Fabrication of Single Atom Nanowires for Applications towards Quantum Computation

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Developments in nanotechnology over the last two decades have opened up the possibility of unparalleled computing power, such as the theoretical development of a quantum computer.The realization of quantum computers depends on our ability to specifically place quantum bits (qubits) in positions where they can be initialized and measured. In our all-silicon model of a quantum computer, we utilize silicon 29 isotopes as our qubits due to their inherent nuclear spin. Phosphorous 31 must be deposited at regular intervals between ^{29}Si atoms so that its spin can initialize the silicon atoms' nuclear spin states via spin diffusion. In this study we aimed to fabricate single atom-wide ^{29}Si nanowires with regular spaced ^{31}P atoms using molecular beam epitaxy (MBE). It is clear that a bottom-up approach is the most feasible and efficient way to fabricate single atom nanowires. In this method, silicon(111) wafers were polished and heated to form the relatively stable 7x7 DAS Reconstructed surface in either U- or F-step conformations. Intentional kinks were made at regular intervals along the steps so that there were high energy corners with many dangling bonds. P and Si atoms deposited via MBE will assemble at these edges and corners. Proper fabrication of stepped edges with regular kinks was assessed using scanning tunneling microscopy (STM) and spectroscopy (STS). Fabrication of qubit arrays represents the first step towards realization of a quantum computer.

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Abstract

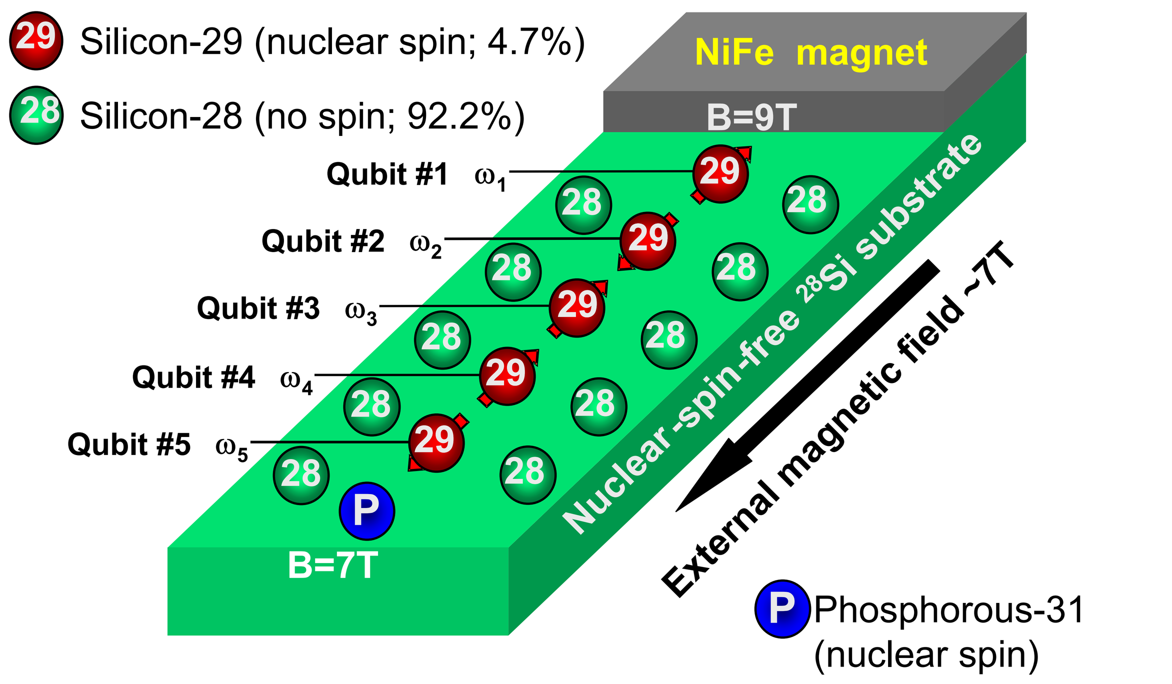
Developments in nanotechnology over the last two decades have opened up the possibility of unparalleled computing power, such as the theoretical development of a quantum computer.The realization of quantum computers depends on our ability to specifically place quantum bits (qubits) in positions where they can be initialized and measured. In our all-silicon model of a quantum computer, we utilize silicon 29 isotopes as our qubits due to their inherent nuclear spin. Phosphorous 31 must be deposited at regular intervals between ^{29}Si atoms so that its spin can initialize the silicon atoms' nuclear spin states via spin diffusion. In this study we aimed to fabricate single atom-wide ^{29}Si nanowires with regular spaced ^{31}P atoms using molecular beam epitaxy (MBE). It is clear that a bottom-up approach is the most feasible and efficient way to fabricate single atom nanowires. In this method, silicon wafers were polished and heated to form the relatively stable 7x7 DAS Reconstructed surface in either U- or F-step conformations. Intentional kinks were made at regular intervals along the steps so that there were high energy corners with many dangling bonds. P and Si atoms deposited via MBE will assemble at these edges and corners. Proper fabrication of stepped edges with regular kinks was assessed using scanning tunneling microscopy (STM) and spectroscopy (STS). Fabrication of qubit arrays represents the first step towards realization of a quantum computer.

