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Impact of anodic aluminum oxide fabrication and post-deposition anneal on the effective carrier lifetime of vertical silicon nanowires

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ABSTRACT

The impact of the anodization process of anodic aluminum oxide fabrication and post-deposition anneal on effective carrier lifetime of Si nanowires are reported. The anodization process with suitable switched-off anodization currents results in enhanced effective carrier lifetime of Si nanowires that are significantly higher than that of early and late switched-off anodization currents. Furthermore, the anodic aluminum oxide template exhibits an efficient passivation upon post-deposition anneal, yielding a maximum value of 228 µs under thermal treatment at 650 °C. First fabrication of Si nanowire solar cell embedded with anodic aluminum oxide template was carried out. Through post-deposition anneal prior to the fabrication of Si nanowire solar cells, the performance of Si nanowire solar cells was significantly improved. This established the impact of thermal treatment on opto-electronic characteristics of Si nanowires embedded with anodic aluminum oxide.

1. Introduction

Anodic aluminum oxide template (AAO) has been intensely studied thank to its remarkable properties such as controlled pore diameters and high aspect ratio of its nanochannels [1–3], which made it a popular template for formation of one-dimensional nanostructures [4–8]. The selective growth of Si nanowires (Si NW) assisted by AAO using gas source molecular beam epitaxy gas source (MBE) is advantageous compared with conventional methodologies such as electron beam lithography [9] and metal-assisted chemical etching [10] with respect to vertically epitaxial structures with controlled diameter, good mechanical stability supported by AAO template, and absence of metallic contamination [11,12]. Furthermore, it was demonstrated that the Si NW were adequately passivated by the AAO, which exhibited promising effective carrier lifetime upon post-deposition anneal; this can be because of field-effect passivation as well as chemical passivation [13]. However, the recombination velocity at the bottom of the Si NW/Si substrate remained high because of the defects at the bottom of the Si NW. It could either be because of the remaining alumina barrier layer or anodization of the Si surface at the bottom of the AAO, which has strong influences on the growth of Si NW. One possible solution to reduce the remaining alumina barrier layer and anodization of the Si surface at the bottom of the AAO is to control the anodization process of AAO fabrication as soon as the consumption of Al is empty. For convenience, the current ratio R was introduced as a controlling parameter of the anodization process; it is defined as

$$R = \frac{I_0 - I_{s/o}}{I_o}$$

I_o and $I_{s/o}$ are the anodization currents in saturation and switched-off states, respectively. With suitable switch-off anodization current (R of 30%), the barrier layers could be properly removed and Si surfaces could be left with slight anodization or as bare Si surface after AAO fabrication. Therefore, selective growth was favorable with these surfaces, which induced a dense of high crystalline Si NW inside dielectric nanochannels. The effective carrier lifetime obtained from the Si NW embedded with AAO fabricated with R of 30% generated under injection level of 2.5×10^{13} cm^{-2} is roughly three and fifty times higher than that with R of 15% and 40%, respectively. Interestingly, the effective carrier lifetime of Si NW with R of 30% drastically increased upon post-deposition anneal, yielding a record effective carrier lifetime of 228 ± 22 µs under thermal treatment at 650 °C. These results confirmed that the AAO is highly effective for passivation of Si NW. Si NW solar cells embedded with AAO fabricated with R of 30% was produced. Before a-Si deposition, the samples were thermally treated at 650 °C. The Si NW solar cells subjected to post-deposition anneal of

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650 °C exhibited an efficiency 20 times higher than that without thermal treatment. This confirmed the validity of the impact of thermal treatment on opto-electronic characteristics of Si NW embedded with AAO. However, the performance of the Si NW solar cell was limited because of insufficient contact between the Si nanowires and a-Si thin film. A simple solution imposed was to increase the growth time of Si nanowires in order to increase the length of the Si NW; this yielded the three times higher efficiency. The Si NW embedded with AAO template demonstrated a potential candidate for fabrication of highly efficient solar cells.

2. Experiment

The experimental procedures of for producing Si NW by selective growth and fabrication of Si NW solar cells are described in Fig. 1(a). The detailed procedures have been described in previous studies [11–14]. As a key mechanism for precise termination control, a cooling system was used to reduce the anodization rate once consumption of Al is empty. The aluminum thin film acts as the anode onto water block (cold plates) whereas the Pt filament acts as the cathode. The water flowing into the cold plates was maintained at 1 °C. The anodized current as a function of time was recorded using power supply (Keithley 2400) combined with a computer. The anodization process was switched off at current ratios R of 15%, 30%, and 40%. The current ratio R is limited to 40% to avoid detachment of AAO template from the Si substrate.

