Electronic Charged States of Single Si Quantum Dots with Ge Core as Detected by AFM/Kelvin Probe Technique

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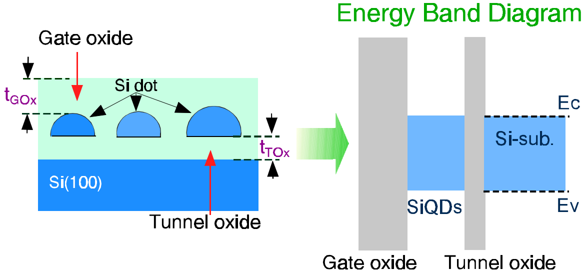
Abstract

Nanometer dots consisting of Si clad and Ge core have been prepared by alternately controlling the selective growth conditions in LPCVD using pure SiH_4 and GeH_4 on 4nm-thick SiO_2.
The changes in surface potential induced by electron charging and discharging at each of isolated dots have been measured using AFM/Kelvin probe force microscopy (KFM).
In electron charging and discharging at a single dot, a Rh-coat AFM tip was electrically biased in the range of -3 to +3V and scanned on the sample surface in a tapping mode.
The Surface potential change confirmed the injected electron and hole are retained in the Si clad and the Ge core, respectively, as expected from the band diagram for an Si/Ge/Si structure.
Surface potential change on an isolated dot induced by electron injection or extraction is decreased with increasing of the dot height.
For the dot height of 16nm, a theoretical consideration confirms the observed potential change is attributed for charging the dot by 3 electrons and 2-3 holes.

Background & Motivation (I)

SiQDs for electronics storage nodes



Key parameters:
- Dot size
- QDs Stacked structure
- SiO_2 thickness

In memory device application

High speed operation & long retention time → Fix tunnel oxide at a certain thickness → Si Dots with Ge core

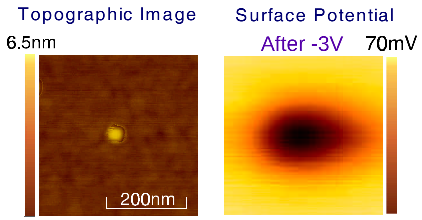
Ge core cladded with Si

→ Good Si/SiO_2 interface instead of poor Ge/SiO_2 interface

Background & Motivation (II)

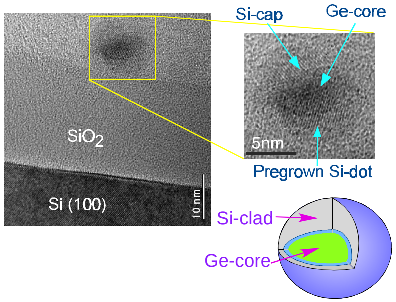
■ Previous works

- Charged States of a Single Si Dot Using AFM/Kelvin Probe Force Microscopy (KFM)



K. Takeuchi et al, 2002 ECS Int. Semicond. Technol. Conf. Proc.No. 33

- Formation of Si dots with Ge core on SiO_2 by highly-selective LPCVD



Y. Darma et al, JJAP **42** (2003) 4129

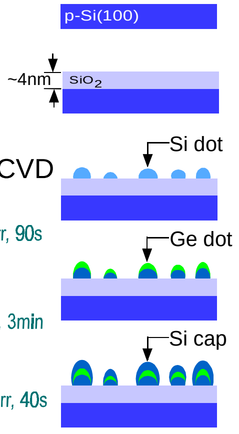
■ This works

→ Characterization of the charged states of a single Si dot with Ge core using AFM/Kelvin Probe Force Microscopy (KFM)

Experimental

Formation of Si Dot with Ge Core

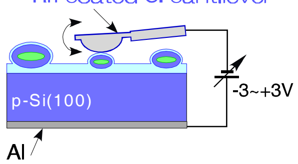
- Precleaned HF-last:
  $NH_4OH:H_2O_2:H_2O$=0.15:3:7; 80°C,10min and 4.5% HF 2min
- Oxidation:
  2% O_2, 1000°C, 10min
- Dot Formation by LPCVD
  - Si-Dot
    100% SiH_4, 560°C, 0.1Torr, 90s
  - Ge-Core
    5% GeH_4, 400°C, 0.2Torr, 3min
  - Si-Cap
    100% SiH_4, 540°C, 0.02Torr, 40s