Motivation: Quantum Computer

Quantum computers will be capable of unprecedented computing power by relying upon quantum phenomena:

- *Superposition* – quantum bits (qubits) exist in 0, 1, or both states, which enables thousands of simultaneous computations (parallelism). In theory, a 30-qubit QC will equal the processing power of a modern computer running at 10 teraflops.
- *Entanglement* – indirect measurement of linked qubits allows quantum computation because direct measurement influences spin state.

Proposed Silicon Quantum Computer



1) *Initialization* via spin diffusion, 2) *Operation* due to unique NMR frequencies of qubits in steep magnetic field gradient, 3) *Read-out* by magnetic resonance force microscopy (of nuclear spin) or electron spin resonance (of P electron spin)

Experimental Approach

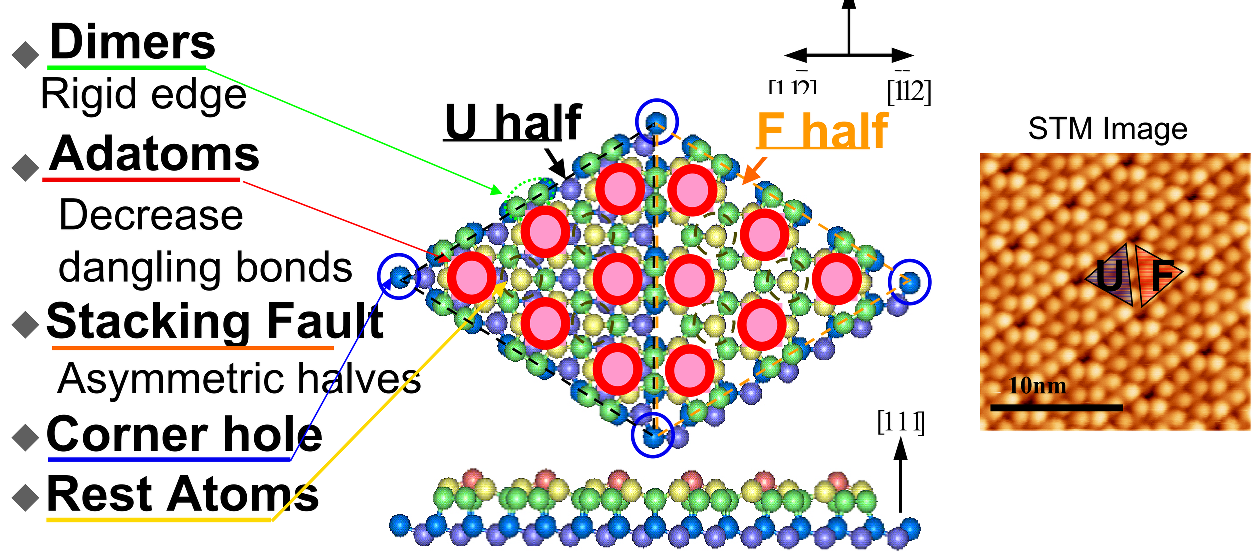
Goal - Fabricate a nanowire array of ^{29}Si qubits with regularly spaced ^{31}P atoms

Bottom-up approach is most efficient to fabricate single atom-thick nanowires:

