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Research Paper Engineering

Application of Silicon Nano Structures Thin Films in Optical Sensing

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ABSTRACT

Oxidized silicon nano structures thin films were prepared by rapid-thermal oxidization of silicon nano structures films that were formed on Si substrates with an anodization technology. These films exhibited high responsivity for incident ultra-violet (UV) light with wavelengths between 300 nm and 400 nm. Under illumination of incident 350 nm UV light and 5 V bias, results indicate that the silicon nano structure thin films have significant potential for applications of UV optical-sensing devices.

KEYWORDS : Optical sensing, gas sensor, Synthesis of Silicon Nanostructures

INTRODUCTION:

Silicon nano structures have many unique features, such as extremely large surface-area-to-volume ratio, high resistivity, and modulated energy band-gap, silicon nanostructure is suitable for the development of sensors, such as photo-detectors [1, 2]. Silicon nanostructure photodiodes with quite high photo-responsivity and quantum efficiency have been reported [3–5]. However, the photo-responsivity of these silicon nanostructures based optical sensing devices is limited to the visible and near infrared ranges, and there are few studies on using silicon nanostructures materials for UV detection. For effective UV sensing, the optical band gap energy (Eg) of a material has to be larger than 3eV. According to Pavlikov et al. [6], the pole sizes must be reduced down to less than 2 nm for silicon nano structures to reach this Eg value, and it is difficult to get such small sizes of uniform silicon nanostructures layers from traditional anodization methods. Recently, silicon-rich oxide (SRO) had received much interest in the field of optical-sensing devices, because of its high UV photoconductive properties [7, 8]. Photo-induced carriers transport this material by a multi-tunneling process between silicon and silicon-oxide nano-particles to generate a photocurrent. As a silicon-based oxide, the oxidized silicon nanostructure that forms from oxidizing silicon nanostructure films has greater sensitivity than its unoxidized counterpart [9, 10]. Unfortunately, the UV responses of these silicon nanostructures based devices thus produced are also poor. It is thought that the pole sizes in these structures of the silicon nanostructures are not small enough to get a large enough band gap to absorb UV light. Silicon nanostructure is a wide-band gap semiconductor and is a good candidate for applications in short-wavelength photo-detectors [11]. By oxidizing silicon nanostructure, a material with nano-structures similar to those of (SRO) can be obtained. This oxidized silicon nanostructure is composed of silicon and silicon-oxide nano-particles in the silicon nanostructures. In this work, we reported the preparation of oxide silicon nanostructure thin films on Si substrates and develop silicon nanostructure based photodiodes to explore their potential applications in UV photo-detectors.

2. EXPERIMENTAL WORK:

Silicon nanostructures films were prepared on heavily doped p^+-type (100) Si substrates with resistivity of 5mΩ cm and an area of 1cm^2 by an electrochemical anodization method. Samples were anodized in HF–ethanol solution in a Teflon cell with a Pt electrode as shown in figure 1.

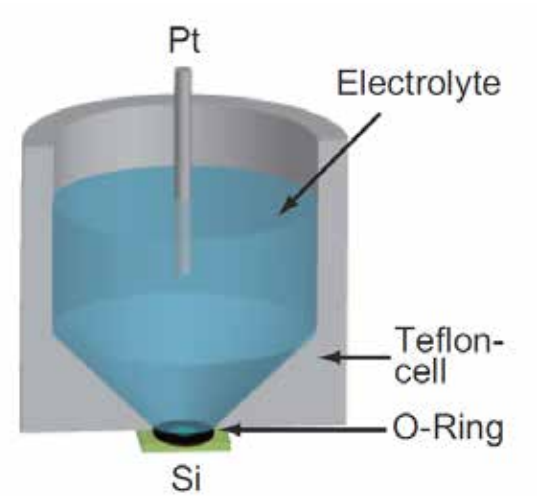

Figure 1: Schematic diagram of the etching system used in this work.

The anodization parameters for the preparation of silicon nanostructures are listed in Table 1. To obtain silicon nano-structured, a low etching current density of 10mA/cm^2 was used during the anodic process. The HF concentration of the etching solution was set as the main variable parameters to control the sizes and distribution of Si nano-particles in the silicon nanostructure films for samples 1, 2, and 3 respectively. If the HF-concentration is increased to more than 30% that form will be too fragile and prone to peeling from the Si substrates. Oxide silicon nanostructures films were obtained from rapid-thermal-oxidation (RTO) treatment of silicon nanostructures at 850 °C for 90 s in O_2. To achieve the aims of both higher reproducibility and smaller particle-sizes, Sample 4 was obtained from Sample 3 after an RTO process, as shown in Table 1. The silicon nanostructures based photo-sensing devices were fabricated by depositing aluminum (Al) inter- electrodes on the tops of the developed oxide silicon nanostructure thin-films to form metal–semiconductor–metal photodiodes. The morphological analysis of prepared films was undertaken using a field emission scanning electron microscope (FE-SEM) (JEOL; JSM-6701F) operated at 10 kV. The photo-responses characteristics of the oxide silicon nanostructure devices were measured with a spectrometer (TRIAX-320) and a potentiostat meter (AUTOLAB; PGSTAT12).

