Developing a Process for Studying Annealing Effects on Mobilities in Silicon Quantum Dots

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Why Quantum Dots?

Silicon quantum dots are a promising next-generation photovoltaic material because the range of the solar spectrum they absorb can be tuned by changing their size. While these crystalline nanoparticles have high mobilities within a single particle, coupling between the dots must be optimized so that charges can move between dots without losing quantum confinement effects [1]. Charge transport is further complicated by amorphous outer layers and surface defects.

Measuring Crystallinity

- X-ray diffraction
  - Incident X-rays reflected from crystal planes
  - Phase difference between reflected rays yields lattice constant $2d \sin\theta = n\lambda$ (Bragg's law)

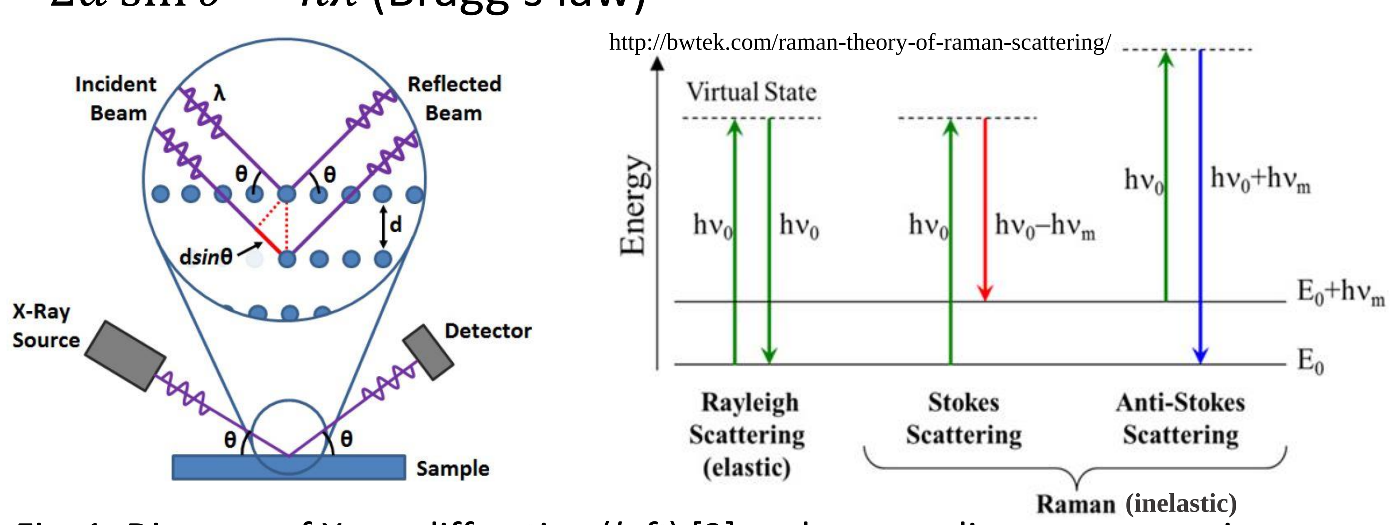


Fig. 1: Diagram of X-ray diffraction (*left*) [2] and energy diagram comparing Rayleigh and Raman scattering (*right*)

- Raman spectroscopy
  - Incident photons from 532 nm laser
  - Most photons scatter elastically (Rayleigh scattering)
  - Some photons reemitted at lower (Stokes) or higher (anti-Stokes) frequencies → Information about low-frequency transitions and crystallinity

Crystallinity from X-Ray Diffraction

Theta-two theta scans, a common X-ray diffraction measurement, with λ=1.54184Å indicate that the dots are partially crystalline.