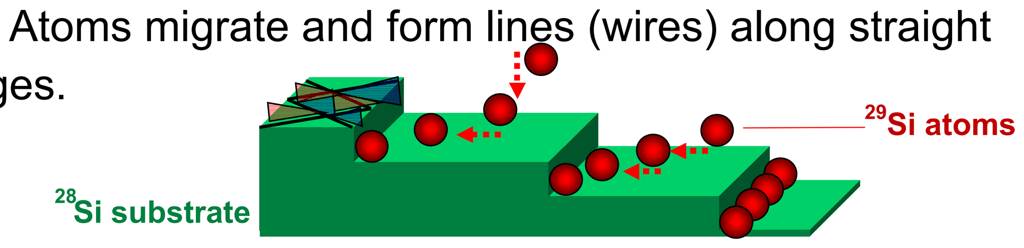
- Prepare silicon(111) 7x7 DAS Reconstructed surface upon which atoms self-assemble into nanowires
- Deposit appropriate quantities of ^{31}P and ^{29}Si atoms using molecular beam epitaxy (MBE)
- Assess fabrication success using scanning tunneling microscopy (STM)

Silicon(111) Vicinal Surface

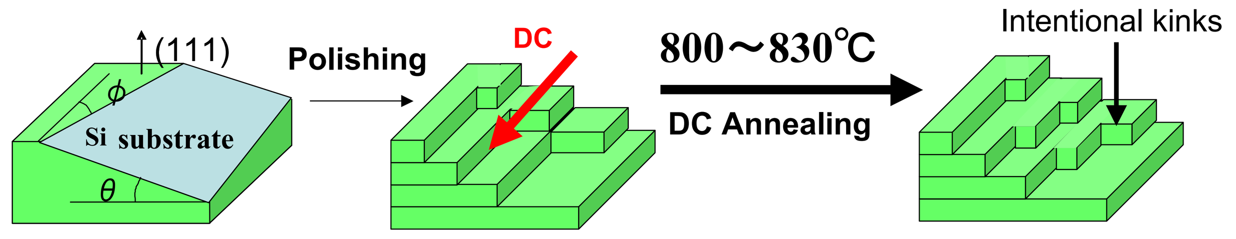
7×7 Reconstruction (DAS)



DAS surface is divided into U or F halves, forming steps on surface. Atoms migrate and form lines (wires) along straight step edges.



Sample Step Preparation



Polishing

Two parameters:
- θ determines density (number) of steps
- Φ determines density (number) of kinks

Why kinks? Kinks are highest-energy corners (most dangling bonds) so when ^{31}P atoms are deposited (before Si atoms) they migrate to the regularly spaced kinks

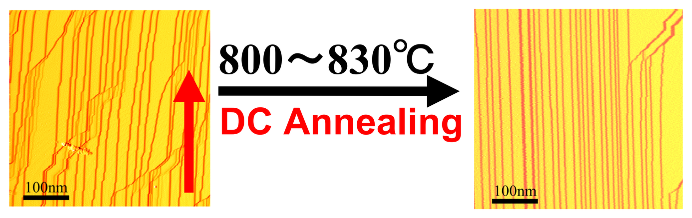
Mechanical polishing is accomplished using silicon carbide, diamond slurry, and nanox

