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Morphology of Si nanowires fabricated by laser ablation using gold catalysts

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ABSTRACT Si nanowires (NWs) were fabricated successfully by laser ablation using Au as catalyst. Si wafers were used as the collector. The diameters of Si NWs ranged from 20 to 150 nm. Different forms of Si NWs were observed at different local sites inside a furnace: Si NWs with a high aspect ratio of length to diameter, Si NWs with defects and Si NWs with Au-containing nanoparticles being embedded. Especially, a nano-particle embedded Si NW is a new nanostructure that is observed for the first time.

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1 Introduction

The interest in one-dimensional semiconductor NWs has increased rapidly over the past years due to their potential applications in the area of nano-science and technology including electronics, mechanics and optical devices [1–7]. Especially, several fabrication technologies for the growth of Si NWs have been reported. Si NWs have been fabricated via the well-known vapor–liquid–solid (VLS) mechanism based on the earlier work of Wagner [8] and other co-workers. In the method, a metal (Au or Fe) as catalyst was used and Si vapor is provided from either laser ablation or Si-containing gas (SiH_4 or $SiCl_4$). Here, we report the fabrication of Si NWs by laser ablation on Si substrates, using metal catalysts.

2 Experiment

Our growth technique utilizes the laser synthesis at a high temperature as a means of growing Si NWs. The laser used was a Q-switched Nd : YAG laser (wavelengh: 532 nm, repetition rate: 10 Hz, and pulse duration: 5 ns full-width-at-half-maximum). The targets for laser ablation were made by mixing Si micro-particles with Au micro-particles at 20% atomic ratio and compressing the mixtures at room temperature under a pressure of around 300 MPa. For the promotion of the NW growth, a 0.6 nm-thick film of Au was deposited onto the Si wafer substrate by sputtering for the case of fabricating NWs using Au catalyst. The substrates were put inside a quartz tube and placed downstream from the center of the tube. The quartz tube was placed inside a furnace (Fig. 1). The condition of Si NW growth was as follows: the furnace temperature was kept at around 1000 °C, the laser was focused to a spot with a diameter of around 1.5 mm at a laser fluence of 1.1 J/cm^2 under a flow rate of 50 sccm and a total pressure of 400 Torr of a mixture of argon and hydrogen gas (5%). The morphology and chemical compositions of synthesized Si NWs were investigated by SEM, TEM and EDX attached to the machine.

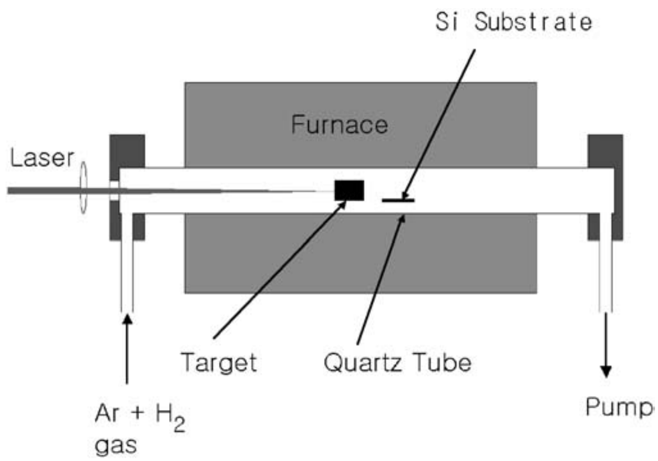

FIGURE 1 Schematic diagram of the laser ablation apparatus for NW growth. A pulsed laser was focused onto a target located within a quartz tube and the temperature was controlled by the furnace. Si wafers were put inside the tube to collect the product carried by the Ar +5% H_2 gas flow

3 Results and discussion

Si vapor produced from a target condenses on Au/Si molten clusters. The molten clusters become super-saturated in Si. Si is then precipitated from the super-saturated liquid Au/Si clusters in one-dimensional form, leading to the growth of NWs. The growth will terminate when the super-saturated clusters passes out of the hot region.