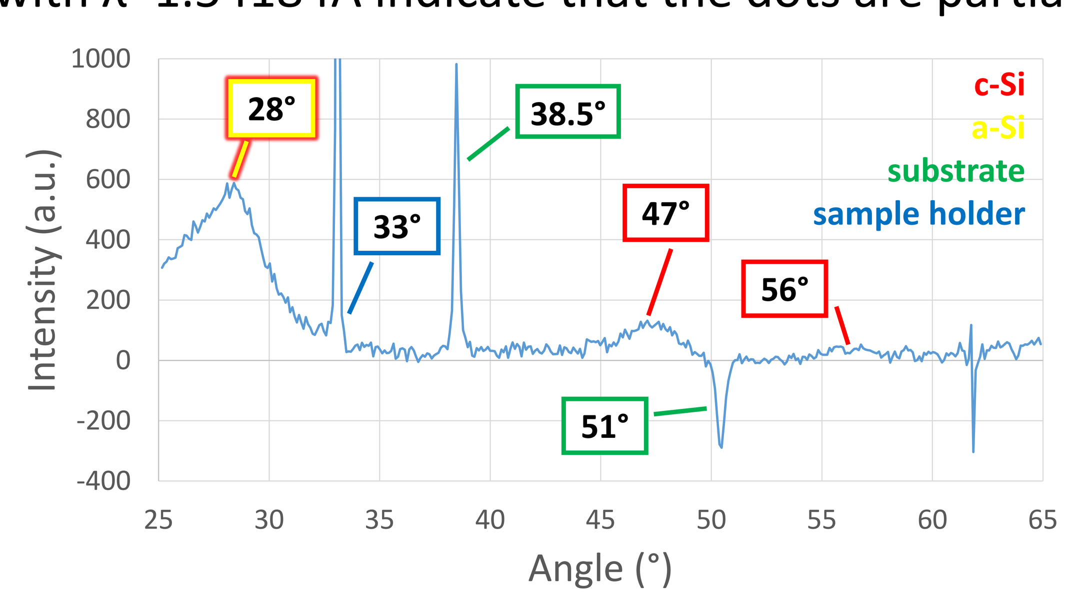


Fig. 2: Theta-two theta scan on silicon quantum dot thin-film transistors. Crystal silicon (c-Si) has peaks at 28°, 47°, and 56°. Amorphous silicon (a-Si) has peaks at 28°, 38°, and 52° [2]. The 38.5° peak is from aluminum in the substrate.

Annealing & Spectroscopy with Raman

- Uses of Raman spectrometer
  - Measure crystallinity
  - Increase crystallinity by coalescing nanoparticles
- Raman spectra of silicon quantum dots
  - Bulk crystalline peak, usually centered at 520 cm^{-1}
  - Grain-boundary tail to left of crystalline peak [2]
  - Amorphous component, with main peak centered at 480 cm^{-1}

