Directed Assembly of Ge Quantum Dots on Si with Low Dose Focused Ion Beam Templating

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Motivation and Goals

Emerging interest in the self-assembly of nanoscale semiconductor structures (quantum dots or nanowires) is prompted by the anticipation of reaching the fundamental limits of silicon-based device miniaturization via lithographic techniques within a decade.

The ability to control the positioning of self-assembled epitaxial Ge island on Si surface will enable many potential applications, including quantum cellular automata (QCA) and incorporation of internal light sources in the photonic structures.

Reliable placement of Ge islands on specified locations is achieved by performing subtle surface modification of Si surface by low-dose focused ion beam (FIB) patterning.

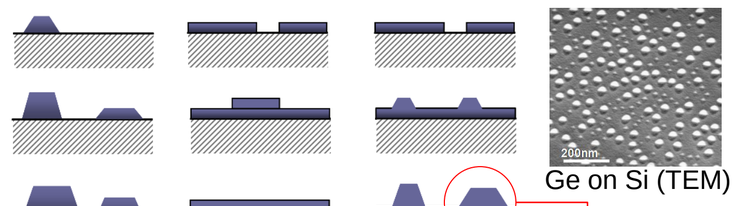
The goal of this study is an investigation of mechanisms influencing the registration fidelity of Ge islands with the encoded sites on relatively large patterns (hundreds of square microns) with nanoscale separation between individual islands.

References:

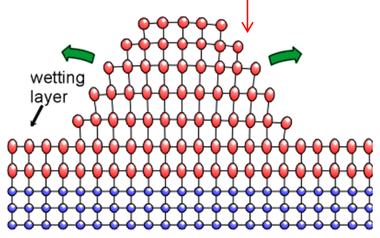
(1)M. Gherasimova, R. Hull, M. C. Reuter, F. M. Ross, Appl. Phys. Lett., **93** 023106 (2008).

(2)R. Hull, J. A. Floro, M. Gherasimova, J. F. Graham, J. L. Gray, A. Portavoce, F. M. Ross, J. Thorp, Journal of Physics: Conference Series, **209** 012003 (2010).

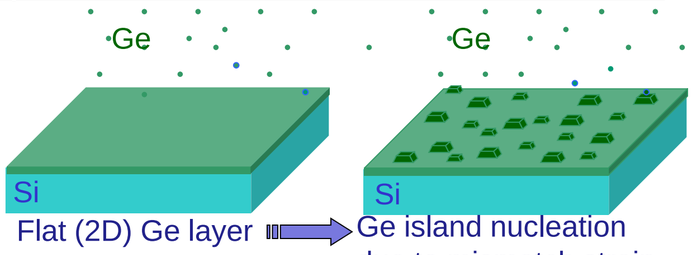
Lattice-mismatched Epitaxy and Ge Island Formation



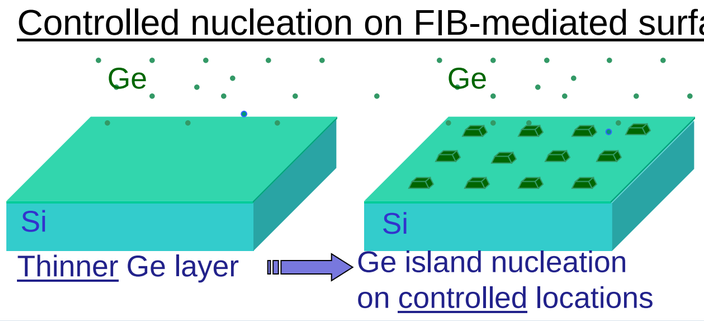
Germanium on Silicon: lattice mismatch 4.2 %



Spontaneous island formation in SK mode:

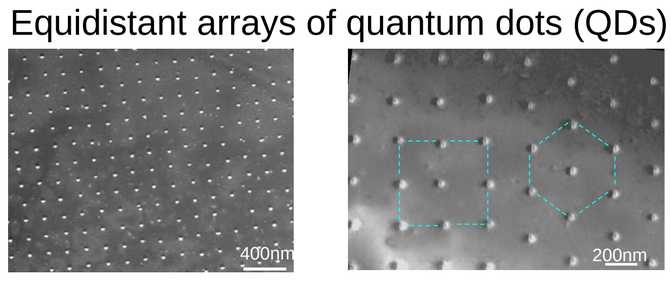


Controlled nucleation on FIB-mediated surface:



