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Fabrication of an ultra-thin silicon solar cell and nano-scale honeycomb structure by thermal-stress-induced pattern transfer method

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ABSTRACT

A 3 μm thick silicon layers with nano-scale honeycomb structure on the surface were fabricated using the mask-less process, "Thermal-stress Induced Pattern Transfer method". The thin silicon layer was deposited on a patterned sapphire substrate with nano-scale pyramids, followed by a metal layer printing on the top of the thin silicon layer. After thermal treatment, a thin silicon layer was peeled off from the patterned sapphire substrate and was transferred to the metal layer. Meanwhile, the periodic patterns on the sapphire substrate were transferred to the thin silicon layer forming the honeycomb structure on the surface of the silicon layer. The whole process was operated at a low temperature below 250 °C without any mask process. Finally, the solar cell was fabricated on the silicon thin layer and its performance was measured. The short circuit current density is 0.11 mA/cm^2.

1. Introduction

Light trapping is an important factor for solar cell [1]. The solar cell energy transfer efficiency depends on the amount of light capture. Therefore, it is important to increase the light absorption and reduce the light reflection. Conventional silicon solar cells are generally textured by an alkali or an acid solution to form the surface roughness for reducing the reflection losses and improving light trapping [2]. Recently, the honeycomb structure has been proven to have a better light trapping effect than that of the conventional random pyramid structure. The honeycomb structure has a great potential on the application of the solar cell [3]. However, complicated processes including photolithography procedure and etching step are needed to fabricate the honeycomb structure on the silicon substrate [4,5]. This doesn't meet the requirements of the low cost and the high throughput for the industrial production. Alternatives such as nanoimprint lithography [6] or colloidal lithography [7] are cheaper than photolithography process but still complicated for mass production. The Mitsubishi electric corporation used wet etching process to get the honeycomb structure on silicon wafer without photolithography [8,9]. However, a mask process of SiNx deposition and laser opening was still needed.

On the other hand, the silicon substrate takes almost 50% of the whole cost in the production of the silicon solar cell [10]. The production cost can be effectively reduced by the reduction of the thickness of the silicon substrate. A thinning wafer technique can significantly reduce the cost of silicon material during slicing process, including SLiM-Cut [11,12], Smart cut [13–15], and macroporous lift-off method [16,17]. However, if we want to produce solar cells with such wafers, it is difficult to texture such a silicon substrate, especially when it becomes thinner and thinner.

In the present work, a mask-less procedure, combining the texturization and lift-off process in one step, was developed to obtain the honeycomb structure on the silicon surface. The Thermal-stress Induced Pattern Transfer (TIPT) method, for which silicon thin film was deposited on pattern sapphire substrate (PSS) and the honeycomb structure was transferred to the silicon film from the PSS directly [18]. It is a cheaper process because the TIPT method is a mask-less process that could obtain thin silicon films at the same time and need no further texturization process. The sapphire substrate could be recycled and reused again. Solar cells were fabricated on the TIPT silicon thin layer and discussed.

2. Experimental details

Fig. 1 shows the experimental process of fabricating the thin silicon solar cell with a honeycomb structure by the TIPT method from sapphire substrate in this study. The 2 inch sapphire substrates with nano-scale pyramid-like structure (Aurotek Corp. Taiwan) were used as the substrates. A 3 μm of p-type microcrystalline silicon layer was deposited on the sapphire substrate surface using SiH_4 and H_2 as the reacting gas by plasma enhanced chemical vapor deposition (PECVD) system. The deposition temperature and the working pressure were 200 °C and 67 Pa, respectively. The silver paste (DuPont PV-412) was printed on the silicon layer immediately after the silicon film deposition. A thermal treatment was carried out to enhance the adhesion between a silver paste and a silicon layer. After thermal treatment, the silicon–metal composite layer was formed with a thickness of ~25 μm and was peeled off from the substrate. An intrinsic layer and n-type emitter layer were

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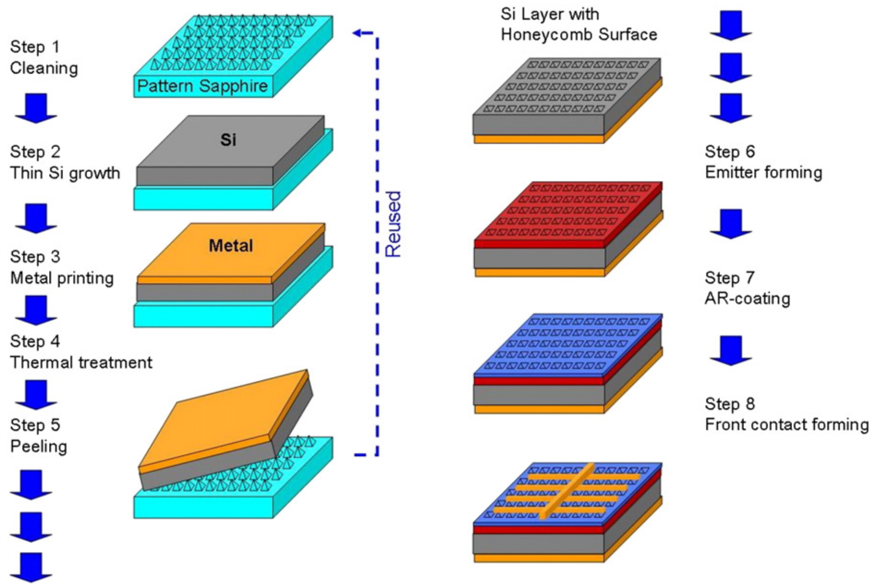

