Growth of Straight Crystal Silicon Nanowires on Nanopatterned Amorphous Substrate with Uniform Diameter and Length, Preferred Orientation, and Predetermined Location

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Semiconductor nanowires (NWs) offer a broad range of potential significant applications, e.g. integrated circuits [1], lasers [2], solar cells [3], and others. For many applications, it is very desirable to grow, on amorphous substrates, straight NWs with well-controlled geometry, orientation, and location. However, a central obstacle in the NW growth on amorphous substrates is that, unlike epitaxial growth on a crystal substrate, the NWs have huge variations in shape, length and orientation, hence greatly limiting the usefulness of these NWs. Here we report a general method, demonstrated in silicon and applicable to other materials, of NW array on an amorphous substrate with the straight NWs having uniform length and diameter, preferred orientation, as well as predetermined location.

One key in our method is a new way to engineer nanoscale catalyst's location, shape, composition and crystalline structures. It has two steps: (a) nanopatterning by nanoimprint lithography (NIL), evaporation, and liftoff to define the location and composition of a novel multi-layer catalysts square array on a SiO_2 substrate, with each square having a size of 126 nm × 124 nm and a composition of Au/α-Si/Au/α-Si (2.9/3.8/3.4/5.7 nm, top to bottom, see Fig. 1a); (b) a pre-growth annealing (1100ºC, ~1 hour, in N_2 ambient) to change each multi-layer square to a single hemispherical Au ball embedded in Si shell (Fig. 1b-d). Then a wet-etching with nitric and HF was used to expose the Au ball (Fig. 1e), followed by SiNWs growth using 8.5% $SiCl_4/H_2$ gas at 1000˚C for 5 min (Fig. 1f).

Comparing to conventional 4.3 nm thick single-layer Au catalyst (Fig.3), the SiNWs grown by our novel catalysts (Fig. 2) yielded nanowires of much more uniformly sized diameters (81 ± 2.5 nm, 3% deviation) and lengths (248 ± 11 nm, 4.6% deviation) while conventional catalyst did not demonstrate a good control over these parameters, as plotted in Fig. 4a. Moreover, the SiNWs obtained using our method had a small variation of out-of-plane angle (Fig. 4c), i.e. about 40% tilted within 10º and 80% tilted with in 30º, which could be further improved; while the SiNWs synthesized using conventional method would be more random and curvy and tended to align parallel to the surface (Fig. 4d).

Besides, we also found that the diameters of the SiNWs could be well controlled in a broad range, demonstrated from 40 nm to 80 nm experimentally. The density of SiNWs was as high as 25 wires/μm^2, among the highest reported values.

Reference:
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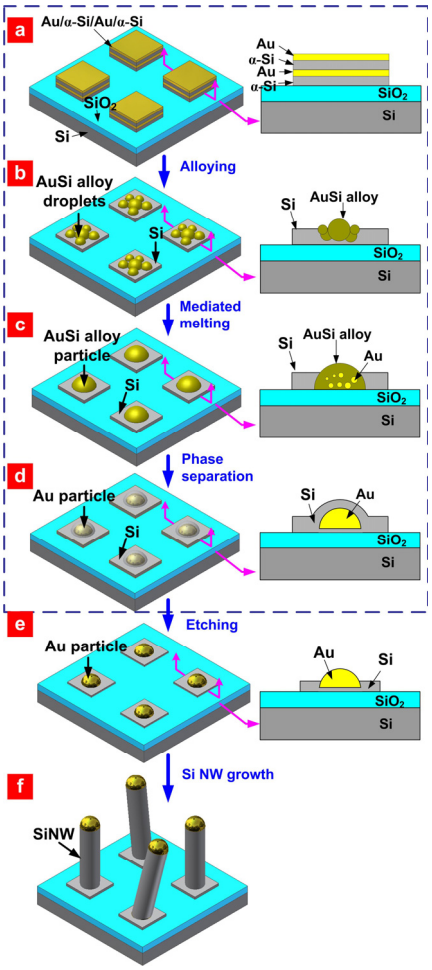

Fig. 1. Scheme of SiNW growth using novel catalysts. (**a**) As-patterned multi-layer catalyst; **b-d**, Au/Si/Au/Si multi-layer goes through annealing at 1100ºC to form single Au ball embedded in Si; (**e**) Formed Au ball sitting on Si after etching Si capping layer; (**f**) Grown SiNWs from Au particles after etching.

