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Rapid thermal-treated transparent conductor on microscale Si-pillars for photoelectric applications

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ABSTRACT

Various silicon (Si)-pillars were designed to modulate surficial lengths for high-performing photodetectors. An electrically conductive and optically transparent indium-tin-oxide (ITO) was coated on Si-pillars to form heterojunction devices. A rapid thermal treatment significantly improves the transparency of an ITO film with a better crystal nature. Si-pillar structures are effective to reduce light-reflection and spontaneously increase Si surficial lengths. An enhanced light-reactive Si surface simultaneously enhances the photo-responses. We found that pillar designs are also efficient to suppress a leakage current. This demonstrates an efficient approach for high-performing photoelectric devices at a low thermal budget.

1. Introduction

A photodetector is one kind of photoelectric devices of conversion between electrical energy and light. Film-based photodetectors need a bias voltage to operate, which easily increases leakage current values, resulting in reduction of photoresponses [1–6]. We may consider optical and electrical aspects to improve photoresponses of photodetectors as follows.

Light-absorbing semiconductor can be tailored into a pillar, which is an attractive platform to increase the light-reactive area of the semiconductor material [7–9]. Moreover, a pillar structure is also effective to reduce the light reflection at a surface; therefore more photons can be delivered into a Si substrate at a certain amount of incident photons [10].

Transparent conductive oxide (TCO) material is essential to most photoelectric devices, which convert electric energy into light, or vice versa. A TCO/semiconductor contact spontaneously forms a heterojunction without an intentional doping, therefore this would provide an advantage for fabrication processes and cost reduction [11]. The front TCO film directly affects the qualities of TCO/semiconductor heterojunction devices in the aspect of rectifying current profiles. A low-thermal process is highly desirable for flexible electronics applications [12].

A heterojunction device employs different material species to form a junction. Due to different work functions, Si and TCO contact can form a heterojunction and establish an electric field in a junction, which is a driving force to collect photo-generated carriers from incident photons. In the aspect of light utilization, a transparent front-TCO layer is absolutely beneficial to drive more incoming photons to Si. Moreover, electrically conductive TCO may remove the requirement of voltage-bias for photodetectors [11].

Each topic is imported to design the efficient photodetectors, however, few researchers have reported for combining of structural designs and device analyses. In this work, we report high-performing TCO/Si-pillar heterojunction photodetector, working at zero bias. Different Si-pillar structures were prepared to modulate the light-reactive surface. A thin indium-tin-oxide (ITO) film was coated on Si-pillar structures at a room temperature (RT) and rapidly thermal-processed to achieve a high quality ITO film/Si heterojunction. We realized a high-performing ITO/Si heterojunction photodetector at a low thermal budget. We demonstrated that photo-responses can be enhanced along to the increase of light-reactive Si surface.

2. Experiment procedures

Si-pillar arrays were fabricated by photolithography technique. A 4-in. p-type Si wafer, having a resistivity of 1–10 Ω cm, was used as a substrate. Prior to an etching process, photoresist (PR) patterns were prepared to modulate Si-pillar geometries. Three-different PR masks were developed on a Si substrate, in variation of a width and a period. After then, ion-etching process was performed to have a depth of 1.1 μm. During this procedure, pre-patterned PR mask served as an etching-barrier.

A thin ITO film was deposited over Si-pillars by a dc sputtering method at RT. This spontaneously induces a heterojunction of ITO

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and Si-pillars. In order to improve the RT-deposited ITO film, a rapid thermal process (RTP) was performed at 300 °C for 5 min under a vacuum condition. A field emission scanning electron microscopy (FE-SEM, FEL Sirion) was used to observe the patterned Si-pillar structures. An interface between an ITO film and a Si substrate was analyzed by a transmission electron microscopy (TEM, JEM-ARM200F, JEOL). The crystallinity of ITO films (Before and after RTP) was examined by X-ray diffraction (XRD, X'Pert, PANalytical) with Cu-*K*α radiation in 2*θ*. The optical property of ITO thin films was measured by a UV–vis–NIR spectrometer (V-570, JASCO). A quantum measurement system (McScience, K3100) was employed to monitor photoresponses. A pulsed light (1 mW) was exposed to a device. The photoresponse was obtained using the light-illuminated current value over the light-off current value.

3. Results and discussions

Various Si-pillars were periodically formed using the PR-mask patterns. From the cross-sectional SEM observations, we can define geometries of different Si-pillar structures. In Fig. 1(a), Si-pillars have a width of 1.7 μm in a period of 3.95 μm. This structure can be notated as 1.7/3.95 Si-pillars and referred as P1. Similarly, P2 and P3 represent 4.84/7 Si-pillars and 4.55/9.86 Si-pillars, respectively, as shown in Fig. 1(b) and (c).

To form a heterojunction, a thin ITO film (80 nm) was deposited over Si-pillars at a RT. We investigated the improvement of ITO film crystallinity by TEM and XRD for RTP effect. From TEM images (Fig. 1d and e), we can clearly distinguish an ITO layer on Si with a native SiO_x-layer at an interface. RT-deposited ITO (RT-ITO) film was initially amorphous (Fig. 1d). However, RTP-treated ITO (ITO-RTP) effectively formed the crystalline structure (Fig. 1e). This improved crystallinity was identified from XRD profiles (Fig. 1f), to specify the advantages of RTP treatment. No noticeable diffraction peaks were obtained from the RT-ITO film. Meanwhile, significant crystalline peaks were appeared from the RTP-ITO film. The strongest peak was detected at 30.6° and all other peaks were indexed to Sn-doped In_2O_3 phase (ITO, JCPDS card no. 71-2194).