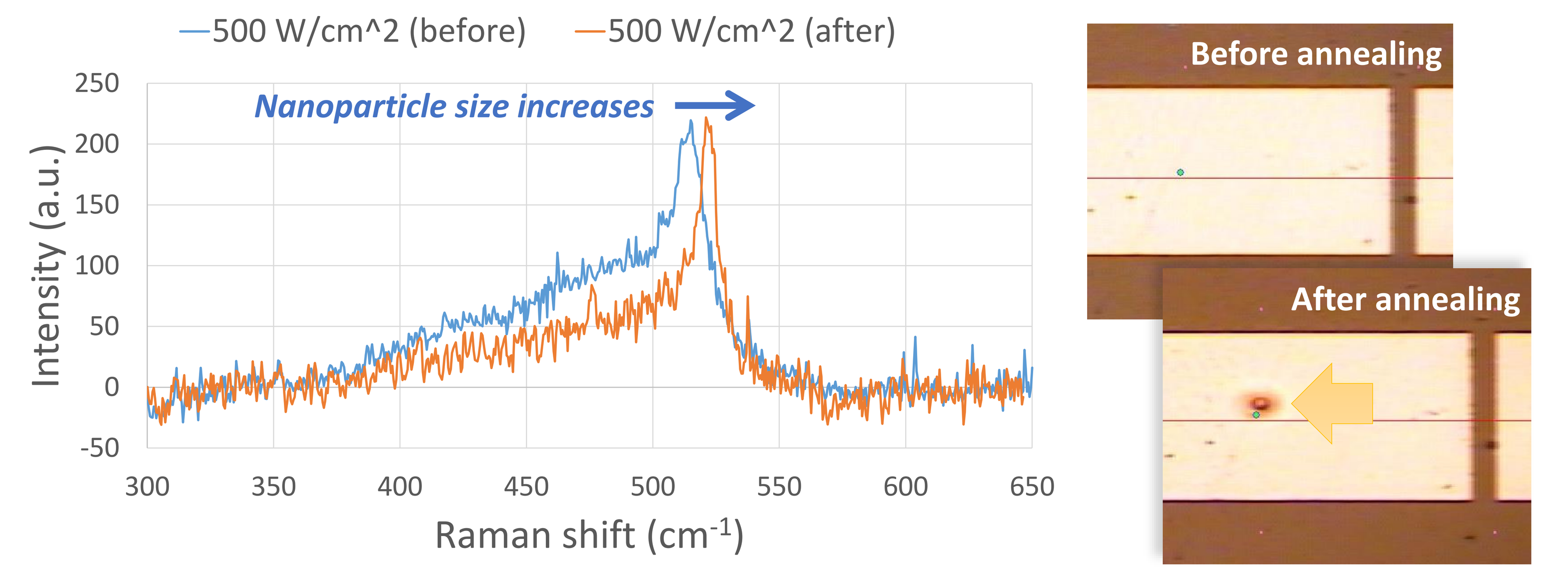


Fig. 3: Raman spectra (*left*) of silicon quantum dots before and after 5 minutes of exposure at 50 kW/cm^2; laser-annealed spot is visible in optical microscope image (*right*)

Fabricating Quantum Dot Transistors

To measure the effect of annealing on mobility, a thin film of quantum dots is deposited onto transistors that can later be characterized.