Regarding selective growth assisted by the AAO template, a gas source MBE system (Air-Water VCE S2020) using Si_2H_6 was used to grow Si nanowires. The optimized growth conditions comprising the growth temperature of 800 °C, Si_2H_6 flow rate of 0.5 sccm, and growth time of 90 min was employed. To improve contact of the Si NW, the growth time was increased to 120 min. Before epitaxial growth, the surface oxide was etched with 1% HF for 10 s at room temperature. After MBE growth, scanning electron microscope (SEM) (Hitachi, SU8230) was used to investigate the morphology of the Si NWs before and after removal of the AAO template. The carrier lifetime measurements were carried out using microwave photo-conductivity decay (μPCD) method (KOBELCO, LTA1512EP) with incident-source wavelength of 349 nm, frequency of 10 GHz and injection level of 2.5×10^{13} cm^{-2}. To reduce the recombination effect atop the Si nanowires, the as-grown samples were passivated by alumina thin film using thermal atomic layer deposition (ALD). In this study, the abbreviation

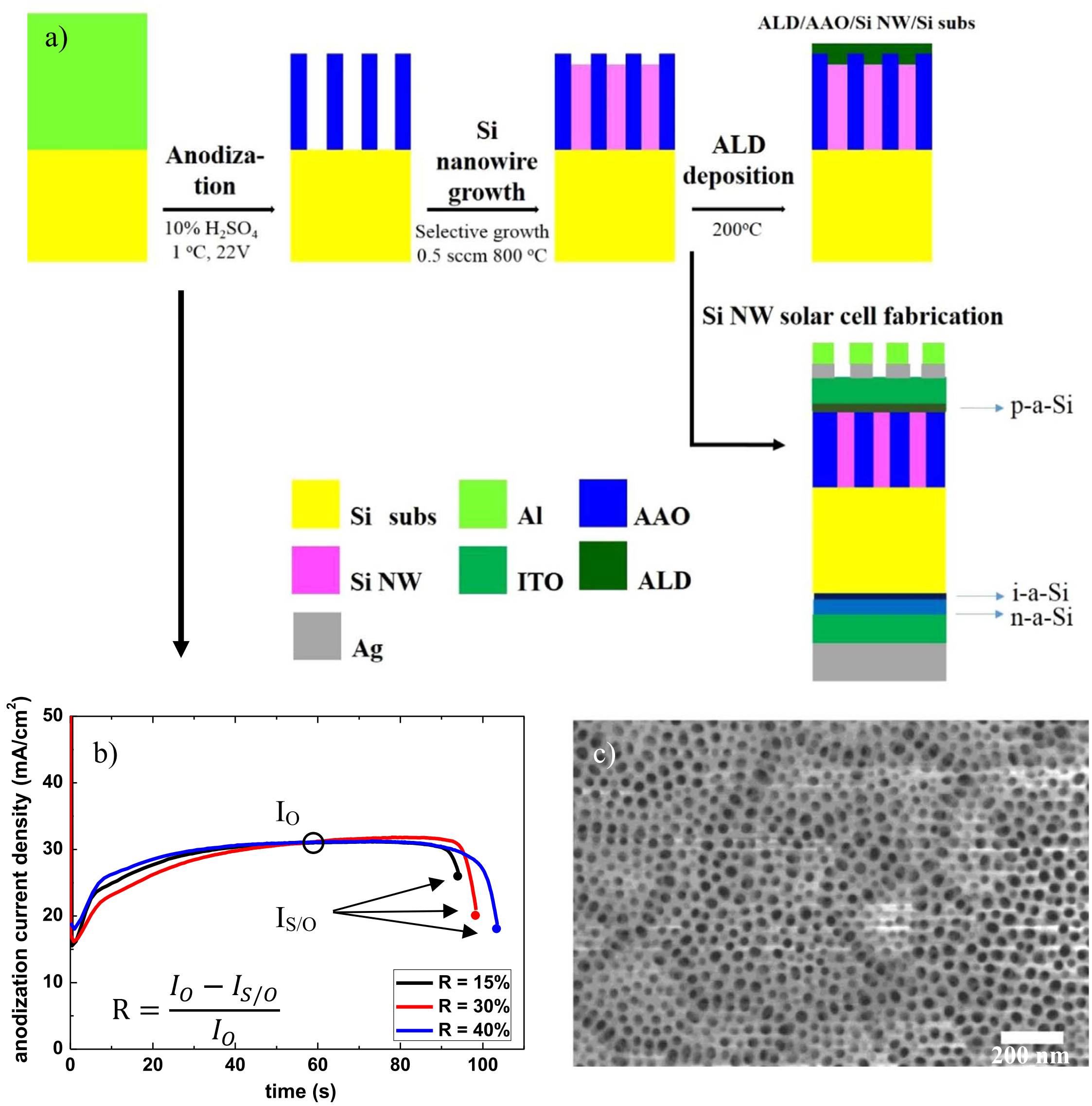

Fig. 1. a) Experimental process of Si nanowire growth assisted with AAO template using selective growth techniques for carrier lifetime measurements and fabrication of Si nanowire solar cell; b) Anodization current density in function of time at current ratio R of 15%, 30% and 40%; c) Top-view SEM of AAO template fabricated with two-step anodization process despite of R.