs Floating Gate MOS Capacitors Fabricated on p-Si(100) & n-Si(100)**



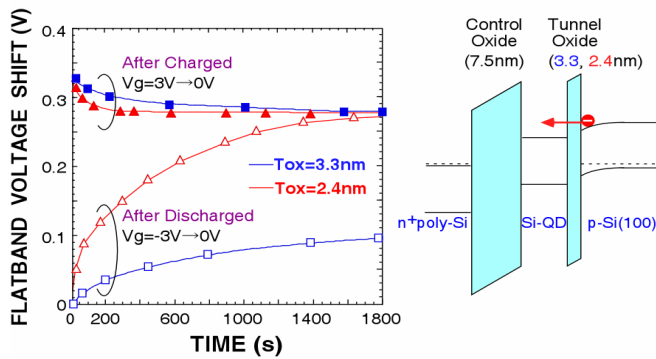
**Capacitance-Voltage Characteristics of Undoped & P-doped Si-QDs Floating Gate MOS Capacitors**



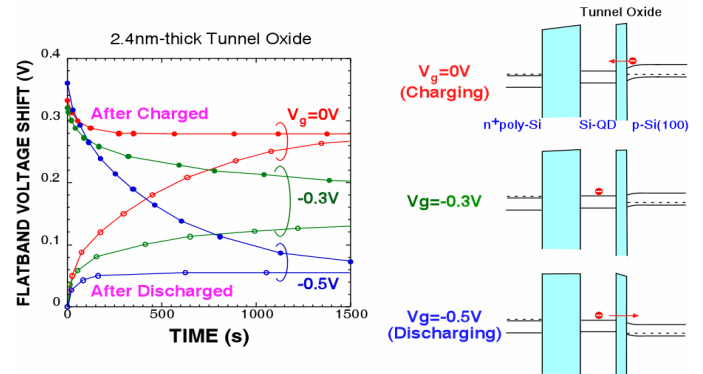
**C-V Characteristics of MOS Capacitors with & w/o Si-QDs Floating Gate Measured in Dark and under Cold Light Irradiation**



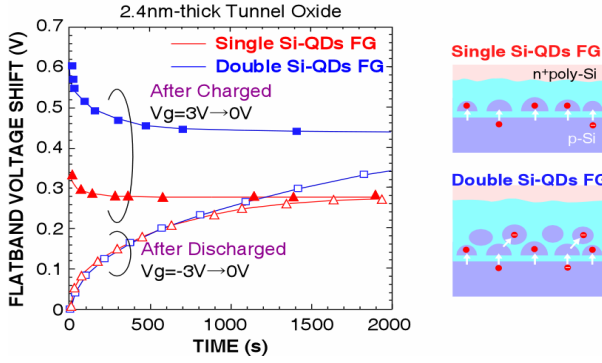
**Retention Characteristics on  $\Delta V_{FB}$  for Single Si-QDs Floating Gate**



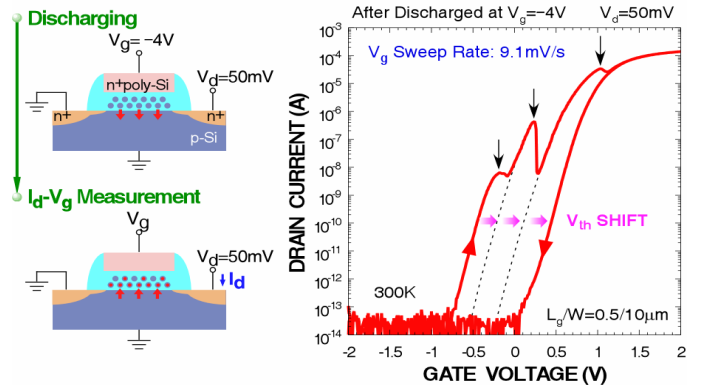
**Gate Voltage Dependence of Retention Characteristics**



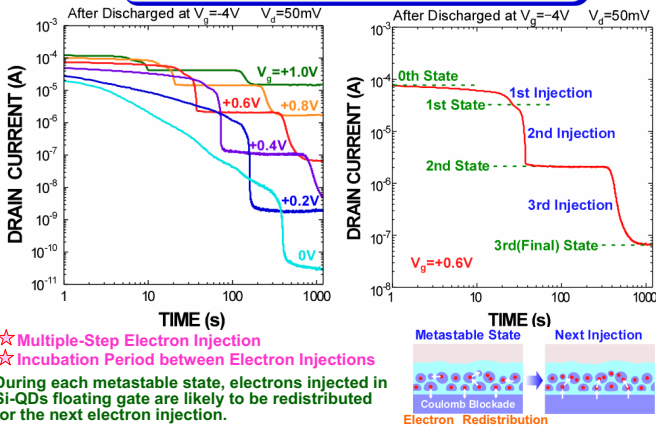
### Retention Characteristics on $\Delta V_{FB}$ for Single or Double Si-QDs Floating Gate



