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 SiH₄ and GeH₄ on 4nm-thick SiO₂. 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.

SiQDs for electronics storage nodes
SiQDs Energy Band Diagram

Key parameters:
- Dot size
- QDs Stacked structure
- SiO₂ thickness

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

Surface Potential Topographic Image

Formation of Si dots with Ge core on SiO₂ by highly-selective LPCVD

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:
P-Si(100)

Oxidation:
2% O₂, 100°C, 10min

Dot Formation by LPCVD

Si-Dot
100% SiH₄, 560°C, 0.17tor, 30min

Ge-Core
9% GeH₄, 400°C, 0.27tor, 3min

Si-Cap
100% SiH₄, 540°C, 0.037tor, 40min

From AFM: Dot density is ~4 x 10⁸ 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

Pure Si dot

Topographic Image

Surface Potential Image

Si dot with Ge core

Initial

e-Injection at -3V

e-Emission at +2V

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

Pure Si dot

Surface Potential Image

Si dot with Ge core

Surface Potential Change (mV)

Length cross section A-A'(nm)
Model of Electron Injection to the Si Dot with and without Ge Core

**Electron injection (AFM/Tapping mode)**

- **Pure Si dot**
- **Si dot with Ge core**

**Charging Model**

- **Pure Si dot**
- **Si dot with Ge core**

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

- **Pure Si dot**
- **Si dot with Ge core**

**Initial**

- Pure Si dot: 84mV, 16nm
- Si dot with Ge core: 15nm, 90mV

**e⁻ Extraction at +3V**

- Pure Si dot: 16nm, 200nm
- Si dot with Ge core: 15nm, 90mV

Calculation of Surface Potential Change due to 1 electron

- Number of Electron Stored in the Dot: ~3 e⁻

- Surface Potential Measured: ΔV = 113mV

- Equivalent circuit of the KFM measurement

Equation:

\[
\Delta V = \frac{q}{C_B} + \frac{q}{C_0} \]

- \(C_B\): Capacitance of the bulk
- \(C_0\): Capacitance of the oxide
- \(q\): Charge of the electron
- \(\varepsilon_0\): Dielectric constant
- \(S\): Electrode area

Calculation of the Electron Number Stored in the Dot

- Tip bias: -3V
- Tip radius: 16 nm

Calculation of Surface Potential Change:

- \(\Delta V_{\text{surf}} = 153\text{mV}\)
- \(\Delta V_{\text{meas}} = 113\text{mV}\)

- Number of Electron Stored in the dot: ~3 e⁻
Calculation of the Hole Number Retained in the Charge Dot

<table>
<thead>
<tr>
<th>Calculation of Surface Potential Change due to 1 hole</th>
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<tbody>
<tr>
<td>$\Delta V_S = 33 \text{mV}$</td>
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<tr>
<td>Surface Potential Measured</td>
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<tr>
<td>$\Delta V_S = 84 \text{mV}$</td>
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| Dot site dependence of surface potential change as a function of dot height |

<table>
<thead>
<tr>
<th>Dot height (nm)</th>
<th>Surface Potential Change (mV)</th>
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<tbody>
<tr>
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<tr>
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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.

Acknowledgment

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