Materials Letters 177 (2016) 80–84

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

High thermosensitivity of silicon nanowires induced by amorphization

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ARTICLE INFO

Article history:
Received 24 February 2016
Received in revised form
25 March 2016
Accepted 23 April 2016
Available online 25 April 2016

Keywords:
Thermoresistive effect
Temperature coefficient of resistance
Silicon nanowire
Amorphization
Focused ion beam

ABSTRACT

In this work, we demonstrate highly thermosensitive silicon nanowires (SiNWs) for thermal-sensing applications. Crystalline Si was amorphized by Focused Ion Beam in the fabrication process of the SiNWs, and subsequently recrystallized by a thermal annealing process to improve their electrical conductivity. A temperature coefficient of resistance (TCR) from −8000 ppm/K to −12,000 ppm/K was measured for the SiNWs. This large negative TCR is attributed to the boundary potential barrier of 110 meV between silicon crystallites in the poly crystalline SiNWs.

1. Introduction

Over the past several decades, electronic sensing devices have been significantly developed, with an emphasis on miniaturization and high sensitivity with various successful applications [1–5]. Nanowires (NWs), as an important achievement of the miniaturization process, are obviously of interest, since these one-dimensional nanostructures offer extremely small sizes with a great integration ability into micro/nano systems [6,7]. For instance, recent research facilitating thermal-sensing nano-systems has focused on highly thermosensitive NWs which are particularly useful for monitoring temperature variations within a narrow range [8].

To estimate the themosensitivity of NWs, temperature coefficient of resistance (TCR) has been widely employed and can be defined as the relative change of resistance to the temperature variation [9]. For example, metal nanowires showed a positive TCR ranging from 2500 to 4000 ppm/K [10], which was similar to that of bulk metals [11]. In addition, the TCR of semiconductive nanowires can be controlled through doping levels, but it has been shown to be relatively low and in a limited range [12,13] (−3700 to 700 ppm/K). Apart from doping, morphologies such as crystalline and amorphous could also vary the thermal properties of a material because the TCR significantly depends on the number of defects and grain boundaries in the crystallographic structures [14,15].

It is well known that focused ion beam (FIB) is a common technique which damages the crystallites to form amorphous nanostructures [16,17]. Moreover, thermal annealing is a simple approach for recrystallizing the damaged material and improving its electrical conductivity for ease of measurements [18]. In fact, the thermal annealing method has also been utilized to improve the quality of solar cell [19], the conductivity and stability of transparent electrodes/heaters [20], and the properties of other electronic devices [18,20]. Therefore, NWs, fabricated by FIB and a subsequent thermal annealing, could be a suitable solution for developing highly-sensitive thermal-sensing nanosystems.

In this study, we fabricated silicon nanowires (SiNWs) from a Silicon on Insulator (SOI) wafer using FIB, wet etching and subsequent annealing processes, and observed an extremely large negative TCR for the SiNWs (−8000 ppm/K to −12,000 ppm/K). We also investigated the change in the morphologies of the SiNWs with the FIB and the annealing process, and discussed the conduction mechanism of the highly thermosensitive SiNWs.

2. Fabrication of SiNWs

We fabricated the SiNWs utilizing a Silicon-On-Insulator (SOI) wafer with the layer thicknesses shown in Fig. 1(a). The device, insulation and substrate layers are highly doped single crystalline Si, silicon dioxide and low doped crystalline Si, respectively. At the

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http://dx.doi.org/10.1016/j.matlet.2016.04.171
0167-577X/