From AFM: Dot density is ~4 x 10^8 cm^{-2}

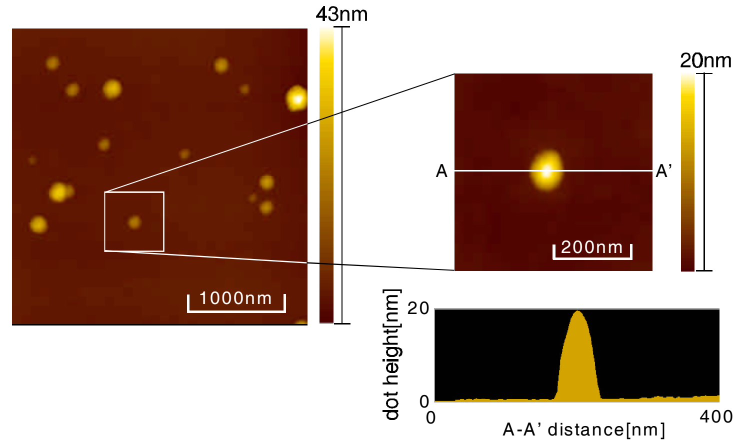
Charged States Characterization using KFM

- Electron Injection/Extraction
  AFM/Tapping Mode: Contact

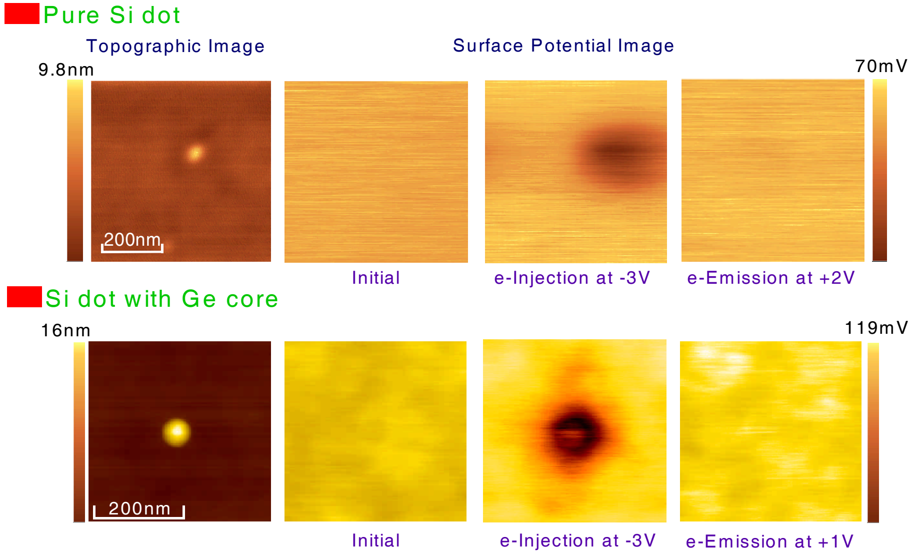


- Topography and corresponding surface potential measurements
  AFM/Kelvin Probe Mode: Non contact