Table 1

Anodization parameters for preparation of silicon nanostructures thin films in this work (an etching current density of 10mA/cm^2 is used for all samples (1 to 3) and Sample 4 was obtained from the rapid-thermal-oxidation (RTO) treatment of Sample 4.

NO	Solution concentration (HF:Ethanol)	Etching time	Post-treatment
1	(10%)	5 min	Without RTO
2	(20%)	5 min	Without RTO
3	(30%)	5 min	Without RTO
4	(30%)	5 min	With RTO

RESULTS AND DISCUSSION

Figure 2 shows the top views of the SEM images of the formed silicon nanostructures and oxide silicon nanostructures thin-films on Si substrates with the preparation parameters listed in Table 1. The thickness of the as-formed layers is about 3 μm. It can be seen in the figure that uniformly distributed Si nano-particles were formed on Si substrates. Average sizes of Si nano-particles were estimated to be about 25nm, 10 nm, and 6 nm in diameters for Samples 1, 2, and 3. It can be seen that the size of the Si nano-particles of silicon nanostructures decreased as the HF-concentration increased in the etching solution. The SEM surface image of Sample 4 that was prepared by oxidizing Sample 3 is shown in Fig. 1 (b). Compared to Sample 3 in Fig. 1(a), the average particle-sizes increased to about 11 nm after RTO treatments. The oxide silicon nanostructures formed may be assumed to be composed of a core Si nano-particle embedded in silicon oxide. Because growing an oxide of thickness x consumes a layer of silicon 0.44x thick [12], the average size of the core Si nano-particle can be estimated to be about 2 nm, which is a quantum size corresponding to the band gap energy of 3 eV.

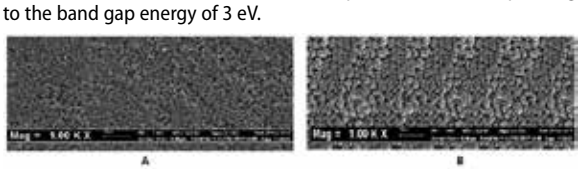

Figure 2. The SEM images of top views of Si nano-sturctures films after anodization (a)without RTO,(b)with RTO

The photo-response spectra of sample 3 and sample 4 are shown in Fig.3. The photo-response spectra of the silicon nanostructures film (Sample 3) is mainly located between 500 and 900 nm, corresponding to the visible to near infrared (NIR) ranges, with a maximum responsivity of about 60 mA/W at 750nm. There were comparatively small responses appearing in short-wavelength ranges of 200–400 nm for the silicon nanostructure samples due to the native silicon-oxide in the silicon nanostructure layer, and this indicates that the UV detection ability of the silicon nanostructure films is unsatisfying. In contrast, the oxide silicon nanostructures sample (Sample 4) exhibited considerably high photo responsivity between 300 and 400 nm with a maximum responsivity of 130mA/W at 350nm. This high UV responsivity is due to the silicon-oxide nano-particles in the oxide silicon nanostructures layers, which had band gap energy greater than 3eV and thus were able to effectively absorb UV light of (300–400) nm. UV photons were absorbed by silicon-oxide nano-particles to generate photo-carriers. The photogenerated carriers then transported through the oxide silicon nanostructure layer by multi tunneling between the Si-embedded silicon-oxide nano-particles to provide the photocurrent. The optical band gap energy of the developed oxide silicon nanostructure films can be extracted from [13]: $(\alpha h\nu)^{1/2}=A(h\nu-Eg)$, where α is the absorption coefficient, hν is the photo energy, and A is a constant, the optical Eg of the oxide silicon nanostructures films is estimated to be about 3.5eV, corresponding to a photon wavelength of 350nm. This result conforms to that of the measured photo-response spectra. In addition, the reflectivity of the silicon nanostructures films decreased from 20% to about 8% after RTO treatment. This reduced reflectivity raised the light-absorption efficiency, thus also helping to enhance the photo-responsivity of the oxide silicon nanostructures films.

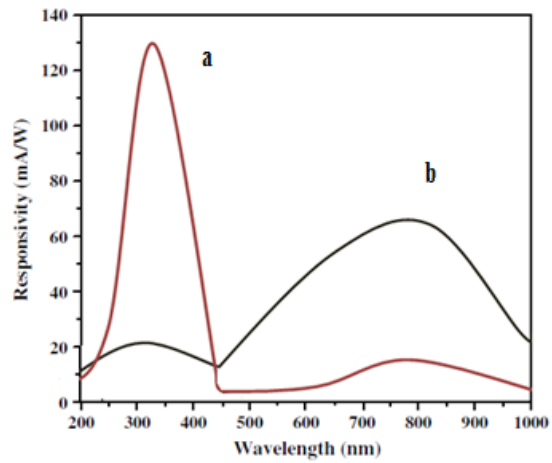

Figure 3. Photo-response spectra of photodiodes based on silicon nanostructures films (a) with RTO, (b) without RTO.

Conclusions

Silicon nanostructure films with uniformly distributed Si nano-particles were obtained from p+-Si substrates by an electrochemical anodization technique, in which a high HF concentration solution and low etching current density were used to control the sizes and uniformity of the nano-particles. Oxide silicon nanostructure films were then formed from the rapid thermal- oxidizing treatment of silicon nanostructures in an O_2 ambiance at 850 °C for 90s. These experimental results reveal that oxide silicon nanostructure has very high potential for the development of UV optical-sensing devices.

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