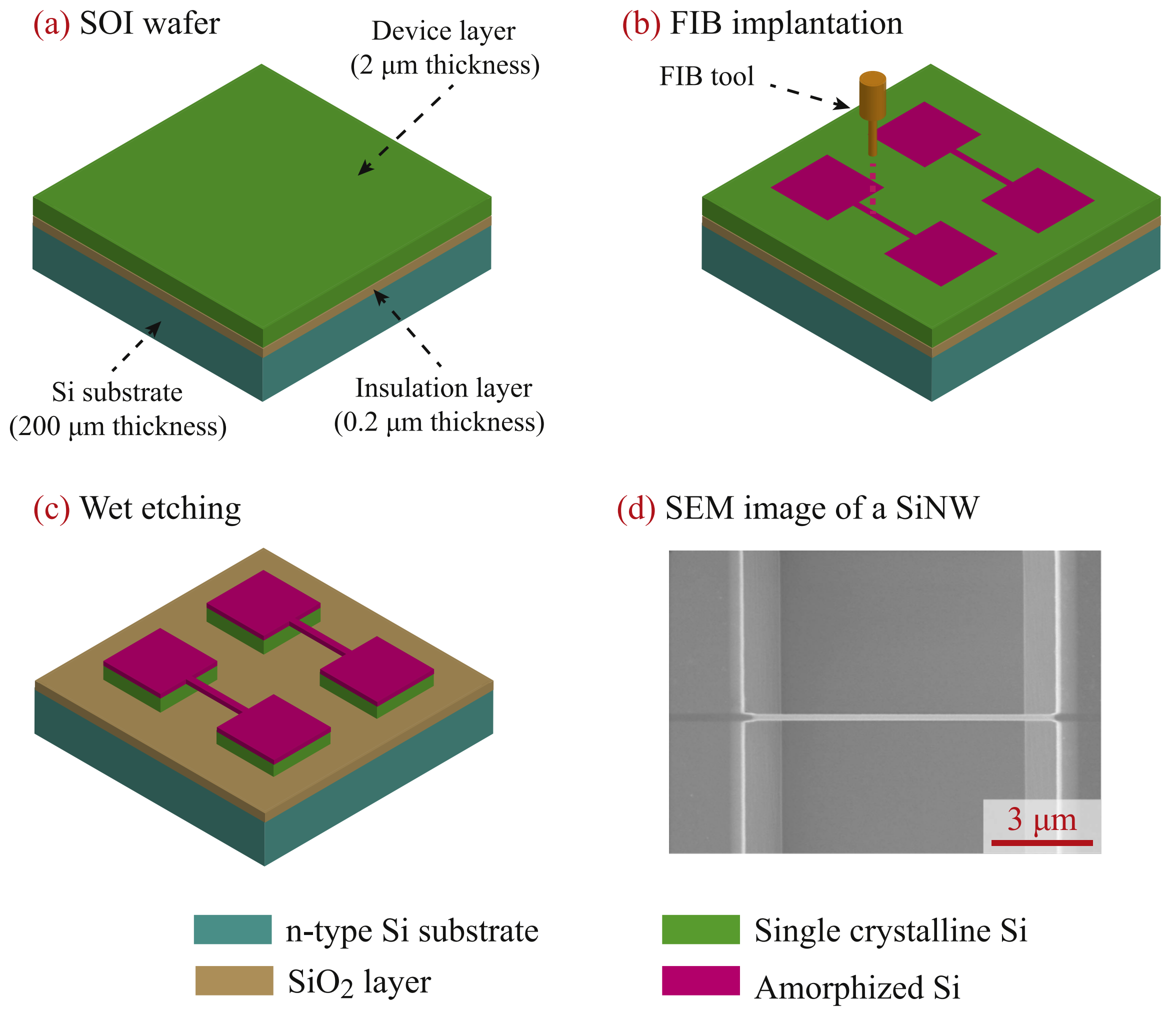

Fig. 1. Fabrication of SiNWs: (a) Silicon on Insulator (SOI) wafer; (b) Ga^+ implantation using FIB; (c) Wet etching to form the SiNWs; and (d) Scanning Electron Microscropy (SEM) image of a SiNW.

FIB step, an implantation of gallium ions (TMHitachi FB2200, voltage 40 kV, beam current 110 pA) was employed with a dose of approximately 7×10^{15} ions/cm^2 to damage the crystalline Si areas and form amorphous morphology (Fig. 1(b)). The amorphized areas include the 200 $\mu m \times 200$ μm electrode pads and the SiNWs with dimensions of $0.2(0.3)\mu m \times 10$ μm. It is noted that with the above FIB conditions, the thickness of the implanted layer was measured to be approximately 60 nm.

In the next step, the SiNWs were released using a wet etching process with tetramethylammonium hydroxide hydroxide (TMAH, 20 wt%) at 90 °C, owing to the low etching rate of the amorphous Si compared to that of single crystalline Si (Fig. 1(c)). Finally, we annealed the amorphized SiNWs at a temperature of 700 °C for 60 min in a high-vacuum chamber, to improve their electrical conductivity for electrical measurements. It is expected that increasing the annealing temperatures could reduce the number of boundaries and defects and enhance the crystallite size [21]. On the other hand, at low annealing temperatures, the improvement of electrical conductivity of the SiNWs might not be enough for ease of electrical measurements and reduction of measurement uncertainty. Fig. 1(d) shows a scanning electron microscope (SEM) image of a fabricated SiNW with a dimension of 10 μm length, 300 nm width and 60 nm thickness.

3. Results and discussion

3.1. Characterization of SiNW morphology

The impact of the fabrication process on the morphology of the implanted Si layer was investigated by Raman measurements (Fig. 2(a)), which indicates a sharp peak (at a wavenumber of 520 cm^{-1}), no peak and a moderate peak for the layer before FIB, after FIB and after annealing processes, respectively. This effect implies a transformation in morphology with the FIB and annealing processes. The change of the layer morphology was confirmed and is shown in Fig. 2(b) and (c), which indicates the disappearance of the boundary between the damaged layer and the single crystalline layer. The high-resolution transmission electron microscopy (HRTEM) image (Fig. 2(d)) shows the amorphous structure of an implanted area after FIB. To confirm the amorphous property of the implanted Si layer, the selected area electron diffraction (SAED) measurements were performed on a small area which included point A, as shown in the inset Fig. 2(d). The broad and diffuse rings in the SAED image are clearly observed. This is a well-known evidence for the amorphous characteristic of the implanted film [22]. This amorphization is attributed to the fact that Ga+ ions collided with the Si atoms during the FIB implantation, leading to the damage of Si crystals. With a large Ga+ dose of 7×10^{15} cm^{-2}, the damaged layer became amorphous Si.