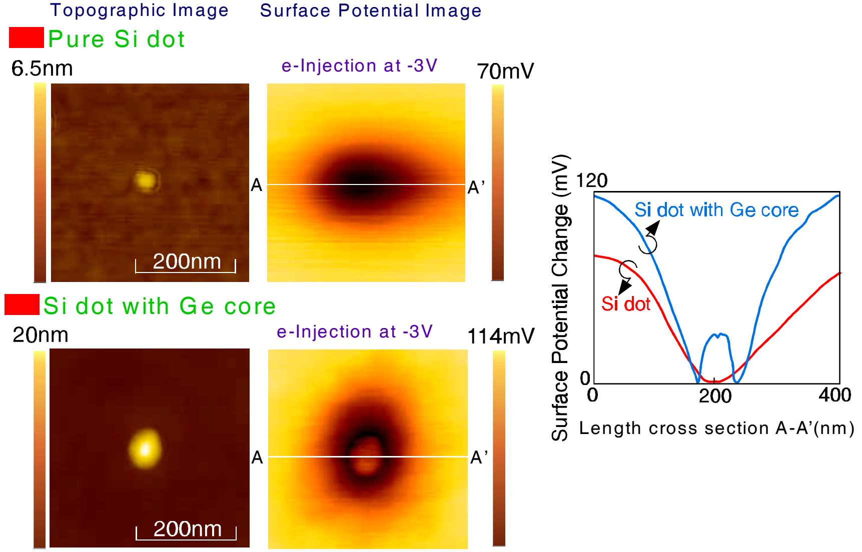
Wide and narrow scan for a suitably isolated dot



Electron Injection & Emission to the Dot Followed by Surface Potential Measurement Using AFM/Kelvin Probe Technique

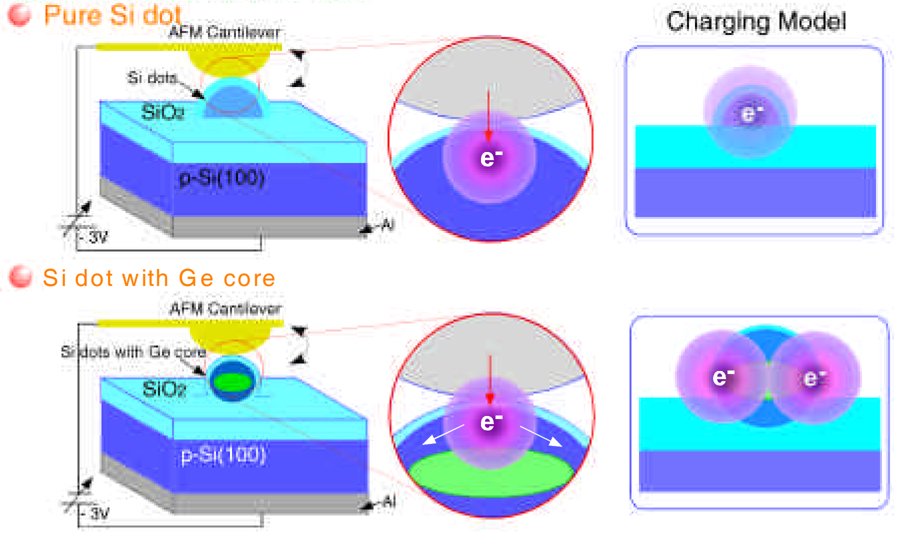


Surface Potential Profile of the Isolated Si Dots with and without Ge Core after Electron Injection

