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Growth and Exfoliation of Selenium and Tellurium for Quantum Chains of Atoms

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Trigonal Se and Te are one-dimensional (1D) van der Waals, or weakly bonded, materials with covalent bonding in one direction and relatively weak bonding in the other two directions. This anisotropic structure suggests the possibility to exfoliate or synthesize isolated 1D chains of atoms, "quantum chains", by analogy with layered two-dimensional (2D) materials [1]. In contrast to earlier work on chains of metal atoms grown or assembled with strong bonds to a substrate, quantum chains of Se and Te would be stand-alone semiconductors weakly bonded to the growth substrate [2], have no dangling bonds, and would enable the creation of variety electronic and optical devices at the atomic scale. This presentation reports on our efforts to isolate single quantum chains of Se and Te using a variety approaches including exfoliation of bulk crystals and direct growth by physical vapor deposition (PVD) on substrates with atomic steps.

For PVD growth of Se, oxidized Si substrates and Se powder are placed in the separate zones of a low-pressure PVD furnace. Depending on growth conditions (source and substrate temperatures, Ar flow and pressure), a variety of Se morphologies are observed including nano- and micro-droplets, nanowires, and 2D-like growth. Examples of droplet and nanowire growth are shown in Fig. 1. Nanowire growth is catalyzed by Si, which is exposed along the cleaved edge of growth substrates (Fig. 1a), while on the SiO_2 surface of growth substrates, droplets (Fig. 1b), nanowires (Fig. 1c), and 2D-like Se form. For some growth conditions, Se droplets grow with a circular structure, while for others the droplets themselves nucleate nanowire growth (Fig. 1c).

Selenium grown with a 2D-like, layered morphology may be peeled from the growth substrate with tape, exfoliated, and deposited on a separate substrate. Atomic force microscopy reveals that this procedure produces 2D Se with micron-scale lateral sizes and thicknesses of tens of nm. We are currently investigating whether this technique can produce nm-scale 1D Se structures as observed for Te [1], and whether exfoliation of bulk Se crystals grown with a flux method may provide a route achieve isolated quantum chains of Se.

The anisotropic structure of Se and Te provides a natural tendency for nanowire formation, but to approach the limit of a single quantum chain, we are investigating template-assisted growth using substrates such as R-plane sapphire. After annealing at 900 ºC in air for three hours, R-plane sapphire substrates develop well-defined terraces of atomic steps (Fig. 3). We hypothesize that the increased surface interaction between Se or Te atoms and the substrate at step edges will encourage quantum chain formation along the atomic steps of the substrate.

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[3] The author acknowledges funding from ARO, W911NF-18-1-0015.

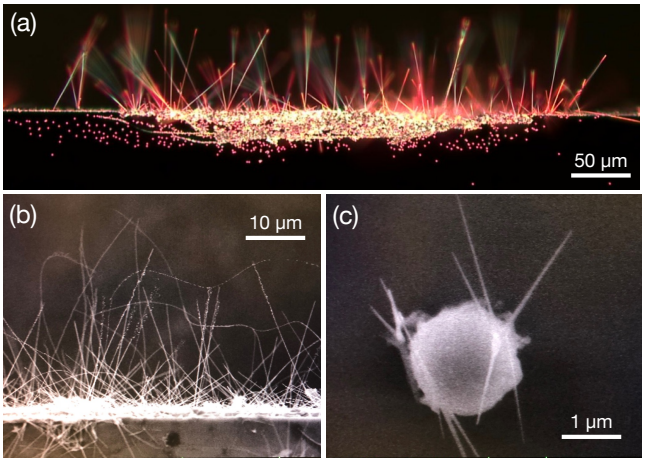

Figure 1. PVD growth 1D selenium. (a) Darkfield optical image of Se nanowire growth catalyzed by Si, with Se droplets formed on the SiO_2 surface. (b) SEM image of Se nanowires. (c) SEM image of Se droplet nucleating Se nanowires on SiO_2.

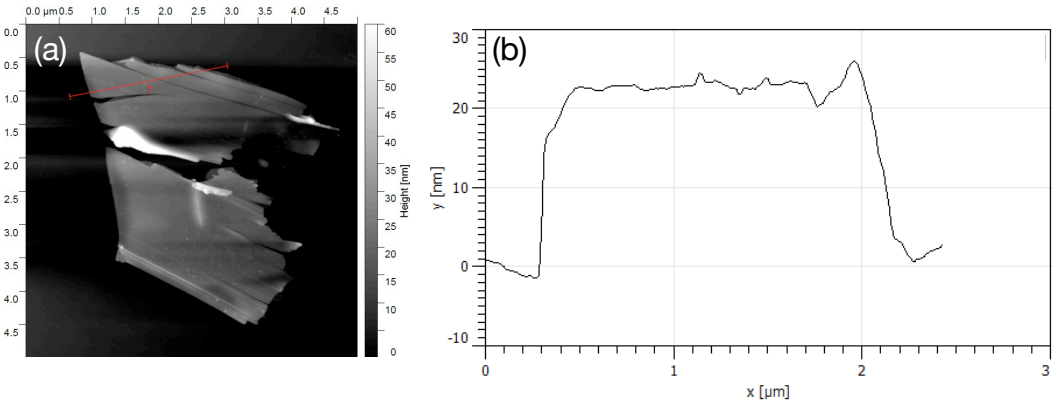

Figure 2. (a) AFM image of mechanically exfoliated 2D Se. (b) Linecut from (a) of an exfoliated Se flake.

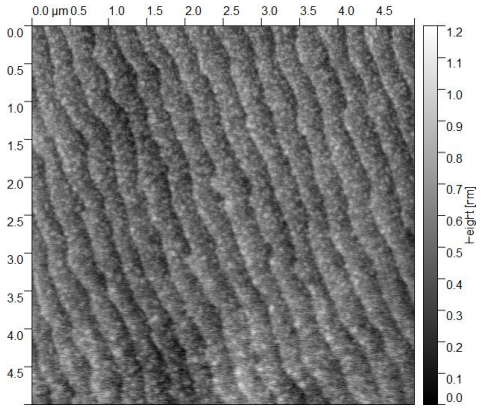

Figure 3. AFM height image of atomic steps on annealed R-plane sapphire as a template for single Se quantum chain growth.

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