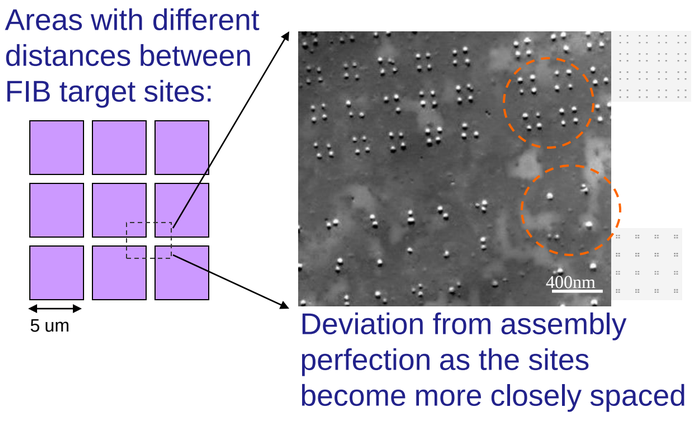
Experimental Results

Equidistant arrays of quantum dots (QDs)



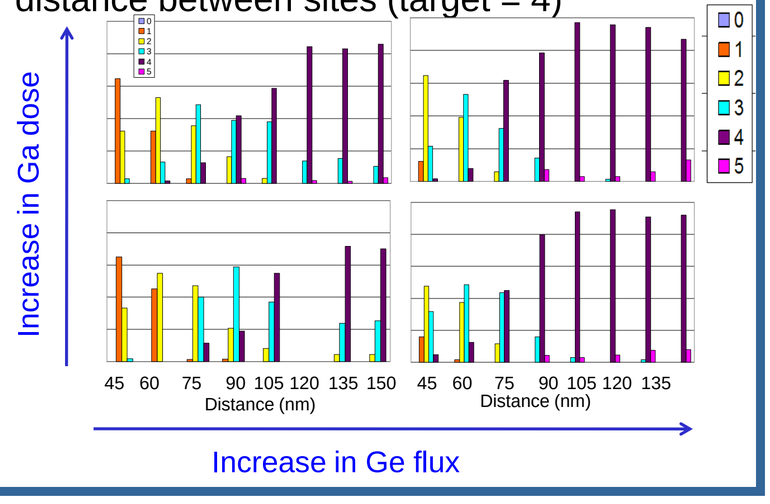
Arrays of clusters of four closely spaced sites – geometry of interest for QCA

Areas with different distances between FIB target sites:



Deviation from assembly perfection as the sites become more closely spaced

Statistics: number of islands per cluster vs. distance between sites (target = 4)

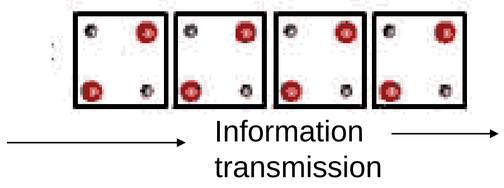


Quantum Cellular Automata

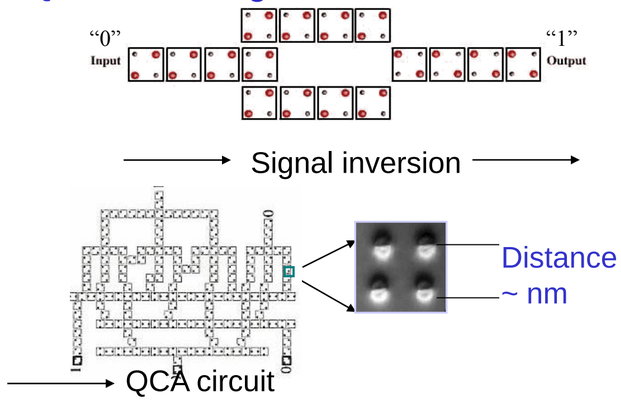
Groups of four islands with an extra charge (or spin) present in two of them:

Clusters of QDs close enough for charge tunneling → Electrostatic communication with the next cell

QCA wire:



QCA based logic:

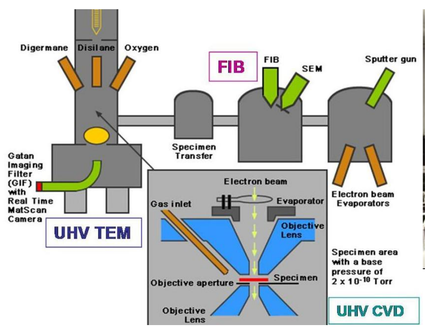


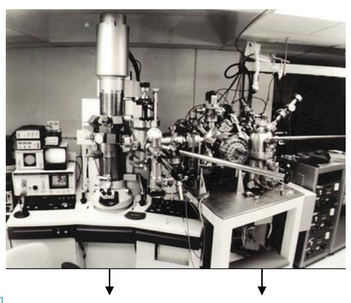
Goals:

