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Improvement of conversion efficiency of multi-crystalline silicon solar cells using reactive ion etching with surface pre-etching

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ABSTRACT

In this study, a large-area (156 × 156 mm^2) sub-wavelength antireflection structure has been fabricated on multi-crystalline Si substrates to reduce their surface reflectivity. A reactive ion etching (RIE) system was used to fabricate nanostructures on the multi-crystalline silicon surface. Reactive gases, comprised of chlorine (Cl_2), sulfur hexafluoride (SF_6) and oxygen (O_2), were activated to fabricate nanoscale pyramids by radio frequency plasma. The pre-etching of poly-Si substrates using acidic and alkaline solutions was studied for creating the microstructures, which may affect the subsequent formation of nano-structures by RIE. Both the solar reflectance and the effective carrier lifetimes of multi-crystalline Si surface are measured to understand the effects of two pre-etching solutions. The pre-etching of silicon wafers using the acidic solution before RIE was found to improve the solar cell efficiency better than that using the alkaline solution. The absolute efficiency of solar cells with acidic pre-etching and RIE texturing can be improved by 0.64% over the traditional conventional cells.

1. Introduction

Solar cell has been pursued as one of the most promising technologies in recovering solar energy, regarded as the most important alternative energy source currently available. The multi-crystalline silicon solar cell is considered to be a promising cell capable of achieving high efficiency at a low cost. However, the technical barriers to be overcome remain high. Especially, the energy loss due to reflection and transmission of the incident light has to be reduced to increase solar cell efficiency. An antireflective surface on the front side of solar cells is often needed to improve the light absorption efficiency.

Many approaches have been used based on isotropic wet acidic etching [1–2]. Substrates with nanowires [3–4], nanopillars [5] and nanodomes [6] are used to effectively reduce the reflection and increase light trapping. Therefore, several other methods have been developed to texture the mc-Si wafers in recent years including laser texturing [7], mechanical V-groove texturing [8] to reduce light reflection have been widely proposed and studied. Although a variety of masked or maskless reactive ion etching (RIE) texturing for fabricating anti-reflection nanostructures [9–18] have been studied, the technology to provide us extremely low reflection and low cost production is still under study. RIE can be utilized to create nanostructures on surface of multi-crystalline Si wafers using plasma and reactive gas can considerably reduce surface reflectance and provide excellent light trapping. However, the decrease in light reflectivity does not necessarily guarantee the improvement of solar cell efficiency. In this paper, the maskless RIE in combination with acidic pre-etching (i.e. acid solution + RIE) or alkaline pre-etching (i.e. alkali solution + RIE) are adopted for the front-side texturing. This study is aimed at identifying the pre-etching conditions for creating the appropriate microstructures for further coupling with the nanostructures created by RIE process to achieve extremely low reflection, in order to optimize the process suitable for the mass production of high efficiency solar cells.

2. Experimental details

In this study, B-doped multi-crystalline silicon (mc-Si) substrates were used to fabricate anti-reflection nanostructures by RIE process. Before RIE texturing, two kinds of pre-etching processes were investigated including acidic (5 wt.% HF + 25 wt.% HNO_3) or alkaline (20% KOH) pre-etching processes, respectively. After the pre-etching process, the substrates were immersed in HF solution ($HF:H_2O = 1:1$) to remove SiO_2 layer and then cleaned with DI water. The fabrication of nanotextures or nanostructures on the surface of the silicon substrate was achieved by RIE process, in which the plasma is generated by applying an RF power to the substrate electrode at a frequency of 13.56 MHz. The RF power applied to the substrate induced a negative dc self-bias on the substrate. The gas reactants used in the RIE process comprised chlorine

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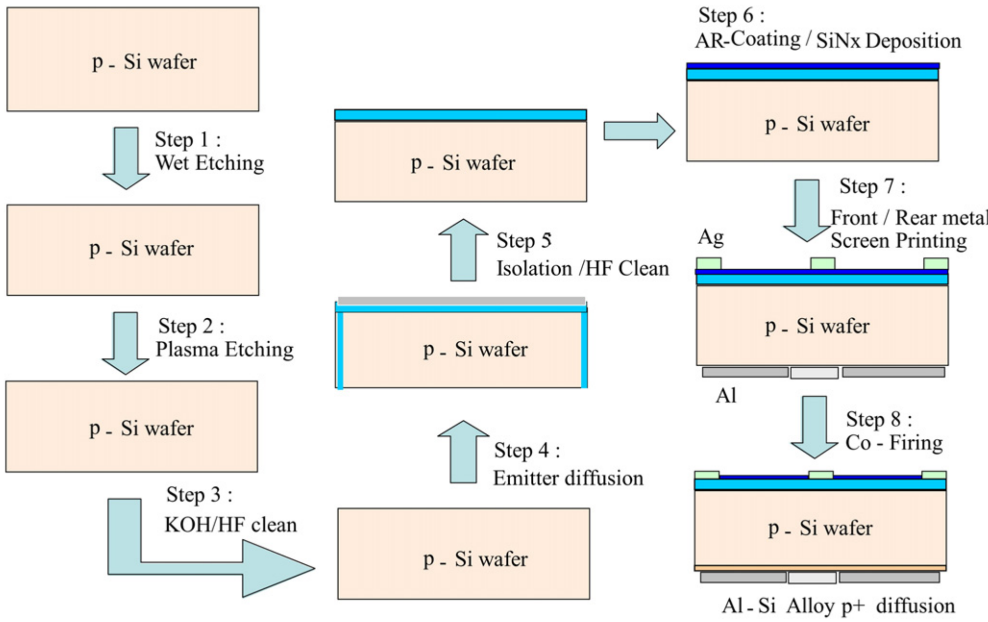

