Ultra-High Aspect Ratio, Plasma Etched Silicon Nanowires: Optical Properties and Mechanical Stability

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Nano-sized vertical (perpendicular to the substrate) silicon nanowires (SiNWs) with a high aspect ratio (HAR) are crucial for many applications such as photonics, photovoltaics, energy harvesting, biosensors and other fields. Here we report the use of e-beam lithography and the cost effective process of colloidal particle self-assembly and followed by Si plasma etching to produce HAR SiNWs. Two different anisotropic processes are employed: a) a cryogenic Si etching process[1] that uses a SF_6/O_2 gas mixture at cryogenic temperature ($T<-100$ °C) and b) a room temperature two-cycle time-multiplexed DRIE process[2] using $SF_6/C4F_8$. Our fabrication process offers full versatility in wire period, diameter and height, showing high etch rate and selectivity to the etching mask material, clean, controllable smooth or scalloped sidewall profile. Sub-200 nm diameter SiNWs with AR over 80:1 are demonstrated.

Figure 1 shows 200 nm and 400nm diameter high AR SiNWs as a result of colloidal (polystyrene spheres as a mask) followed by the cryogenic plasma process. Additionally, Figure 2 shows 150-250nm diameter, ultra-high AR SiNWs etched using the room temperature time-multiplexed DRIE process.

The optical properties of SiNWs of different diameter, height, period are evaluated by measuring the total reflectance (both specular and diffuse). We found that the total reflectance of silicon can be reduced significantly (below 2%) in a wide range of the optical spectrum, as shown in Figure 3. The process of colloidal lithography imports defects in the hexagonal lattice, which are transferred as order defects of the SiNW arrays. A comparison of the optical response of ordered and quasi-ordered SiNW arrays was made. We will show that lattice defects and the structural randomness enhance the antireflective properties of ordered SiNW arrays.

We also study the mechanical stability of the fabricated tall nanowires, and show that a critical AR exists above which SiNWs bend due to adhesion forces among them. This critical AR increases as the pitch increases and is approximately 49:1 for period 1 um and diameter of 200 nm (Figure 4). We then wet the SiNWs and dry them looking for possible bending and collapse due to capillary forces. We find that capillary forces are probably less important than adhesion forces, which dominate due mainly to the high surface energy of silicon.

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[1] K. Ellinas, A. Smyrnakis, A. Malainou, A. Tserepi and E. Gogolides, Microelectronic Engineering **88**, 2547 (2011)

[2] A. Zeniou, K. Ellinas, A. Olziersky and E. Gogolides, Nanotechnology **25**, 035302 (2014)

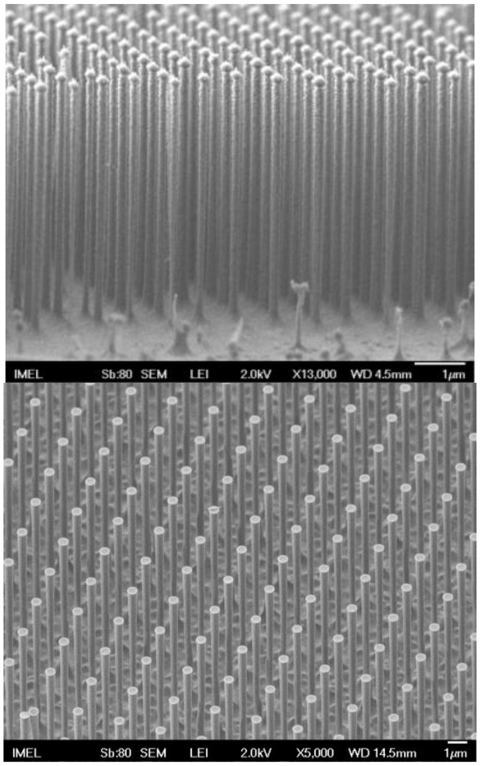

Figure 1: SiNWs fabricated by colloidal (up) and e-beam (down) lithography followed by the cryogenic plasma etching process. The diameter of the wires is ~200 nm and 400nm with an aspect ratio of 26:1 and 23:1 respectively.

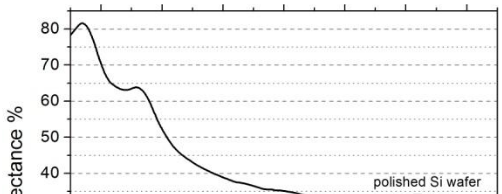

Figure 3: Total, specular and diffuse reflectance of a Si surface with perpendicular SiNWs (diameter 150-200nm, height 2.5 μm, period 520 nm) compared to the reflectance of a polished Si wafer.

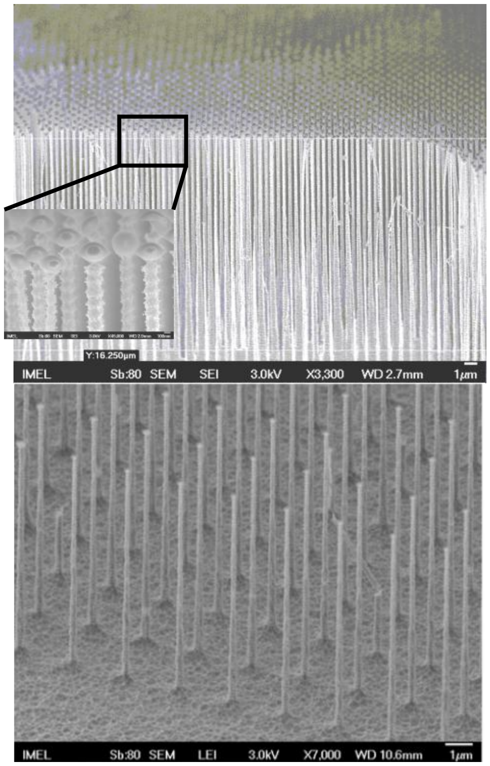

Figure 2: SiNWs fabricated by colloidal (up) and e-beam (down) lithography followed by the room-T time-multiplexed DRIE process. The diameter of the wires is ~ 150–250nm with an aspect ratio of >80:1 and 40:1 respectively.

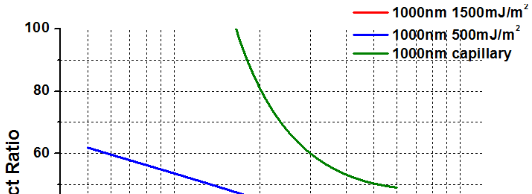

Figure 4: Critical AR for bending of SiNWs versus the diameter of SiNWs for a 1000nm pitch. Two curves are shown for different surface energy of Silicon. Clean Si (large surface energy) bends at lower AR. Capillary coalescence critical AR is also shown.