- nanoscale QD placement precision combined with large area fidelity
- ability to functionalize the islands (add electronic or magnetic dopants)

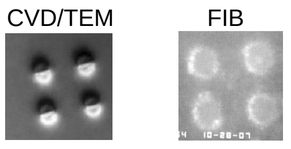
Experimental Approach

Ultra High Vacuum (UHV) Transmission Electron Microscope (TEM) at IBM with integrated Focused Ion Beam (FIB) chamber and Ge deposition capability

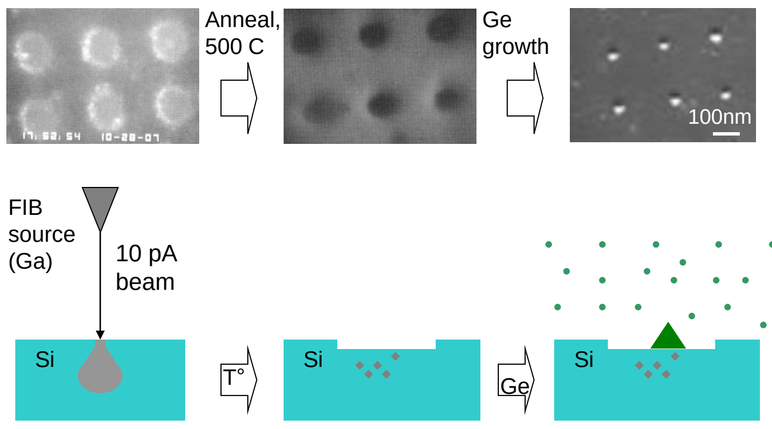




CVD= Chemical Vapor Deposition
Chamber pressure ~2x10^{-10} Torr

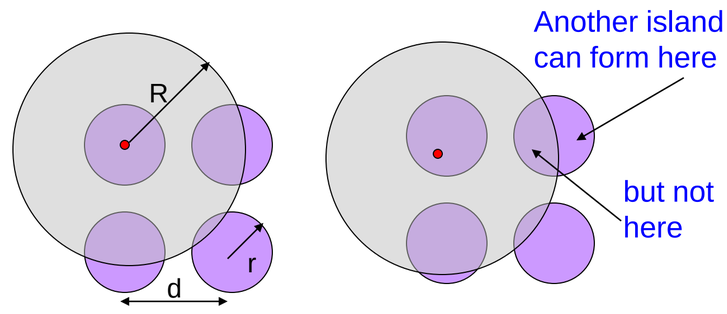


Controlled Ge nucleation mechanism



Analysis and Conclusions

Model: nucleation exclusion zone

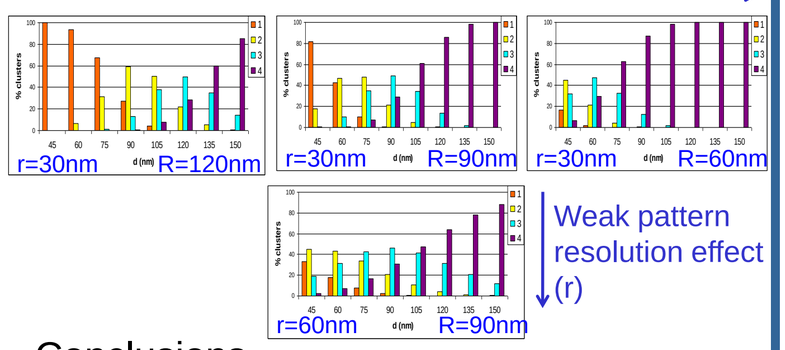


Assumptions:

- An island is equally likely to nucleate anywhere within a circle of radius **r** (FIB-encoded sites)
- Nucleation does not occur outside of the these areas
- Once an island nucleates, another one cannot nucleate closer than a distance **R** from it

Sample Model Calculations

Strong exclusion zone effect (R): growth conditions →



Conclusions

- Competition between nucleation sites (related to the growth conditions and kinetics) dominates as the factor limiting the fidelity of directed assembly
- The role of FIB resolution and accuracy is less significant in this growth regime

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