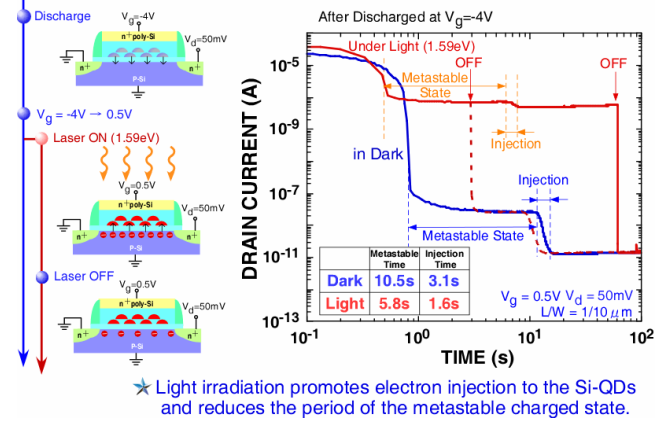
### $I_d$ - $V_g$ Characteristics for MOSFET with Doubly-Stacked Si-QDs Floating Gate



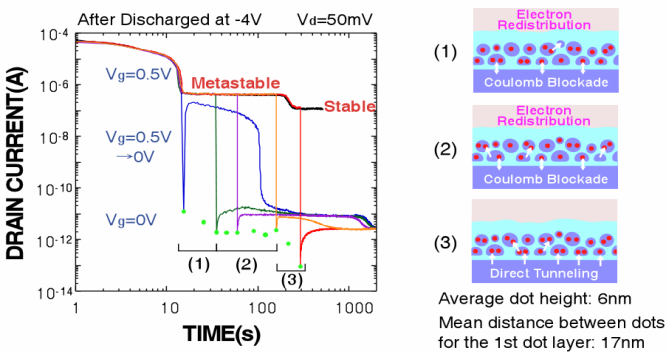
### Transient $I_d$ Characteristics by Electron Charging to Doubly-Stacked Si-QDs Floating Gate



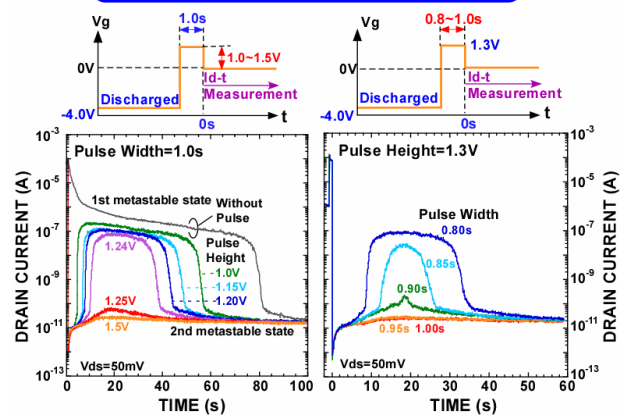
### $I_d$ -t Characteristics in Dark and under Light Irradiation



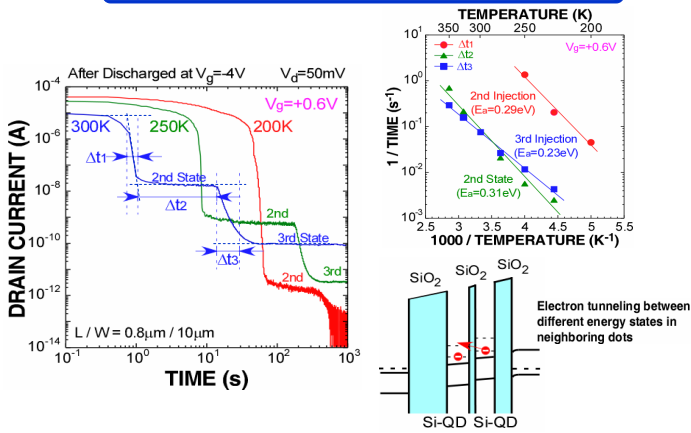
### Transient $I_d$ Characteristics by Electron Charging to Doubly-Stacked Si-QDs Floating Gate



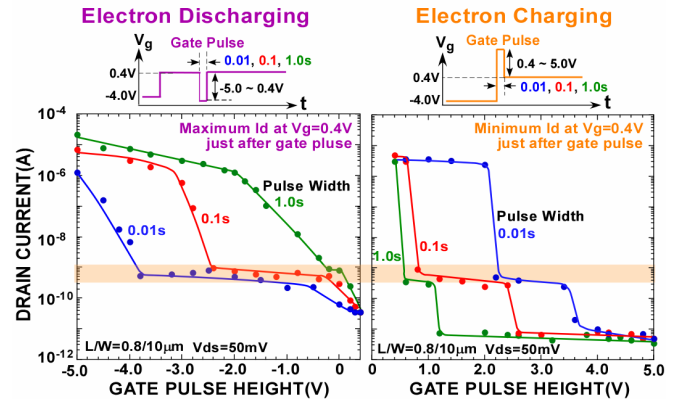
### $I_d$ -t Characteristics after Applying Pulsed Gate Biases at Different Pulse Heights & Widths



### Temperature Dependence of $I_d$ -t Characteristics



### Changes in Drain Current by Applying Pulsed Gate Bias for Charging & Discharging



### SUMMARY

#### Electron Injection to & Extraction from Isolated Si-based QD

- Si-QD: Single Electron Storage at RT  
Verification of Coulomb Repulsion among Charges Stored in single Si-QD  
Control of Charged States with Ionized Impurities
  - Si-QD with a Ge Core :  
Storage of Electrons in the Si Clad & Holes in the Ge Core
- MOS Cap. and n-MOSFETs with Si-QDs Floating Gate
- Room Temperature Memory Operation
  - ★ Multistep Electron Charging & Discharging

#### Well-defined & Multivalued Memory Operation

- ➡ Optimization of Dot Size & Oxide Thickness
- Control of Dot Arrangement

#### Acknowledgements

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