Comprehensive Study of SF_6/O_2 Plasma Etching for Mc-Silicon Solar Cells *

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The mask-free SF_6/O_2 plasma etching technique is used to produce surface texturization of mc-silicon solar cells for efficient light trapping in this work. The SEM images and mc-silicon etching rate show the influence of plasma power, SF_6/O_2 flow ratios and etching time on textured surface. With the acidic-texturing samples as a reference, the reflection and IQE spectra are obtained under different experimental conditions. The IQE spectrum measurement shows an evident increase in the visible and infrared responses. By using the optimized plasma power, SF_6/O_2flow ratios and etching time, the optimal efficiency of 15.7% on $50 \times 50\,mm^2$ reactive ion etching textured mc-silicon silicon solar cells is achieved, mostly due to the improvement in the short-circuit current density. The corresponding open-circuit voltage, short-circuit current density and fill factor are 611 mV, 33.6 mA/cm^2, 76.5%, respectively. It is believed that such a low-cost and high-performance texturization process is promising for large-scale industrial silicon solar cell manufacturing.

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Most commercial solar cells employ texturization and silicon nitride coating to achieve anti-reflection surface in the field of photovoltaic industry. Recently, reactive ion etching (RIE)[1−12] has attracted great attention for its low-cost, large-area and mask-less texturization property. As a kind of dry plasma etching process,[12−16] RIE has been widely performed in many fields. The optimized reflection spectra have been demonstrated on the four-inch mono-silicon wafers and $100 \times 100\,mm^2$ mc-silicon wafers by RIE.[4] A damage-free RIE texturing process has been developed and produced with 0.7% absolute efficiency (Eff) gain on $156 \times 156\,mm^2$ mc-silicon cells. The short-circuit current density (J_{sc}) has significantly increased while maintaining decent fill factor (FF) without an open-circuit voltage (V_{oc}) loss after the optimized sintering process.[2] Large-area mc-silicon solar cells have also been fabricated by optimizing the processing steps by using RIE and achieve excellent current–voltage characteristics. In addition, RIE also shows the possibility for fabricating the thin mc-silicon solar cells with low cost and high efficiency.[1] In this Letter, the optimized texturization for mc-silicon solar cells by mask-free SF_6/O_2 plasma etching is demonstrated. By adjusting the plasma power, SF_6/O_2 flow ratios and etching time, an optimized texturization is obtained with holes of only hundred-nanometer scale, which is obviously less than the fluctuations of the usual mc-silicon surface by wet acidic texturing. With the optimized the plasma power, SF_6/O_2 flow ratios and etching time, the optimal current–voltage characteristics due to the optimized texturization by SF_6/O_2 plasma etching is obtained. It is believed that such a low-cost and high-performance texturization process reported here is promising for large-scale industrial manufacturing and application of silicon solar cells.

The solar-grade p-type mc-silicon wafers of size $50 \times 50\,mm^2$ are used as the experimental samples. Figure 1 presents the complete fabrication sequence for mc-silicon solar cells by SF_6/O_2 plasma etching. After removing the saw damage by isotropic acidic etchants, the RIE based on SF_6/O_2 gases is carried out on mc-silicon wafers. In the conventional diffusion tube furnace, the $50\,\Omega$/emitter is obtained through 10 min diffusing at 850℃ and 20 min drive-in at 820℃. After edge isolation, the phosphosilicate glass (PSG) is removed by a solution composed of hydrochloric acid of 1% and fluohydric acid of 2%. The passivation and anti-reflection dielectric layer of SiN_x:H film with a refraction index of 2.03 and thickness of 80 nm is deposited by the plasma enhanced chemical vapor deposition (PECVD) system. Screen-printing is carried out to achieve the metallization of frontside and backside with aluminum paste and silver paste followed by the drying and co-firing in the in-line tube. By being processed parallel to the RIE cells, the conventional acidic textured referenced cells are used to compare the reflection spectra, current–voltage characteristics and IQE spectra.

Figure 2 presents the mc-silicon etching rate as a function of the plasma power. The etching rate increases significantly with the plasma power. The variance ratio decreases when the plasma power changes from the range of 100–300 W to the range of 300–500 W. This is due to the fact that more fluorine and oxygen ions are produced with the increase of the plasma power, resulting in a persistent increase of the etching rate. However, in the range of 300–500 W, the mean free path of the ions diminishes due to the increased amount of ions, resulting in the decrease of the variance ratio.[3] For the larger plasma power, the reflectance becomes higher due to the decreased

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anisotropic etching by the fluorine ions. In the blue-wave range, the IQE spectra are slightly lower than that of acidic texturing due to the surface damage caused by the RIE process. The obvious improvement of visible and red response of samples by plasma etching at the plasma power of 100 W could be observed, which is due to the better light trapping properties.