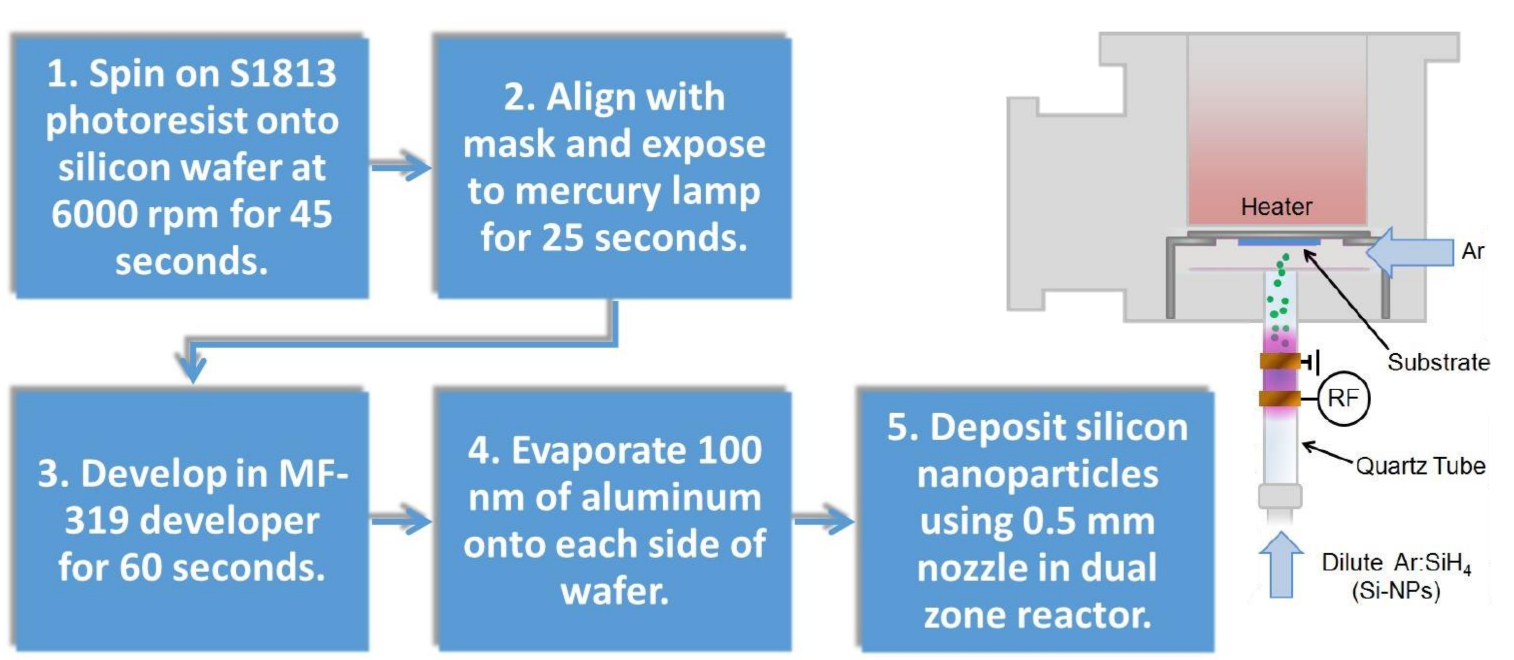
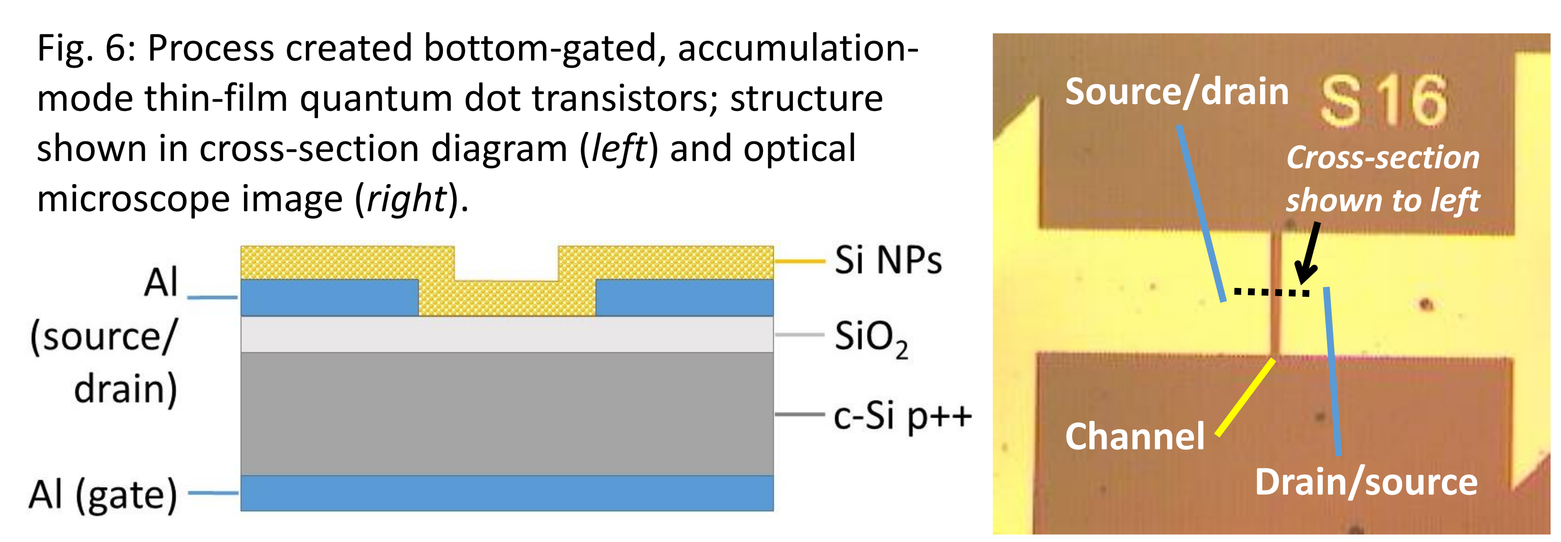


Fig. 5: Flowchart for fabricating quantum dot transistors (*left*) and diagram of dual zone reactor for growing nanoparticles (*right*) [2].

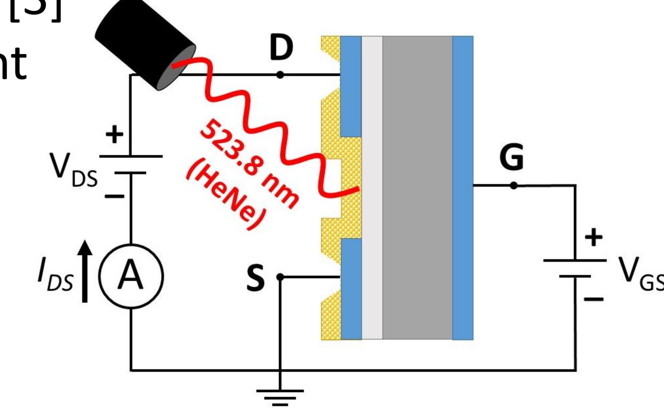
Fig. 6: Process created bottom-gated, accumulation-mode thin-film quantum dot transistors; structure shown in cross-section diagram (*left*) and optical microscope image (*right*).