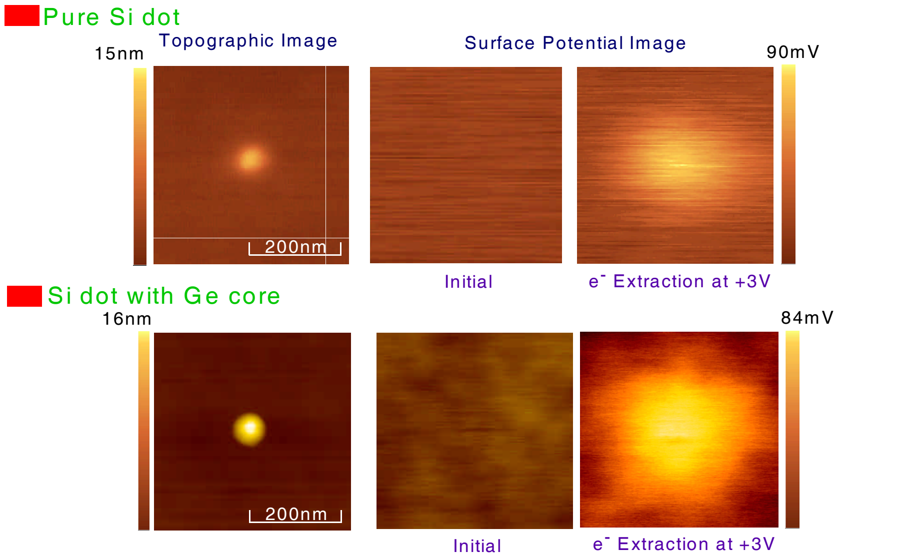


Model of Electron Injection to the Si Dot with and without Ge Core

Electron injection (AFM/Tapping mode)

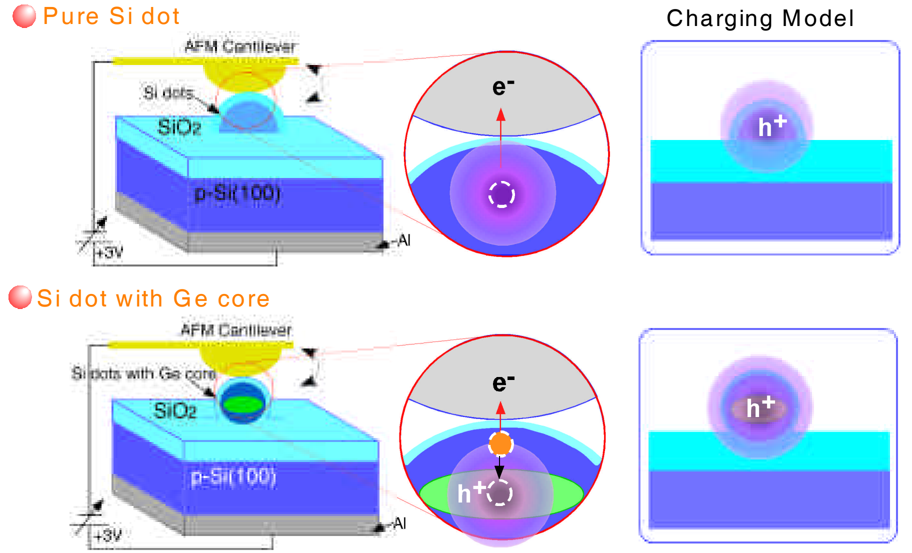


Electron Extraction from the Neutral Dot Followed by Surface Potential Measurement Using AFM/Kelvin Probe Technique

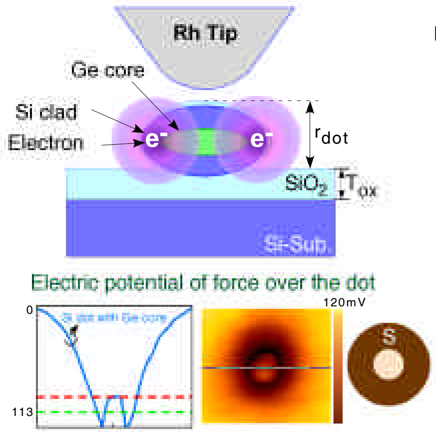


Model of Electron Extraction from Neutral Si Dot with and without Ge Core

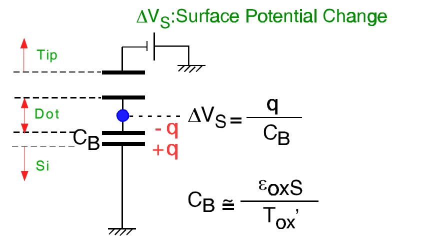
Electron Extraction (AFM/Tapping mode)



Calculation of the Electron Number Stored in the Dot



Equivalent circuit of the KFM measurement



$$\Delta V_S = \frac{q}{C_B}$$

$$C_B \cong \frac{\varepsilon_{ox} S}{T_{ox}'}$$

$$T_{ox}' = T_{ox} + \frac{\varepsilon_{ox}}{\varepsilon_{Si}} \frac{r_{dot}}{2}$$ ε: dielectric constant