In order to investigate the optical transparency, ITO films were deposited on glass substrates. One glass sample was prepared for as-deposited condition (RT-ITO) and the other was RTP-treated (RTP-ITO). The RTP-treatment was efficiently improved overall transmittance for broad wavelength (λ) range, as shown in Fig. 2 (a). For a comparison, we obtained the average transmittance values (ATV) in the range of 300 nm $\leq \lambda \leq$ 1100 nm. The RT-ITO film gave an average transmittance value of 69.7%. Meanwhile, a much improved ATV value (80.4%) was obtained from the RTP-ITO film. This mostly attributes to crystallization of the ITO film after RTP-treatment. It is possible to think that more photons can be delivered through a crystalline ITO film than does so through an amorphous ITO structure.

Besides the optical property of ITO, the Si-pillar structures also influence the light behaviors at a surface, where the incident light interacts with Si-pillars. The Si-pillar structures are directly related to the light reflection (Fig. 2b). We have measured the average reflectance value of P1, P2 and P3, corresponding to 13.99%, 15.59% and 13.82%, respectively. This reflectance reduction effect can be inferred from the Si-pillar structures. In order to evaluate the surficial changes of Si-pillars, we obtained the enhancement of a surficial length on the base of a reference length (100%) for flat Si, as shown in Fig. 2(c). We can obtain the surficial length enhancement of 156.0% for P1, 131.7% for P2 and 122.6% for P3, respectively. Generally, we can consider the surface area by squaring the surficial length. Thus, each Si-pillar has different heterojunction surface area. P1 has the largest value of the surface area (Table 1).

In order to fabricate heterojunction devices, metal electrodes (Al) were deposited on a front and a back side. To examine the enhanced surface effect, we measured current–voltage (*I–V*) profiles under dark condition, as shown in Fig. 2(d). Each heterojunction generally showed a rectifying current flow. However, current amounts are different for each Si-pillar structures. To quantify current flows, a rectifying ratio was obtained by comparing a forward current (I_F) value (at +0.5 V) over a reverse saturation current (I_{RS}) value (at −0.5 V). A rectifying ratio tends to increase with respect to Si surface enhancement (Table 1). It is very noticeable the decrease of I_{RS} values as the Si surface increases. This is very interesting results to observe that Si-pillar structures

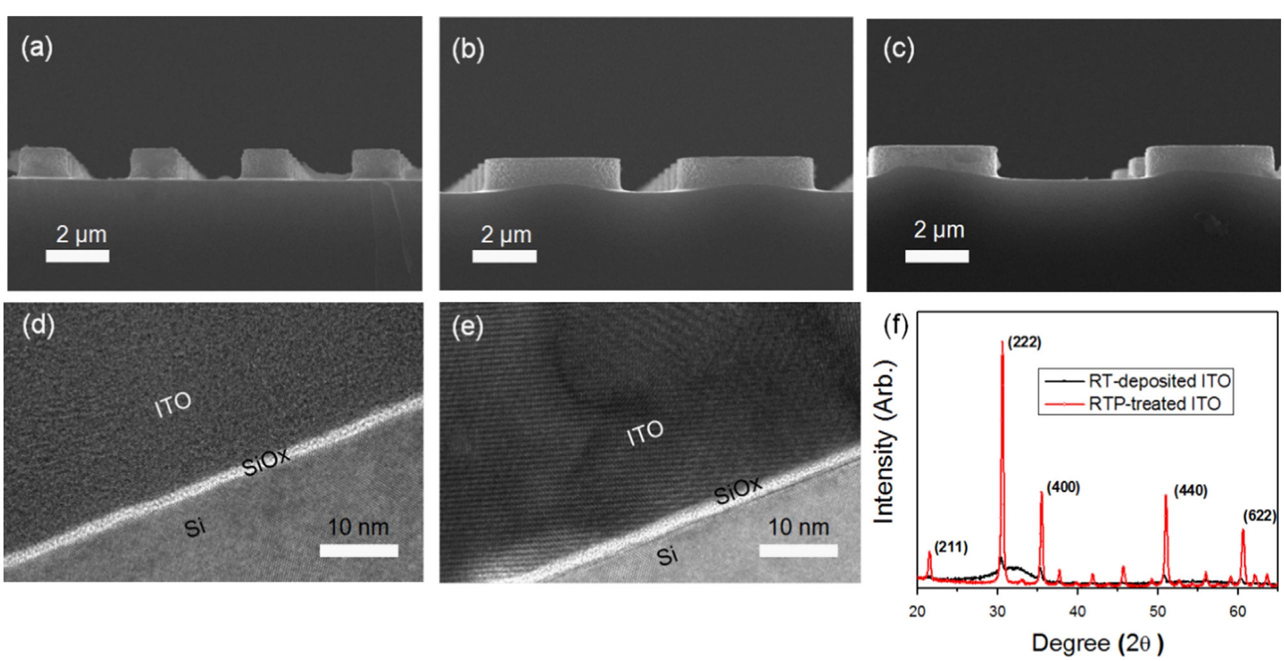

Fig. 1. SEM images of (a) P1, (b) P2 and (c) P3. TEM images of (d) RT-ITO film and (e) RTP-ITO film. (f) XRD profiles of ITO films.