Transistors & Transfer Characteristics

- Factors that affect current
  - Gate voltage turns transistor "on"
  - Photons generate charge carriers [3]
  - Higher mobility → Higher current for same drain voltage
- Ways to increase mobility
  - Embed in amorphous silicon
  - Anneal (thermal or laser)

Fig. 7: Circuit diagram for measuring phototransistor current-voltage characteristics



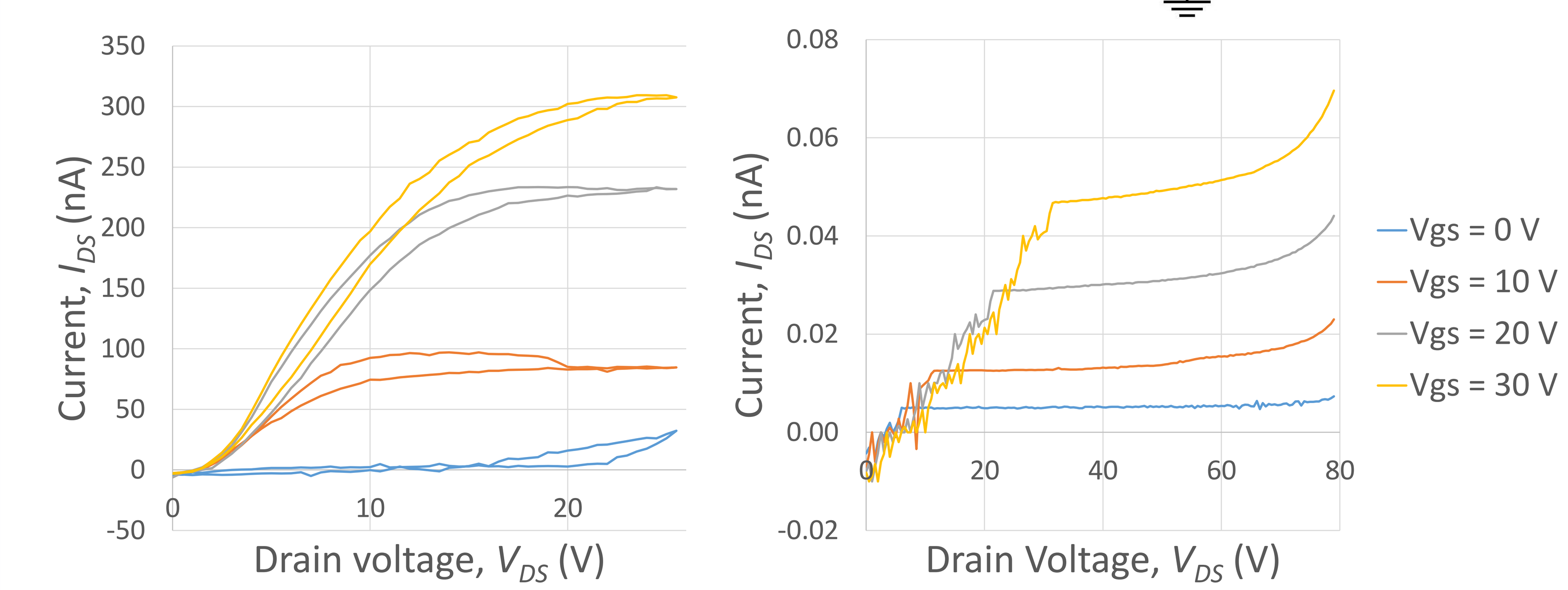


Fig. 8: Currents are orders of magnitude higher in the transfer characteristic of a nanocrystalline silicon transistor (*left*) than that of a silicon quantum dot transistor (*right*).

Future Work

- Measure transfer characteristics of quantum dot transistors after annealing at increasing laser powers and extract mobilities
- Measure effects of annealing on bandgap energy via photothermal deflection spectroscopy and photoluminescence measurements [4]
- Investigate structural changes with TEM [4]

Acknowledgements

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