S: electrode area

r_{dot} : 16 nm, Tip bias: -3V

Calculation of Surface Potential Change due to 1 electron

ΔV_S=38mV

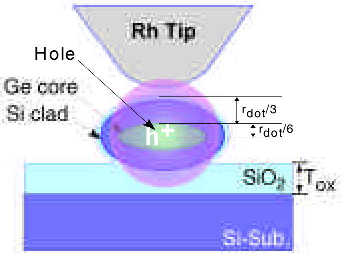
Surface Potential Measured

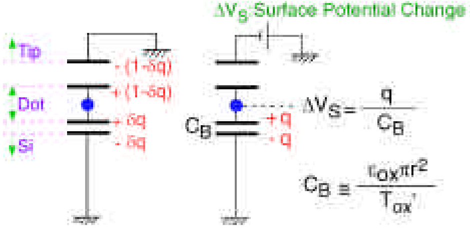
ΔV_S=113mV

Number of Electron Stored in the dot: ~3 e^-

Calculation of the Hole Number Retained in the Charge Dot

Equivalent circuit of the KFM measurement





$\Delta V_S = \frac{q}{C_B}$

$C_B \cong \frac{\varepsilon_{ox}\pi r^2}{T_{ox}'}$

$T_{ox}' = T_{ox} + \frac{\varepsilon_{ox}}{\varepsilon_{Si}}\frac{r_{dot}}{3} + \frac{\varepsilon_{ox}}{\varepsilon_{Ge}}\frac{r_{dot}}{6}$

ε: dielectric constant

$r = r_{dot} + \Delta r$: The spread of the electric line

r_{dot} : 16 nm

Calculation of Surface Potential Change due to 1 hole

$\Delta V_S = 33\text{mV}$

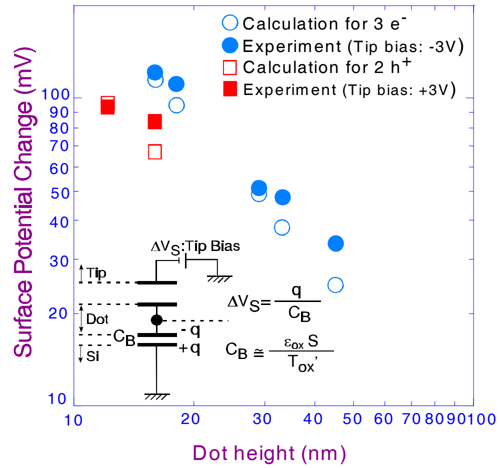
Surface Potential Measured

$\Delta V_S = 84\text{mV}$

Number of Hole Stored in the dot: 2-3 h^+

Surface potential change induced by electron injection/emission as a function of the dot height

Dot Size Dependence of Surface Potential Changed by Electron Injection / emission

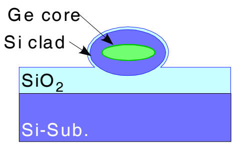


Summary

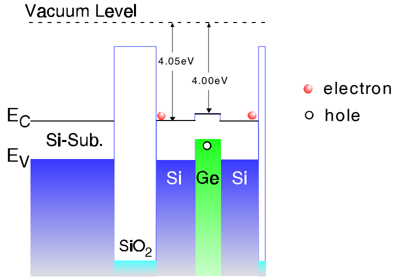
Electron and hole in Si dot with Ge core

Surface potential image from the AFM/Kelvin probe measurements confirm that the electrons were stored in the Si clad and the holes were stably retained in the Ge core as expected from the energy band diagram for an Si/Ge heterojunction.

Si dot with Ge Core



Simplified Energy band diagram



For the dot height of 16nm and the tip bias of -3 and +3V;

- 3 electrons stored in the Si clad
- 2-3 holes retained in the Ge core

Acknowledgment

We would like to thank H. Murakami, R. Takaoka, H. Yamashita, T. Shibaguchi for their contribution in sample preparation and characterization