Growth of CrSi2 Nanostructures Using CrCl2 Powder on Si Substrates

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Growth of CrSi₂ Nanostructures Using CrCl₂ Powder on Si Substrates

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Abstract

Chromium disilicide (CrSi₂) nanostructures were grown by the exposure of Si (111) substrates to CrCl₂ vapor in an argon gas flow at atmospheric pressure without using any metal catalyst. Dependence of the growth condition on the structural property was investigated. Hexagonal-shaped CrSi₂ microrods were grown at 750 °C with 0.05 g of CrCl₂. As the quantity of CrCl₂ increased to 0.1 g, the bundle of CrSi₂ nanowires with microrods and web-liked CrSi₂ nanostructure with turning angles were grown at 750 °C and 700 °C, respectively. The preliminary discussion on the growth mechanism of CrSi₂ micro- and nanostructures was carried out.

Keywords: CrSi₂, microrods, nanostructures, thermoelectric material

I. Introduction

Chromium disilicide (CrSi₂) is an indirect narrow-gap (Eg=0.35 eV) semiconductor that has been targeted and used for robust, stable, and inexpensive thermoelectric (TE) materials and has shown promise for photovoltaic applications [1-2]. Although CrSi₂ possesses many advantages such as low cost, excellent thermal stability and outstanding oxidation resistance, it has modest ZT value compared with those of the more well-known TE materials [3]. Nano-scale thermoelectric materials are considered to have potential ability to enhance the energy conversion performance of thermoelectric materials [4]. Theoretical calculations and proof of principle experiments of nanoscale systems have demonstrated both a decrease in thermal conductivity and an increase in the power factor σS² relative to the corresponding bulk systems [4-8]. Hochbaum et al. [8] reported that the Si nanowires with diameters of about 50 nm exhibit 100-fold reduction in thermal conductivity, yielding ZT = 0.6 at room temperature. Recently, various nanostructures of CrSi₂ have been successfully synthesized, such as nanowires, nanowebs, and core-shell nanocables [2-3,9-10]. However, it is important to develop a simple and controllable growth process for the fabrication of the CrSi₂ nanostructures. In this study, the preliminary growth of CrSi₂ nanostructures was carried out, and dependence of the growth condition on the structural property was investigated. In addition, the preliminary discussion on the growth mechanism of CrSi₂ micro- and nanostructures was carried out.

2. Experiment

CrSi₂ nanostructures were grown by the exposure of Si(111) substrates to CrCl₂ vapor in an argon gas with the flow rate of 4500 sccm at atmospheric pressure. The
Si(111) substrates covered with native oxide layers were placed approximately 10 cm downstream apart from the CrCl₂ powder in the furnace [2]. 0.05 g-0.1 g of CrCl₂ source was maintained at 872 °C, and Si substrates were reacted at different temperatures in the range of 700 °C-750 °C and kept for 10 min. In this study, the source material and substrate are moved into the furnaces after the temperature of the furnaces up to the reaction temperature, in order to ensure the source material reacted at the reaction temperature and control the growth process easier.

The morphological and structural properties of samples were characterized by filed emission scanning electron microscopy (FESEM) and X-ray diffraction (XRD). In addition, the compositional analysis of the samples was carried out using energy dispersive spectroscopy (EDS).

3. Results and Discussion

Figure 1 shows cross-sectional SEM images of the CrSi₂ samples grown at different temperature of substrates with different quantity of CrCl₂. Free-standing microrods less than 10 μm in length and less than 5μm in width are grown at 750 °C with 0.05 g of CrCl₂ and microparticles are also observed, as shown in Fig.1 (a). As the quantity of CrCl₂ increased to 0.1 g, the width of the microrods is slightly increased and the length up to 30 μm, as shown in Fig. 1 (b). However, the size of microrods depends on the quantity of CrCl₂. Additionally, the bundle of nanowires is grown at the top of the microrods, and the white nanoparticles are attached to the apexes of the nanowires, as shown in the inset in Fig. 1 (b). It is considered that the sufficient CrCl₂ vapor supply in the growth process leads to growth of the nanowires. It has been reported that CrSi₂ nanowires grow out perpendicularly and evenly from both sides of the microrod-like CrSi₂ stems using Cr powder and NiCl₂ as source materials [11]. The film with the thickness of 30 μm, consists of the microparticles, is formed at 700 °C with 0.1 g of CrCl₂, as shown in Fig. 1 (c), and nanowires are grown at the top of the film, as shown in the inset in Fig. 1 (c). It is seen that the morphology property of the samples depends on the quantity of CrCl₂ and the temperature of substrates.