Typical SEM images of the Si NWs obtained are shown in Fig. 2. The shape of the Si NW varied with substrate positions. The surface of the target and the collector near the target were covered with a dense array of high aspect-ratio,

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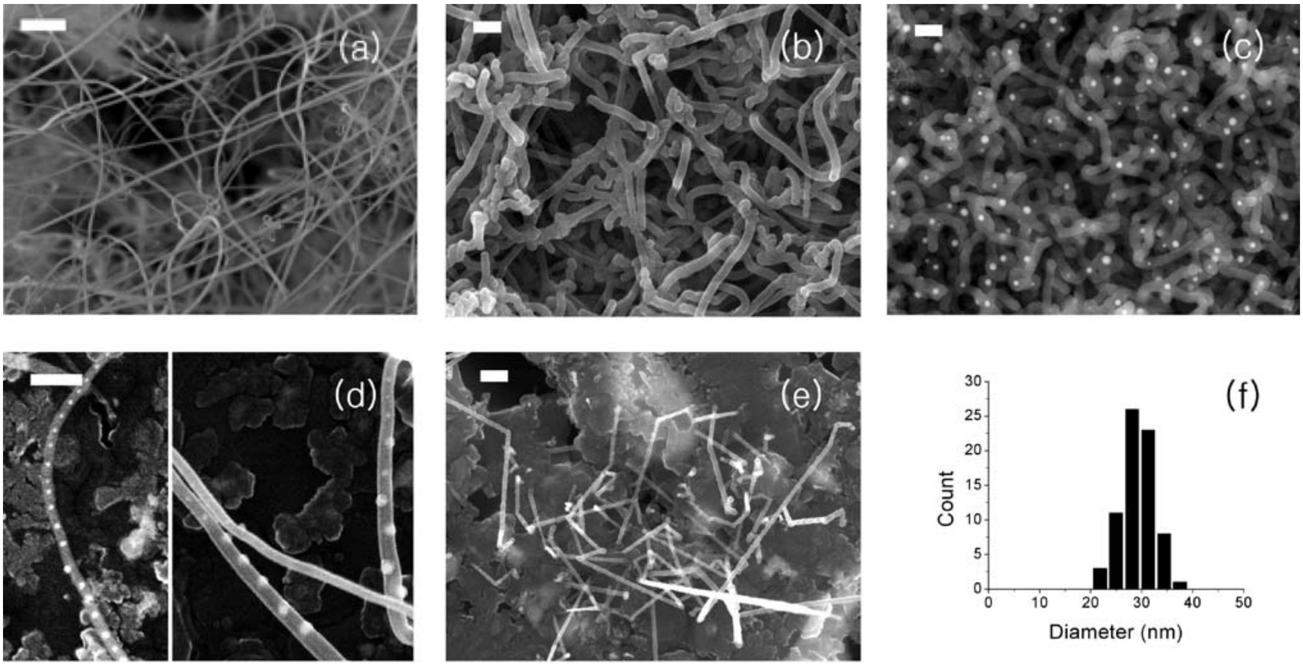

FIGURE 2 SEM images of various Si NWs. **a**-**e** are Si NW fabricated using Au catalyst: **a** straight SiNWs fabricated on the target. **b** Curved Si NWs on 2 cm substrate from the target. Au-embedded SiNWs fabricated on **c** 4 cm and **d** 10 cm from target. (*White dots* in pictures are nano-particles containing Au) **e** Mono-dispersed NWs (grown from mono-dispersed Au nano-particles) and **f** diameter distribution of Si NWs of **e**. Scale bar: **a** 1 μm, **b**-**e**: 200 nm

straight freestanding Si NWs with a length of several microns (Fig. 2a). Curved NWs due to growth defects were observed on substrates downstream 2 cm from the target (Fig. 2b). The diameter of the NWs ranged from 20 to 200 nm.