Flashing

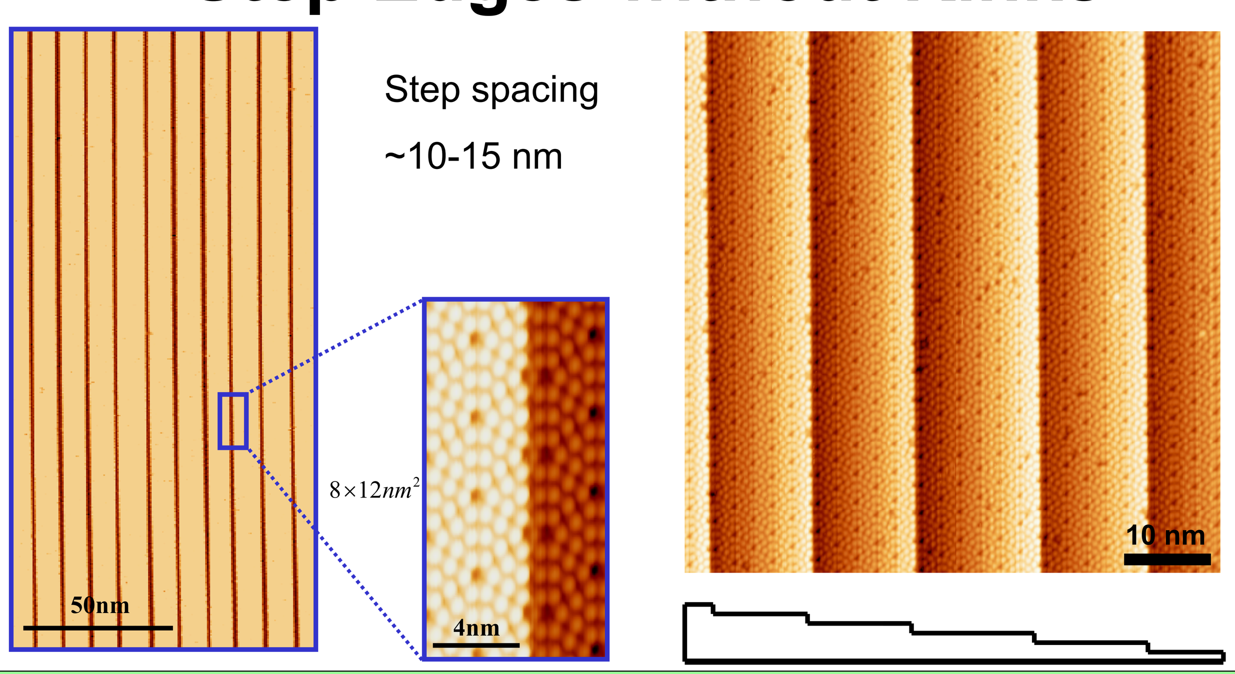
Standard heating and annealing to remove contaminants on sample surface

DC Annealing

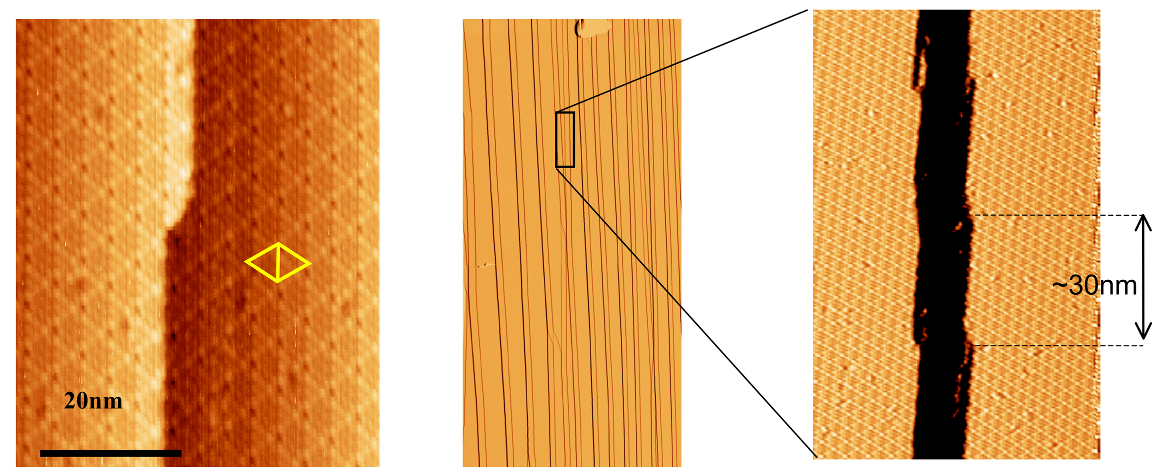
Straighten uneven step edges to make parallel nanowires



Step Edges without Kinks



Step Edges with Kinks



Regular kink array (~30 nm) for controlled phosphorous deposition

Conclusions

- Fabrication of regular step arrays on a vicinal silicon(111) DAS surface is possible using our techniques
- Steps can be produced with or without kinks, depending on the desired nanowire composition
- This research represents the first step towards realization of the proposed silicon quantum computer

Future Work

Short Term

- Deposit ^{31}P and ^{29}Si on stepped surface using MBE
- Assess nanowire fabrication using STM, AFM and STS

Long Term

- ^{29}Si qubit array manipulation and computation (initialization, operation and read-out)

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