Figure 2 shows XRD spectra of the CrSi₂ samples grown at different temperature of substrates with different quantity of CrCl₂. The peaks in the spectra, except the peaks from the Si substrates, can be indexed to the hexagonal crystal structure of CrSi₂. No other chromium silicide phases or impurities are detected. CrSi₂ is the most thermodynamically favorable phase to form among various phases of chromium silicides [2]. It is confirmed that the samples are mainly composed of CrSi₂. The silicide can be formed either by the direct reaction of halide source with Si substrate or through a nucleation mechanism [11]. The growth of the CrSi₂ microrods or nanowires could be described by the following plausible reaction equations [2].

\[
2\text{CrCl}_2 (g) + 5\text{Si} (s) \rightarrow 2\text{CrSi}_2 (s) + \text{SiCl}_4 (g) \quad (1)
\]

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\text{CrCl}_2 (g) + 2\text{SiCl}_4 (g) \rightarrow \text{CrSi}_2 (s) + 5\text{Cl}_2 (g) \quad (2)
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\]
direction of the microrods with hexagonal structure is parallel to the CrSi$_2$ [0001] [3].

Figure 4 shows SEM images and corresponding EDS results of the CrSi$_2$ sample grown at 750 °C with 0.1 g of CrCl$_2$. The bundle of nanowires with microrods is densely distributed on the surface of the Si substrate, as shown in Fig. 4 (a). The microrods also possess hexagonal structure as same as the sample grown at 750 °C with 0.05 g of CrCl$_2$, and the nanowires are grown at the top and along the surface of the microrods. EDS results in Fig. 4 (b) indicate that the atomic ratio between Cr and Si in nanowires and microrods is approximately 1:2, while a lot of O is contained in nanowires. Additionally, Si and O are the main elements contained in the nanoparticles, which reveals that the nanoparticles probably consist of silicon oxides. The formation of silicon oxides could be described by the following plausible reaction equation [13]:

$$\text{SiCl}_4 (g) + 2\text{H}_2\text{O} (g) \rightarrow \text{SiO}_2 (S) + 4\text{HCl} (g)$$ \hspace{1cm} (3)

As shown in Fig. 4 (c), the bundle of nanowires is well-aligned and has high density.

Figure 5 shows SEM images of the CrSi$_2$ sample grown at 750 °C with 0.1 g of CrCl$_2$. It is clearly observed that the structure of the sample is composed of microrods, nanowires and nanoparticles, as shown in Fig. 5 (a). Magnified SEM images show that a lot of nanoparticles are attached on the surface of the microrod and the top of the nanowires, as shown in Fig. 5 (b) and (c). It is considered that the nanoparticles act as the catalyst for the growth of the nanowires. The interface between microrod and nanowires indicates that the secondary nucleation occurred on the surface of the microrods, and then the sufficient vapor supply in the system leads to growth of the nanowires.

Figure 6 shows SEM images of the CrSi$_2$ sample grown at 700 °C with 0.1 g of CrCl$_2$. CrSi$_2$ with web-liked structure is densely distributed on the surface of the Si substrate, as shown in Fig. 6 (a) and (b). The web-liked structure is composed of nanowires with a thickness less than 100 nm. No nanoparticles are observed at the top of the nanowires. Magnified SEM image in Fig. 6 (c)
illustrates that the turning angles about 60 ° are observed in the nanowires. It is estimated that the growth direction of the nanowires with turning angles is parallel to CrSi2 <11-20> [9].

CrSi2 nanowires are developed by a simple and controllable growth method. According to the results mentioned above, the quantity of CrCl2 and the temperature of substrates affect the final morphology of the samples. The growth mechanism is not clear, but it is considered as follows. Because of no additional catalytic metal particles are employed in the growth process, the growth of CrSi2 microrods and nanowires presented here is not due to the vapor-liquid-solid (VLS) mechanism. The growth of the CrSi2 microrods or nanowires is carried out by two reaction equations. Equation (1) is the dominant reaction on Si substrates.

4. Conclusions

CrSi2 nanostructures were grown by the exposure of Si (111) substrates to CrCl2 vapor in an argon gas flow at atmospheric without using any metal catalyst. The sufficient CrCl2 vapor supply and proper temperature of Si substrates are the crucial factors for the growth of CrSi2 nanostructures. Hexagonal-shaped CrSi2 microrods were grown at 750 °C of the substrate with 0.05 g of CrCl2. The bundle of CrSi2 nanowires with microrods and web-like CrSi2 nanostructure with turning angles were grown at 750 °C and 700 °C of the substrates with 0.1 g of CrCl2, respectively. This result leads us to expect that further optimization of growth condition and pretreatment of the substrates grow well-aligned and high density of CrSi2 nanostructures for thermoelectric applications.

References