Some nano-particles embedded NWs were observed on substrates downstream 4 cm (Fig. 2c) and 10–12 cm (Fig. 2d) from the target. On 4 cm substrates NWs were curved and nano-particles were arranged randomly. On 10–12 cm substrates NWs were straight and nano-particles were embedded periodically on the NWs. Straight NWs were observed on 6–8 cm substrates but without nano-particles. The diameters of these particles ranged from several tens to hundreds of nanometers. The EDX observation shows that nano-particles mainly contain Si, Au and O. Oxygen was detected due to the nano-particles being encapsulated by silicon oxide. Since both Au-containing nano-particles and Si NW were generated from the ablation of a solid SiAu target, nanoparticle-embedded NWs as shown in Fig. 2c and d are expected to be formed from the ablation of a SiAu target. The formation process of this kind of nano-particles-embedded NWs could be explained as follows: the nano-particles are formed by collision inside the laser-produced plasma surrounded by ambient inert gas. Some of the Au-containing nano-particles ejected from the target are randomly attached to the surface of the Si NWs, and then "sink", or even completely submerse into the NW. The surface tension between droplet-NW interfaces drives the Au-containing nano-particles into the Si NWs [9].

Figure 3 shows the TEM picture of a Si NW. The electron diffraction pattern (Fig. 3a) shows that Si NW is single crystalline and the growth direction is (111). The HRTEM picture (Fig. 3b) shows atomic layers at the core of Si NW. The crystalline core was surrounded by an amorphous silicon-oxide sheath (Fig. 3c). In this particular case, the thickness of the sheath was relatively large so that it amounts to about

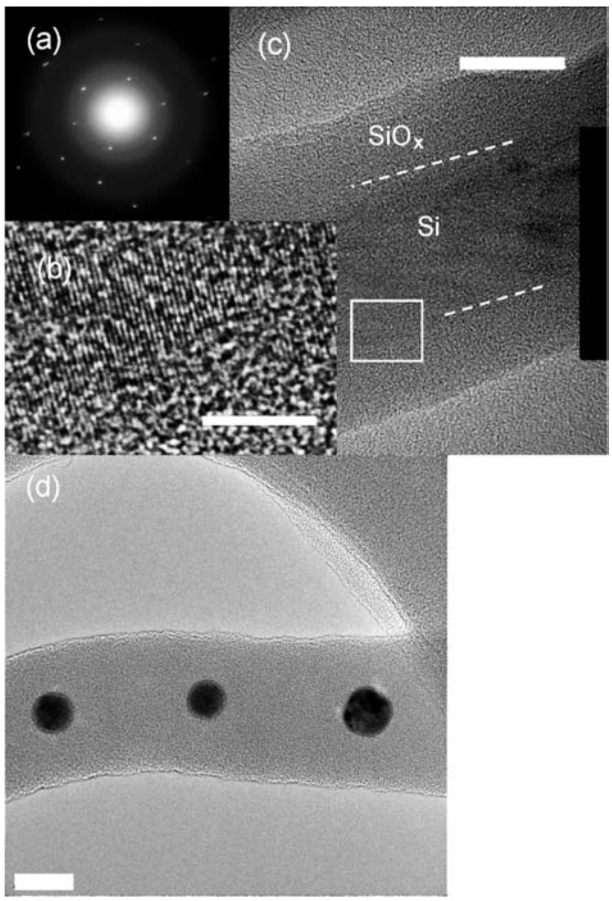

FIGURE 3 TEM image and electron diffraction pattern of Si NW. **a** Diffraction pattern show that the Si NW is single crystalline and grow direction is (111) **b** HRTEM image of square part of **c** (scale bar: 5 nm) **c** TEM image in low resolution (scale bar: 20 nm) **d** TEM image of Au-embedded SiNW consisted of amorphous Si or silicon oxide

two thirds of the NW diameter. Figure 3d is TEM picture of nano-particles embedded Si NW and it shows that the NWs consisted of amorphous Si or silicon oxide.

When a Au-coated Si substrate was replaced by a Si substrate on which Au nanoparticles (25 nm dia.) were spread, the diameters of fabricated Si NWs were controlled and had a smaller dispersion as shown in Fig. 2d and e.

4 Summary

Si NWs were fabricated successfully by laser ablation using metal catalysts such as Au. Different forms of Si NWs were observed: straight, curved, and nano-particle embedded NWs. Especially, the growth of nanoparticles-embedded Si NW by laser ablation was observed for the first time and might have the potential possibility to fabricate a nanocluster within one-dimensional NW and a nano coaxial cable.

NWs fabricated by laser ablation have the diameter distribution with a variation of ± 10 nm. This dispersion can be reduced by using a template coated with mono-dispersed nm-catalyst particles.

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