Fig. 1. Process flow diagram for the solar cell made from TIPT method.

sequentially deposited on the silicon–metal composite layer by PECVD. An indium tin oxide (ITO) layer with a thickness of ~80 nm was deposited as the anti-reflection layer. A silver grid electrode layer, defined by a shadow metal mask, was sputtered on the ITO layer with a thickness of 200 nm. A 4 cm^2 solar cell with 3 μm thickness was obtained in the final step.

Scanning electron microscope (SEM, model JEOL-5400) equipped with an energy dispersive X-ray spectrometer (EDX) was utilized to observe the surface morphology and characterize the composition of the silicon layer, respectively. The accelerating voltage and working distance of SEM and EDX were 10 kV and 10 mm, respectively. The energy conversion efficiency of the solar cells was measured by a solar simulator system (QuickSun 120CA, Endeas Co.)

3. Results and discussion

3.1. Thin silicon wafer and solar cell

For the thin silicon solar cell production, a 4-inch polished sapphire substrate was used to prove the concept of TIPT method at the early stage. After thermal annealing at 250 °C, thin silicon layer was combined with the silver paste and peeled from the sapphire substrate as shown in Fig. 2. Fig. 3 is the EDX analysis result of a peeled silicon layer. It shows that the silver atoms were detected in the silicon layer, suggesting that silver atoms diffused into the silicon layer during a thermal annealing process. These silver atoms in the silicon layer will become the recombination center for minority carriers and further decrease the efficiency of the solar cell. It is known that the diffusivity of the silver in the silicon is $D = 2 \times 10^{-3} \exp(-1.6\,eV/RT)$ [19]. The temperature of thermal treatment process must be lowered to prevent the silver atoms from diffusing into the silicon layer.

For the purpose of reducing the temperature of thermal treatment process, a thermal-setting conductive silver adhesive (Polychem UV/EB International Corp.) was used as the metal layer instead of DuPont

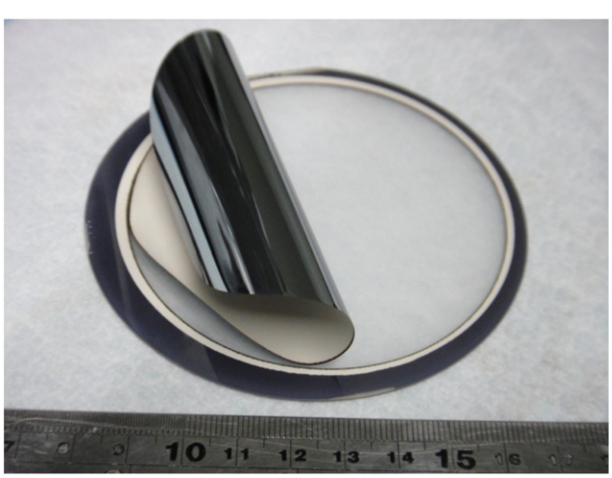

Fig. 2. A 4 inch TIPT sample peeled from polished sapphire substrate.

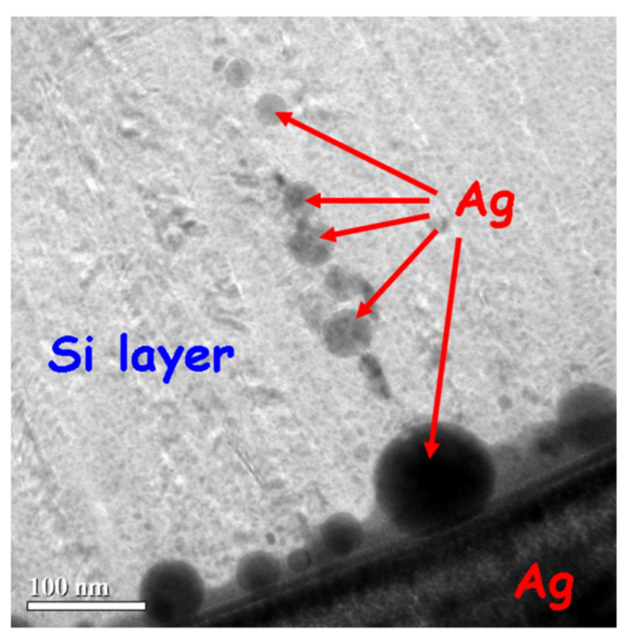

Fig. 3. SEM picture of thin silicon layer peeled from sapphire substrate with annealing temperature at 250 °C.