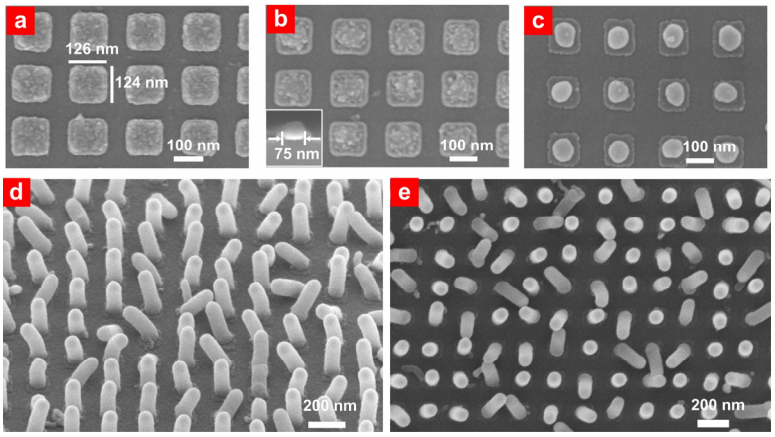

Fig. 2. SEM images of catalyst arrays and synthesized SiNWs. (**a**) NIL-patterned α-Si/Au/α-Si/Au multi-layer catalysts; (**b**) Annealed catalysts with the cross-sectional view shown in the inset; (**c**) Catalyst with Si capping layer etched away. **d-e**, SiNWs synthesized using the catalysts as shown in image **c**: (**d**) 45º side view; (**e**) Top-view.

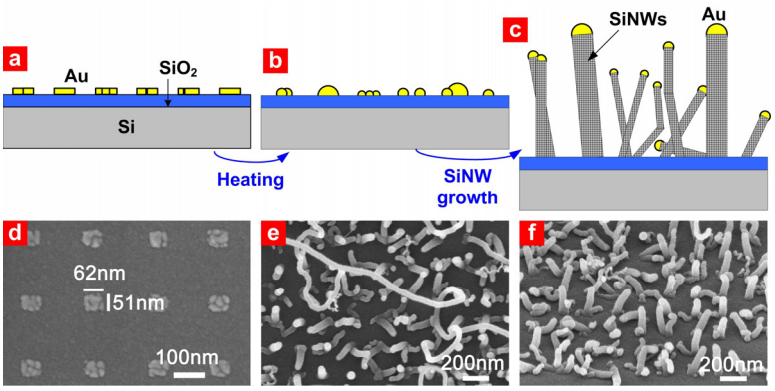

Fig. 3. SiNW growth using conventional single-layer catalyst. a-c, Schemes of: (**a**) As-patterned thin Au particles; (**b**) Random Au particles upon heating before growth; (**c**) Random nanowires grown from Au particles. **d-f**, SEM images of: (**d**) 4.3 nm thick single-layer Au particles; **e-f,** top-view and 45º side view of synthesized SiNWs.

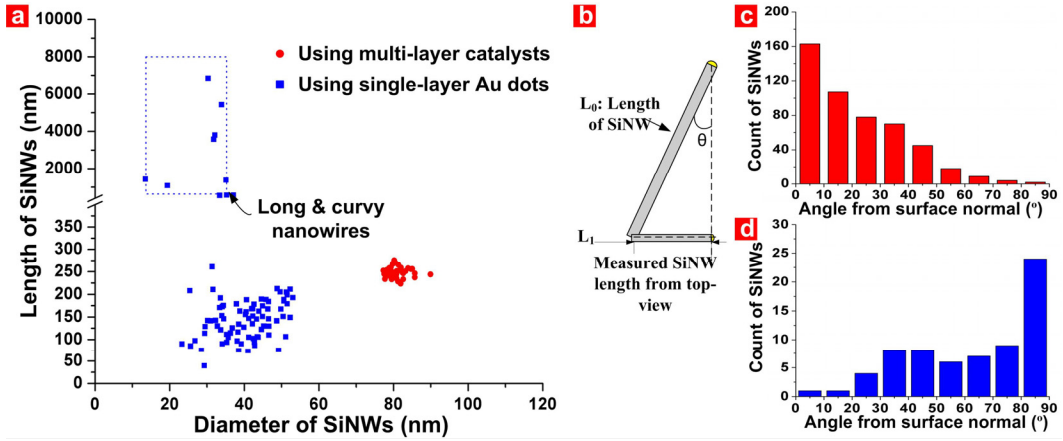

Fig. 4. Comparison of SiNWs grown using novel multi-layer catalysts and single-layer catalyst. (**a**) Distributions of SiNW length and SiNW diameters. (**b**) A scheme showing the calculation of out-of-plane angle θ of SiNWs. **c-d,** Distributions of θ of SiNWs synthesized using: (**c**) novel catalysts; (**d**) conventional single-layer catalyst.