Fig. 1. The fabrication process of solar cell devices.

(Cl_2), sulfur hexafluoride (SF_6), and oxygen (O_2). In order to investigate the effects of the pre-etching on the effective lifetime, symmetrical lifetime test structures were fabricated. After the RIE process, the mc-Si wafers were passivated by amorphous hydrogenated-nitride film (SiNx:H) deposited by plasma-enhanced chemical vapor deposition. The measurements of effective lifetime and surface recombination velocity were achieved using the Quasi-Steady-State-PhotoConductance method (Sinton WTC-120) in the generalized mode. The lifetime values reported in this work were extracted at a minority carrier density of 10^{15} cm^{-3}. The mc-Si solar cell fabrication with RIE using damage

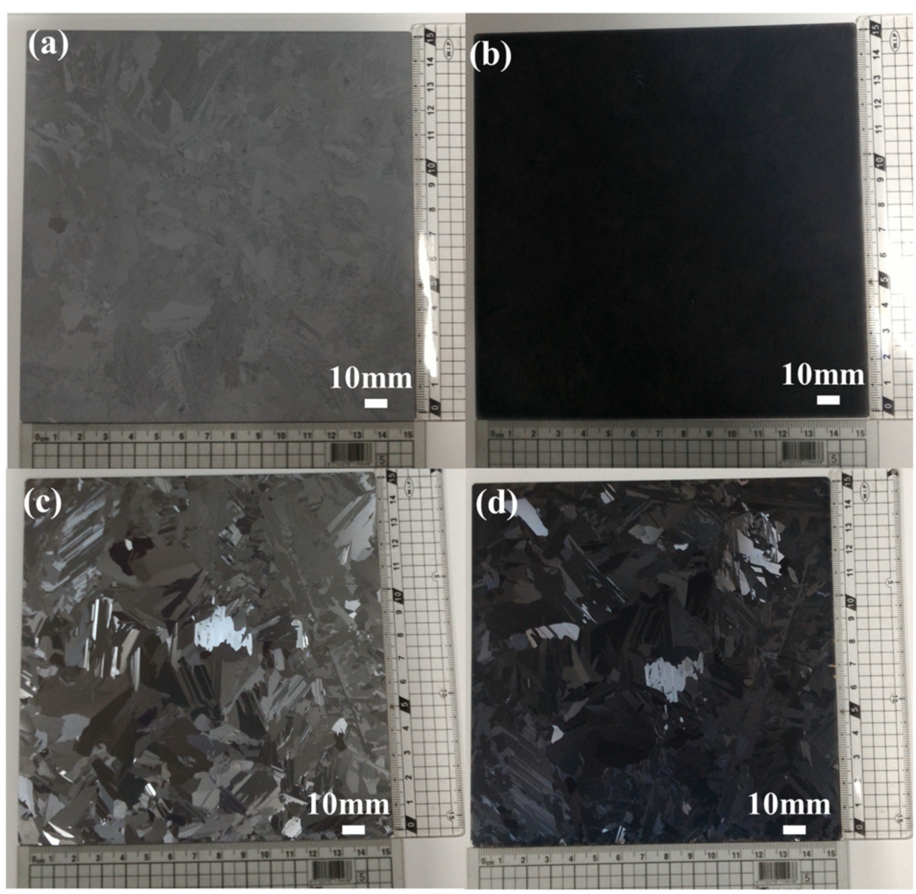

Fig. 2. The optical images of (a) is the original substrate with acidic pre-etching, (b) is the substrate with acidic pre-etching under optimized RIE process conditions (c) is the original substrate with alkaline pre-etching and (d) is the substrate with alkaline pre-etching under optimized RIE process conditions.