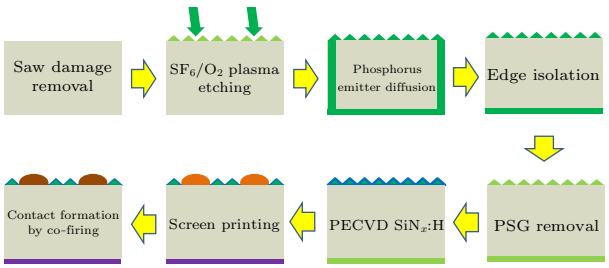

Fig. 1. The complete fabrication sequence for mc-silicon solar cells by SF_6/O_2 plasma etching.

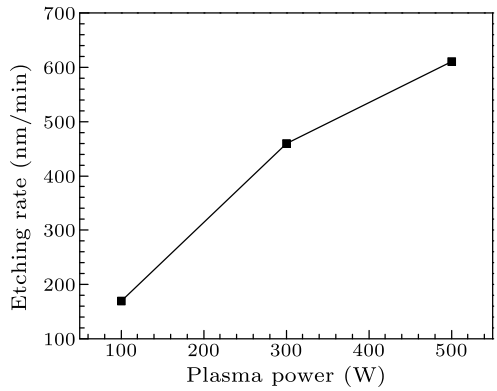

Fig. 2. Mc-silicon etching rate as a function of the plasma power.

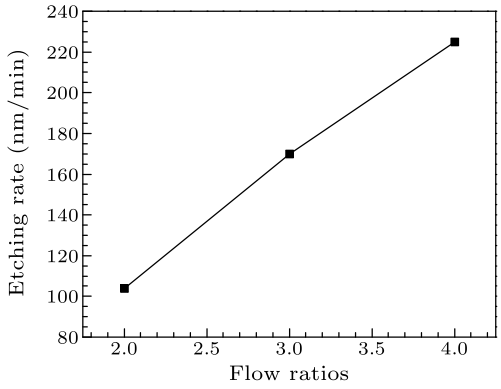

Fig. 3. Mc-silicon etching rate as a function of the SF_6/O_2 flow ratios.

Figure 3 presents the mc-silicon etching rate as a function of the SF_6/O_2 flow ratios. With the increase of SF_6 gas, the etching rate distinctly mounted up due to the enhancement of the free radicals of fluorine ions. The reflection spectra tend to become consistent in the wavelength range of 1000–1200 nm. When the flow ratios change from 2:1 to 3:1, holes become smaller, resulting in a lower reflectance. However, when the flow ratios further increase to 4:1, holes become larger in the much smoother surface, resulting in a higher reflectance. The increase of reflectance with the flow ratios changing from 3:1 to 4:1 indicates that the increased fluorine ions smooth the pre-etching surface. The IQE spectra of all the mc-silicon solar cells by SF_6/O_2 plasma etching show a better red response, indicating that more infrared light is coupled into the mc-silicon. The better visible and red responses of the IQE spectra of samples by plasma etching at the SF_6/O_2 flow ratio of 3:1 show that no degradation of the bulk diffusion length occurs. Therefore, the flow ratio of 3:1 is fixed for the further investigations. The SEM image of the etched mc-silicon surface at the SF_6/O_2 flow ratio of 3:1 and at the plasma power of 100 W is shown in Fig. 4.

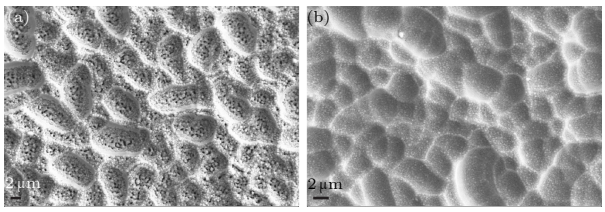

Fig. 4. SEM images: (a) the etched mc-silicon surface at the SF_6/O_2 flow ratio of 3:1 and at the plasma power of 100 W, and (b) acidic textured referenced cells.

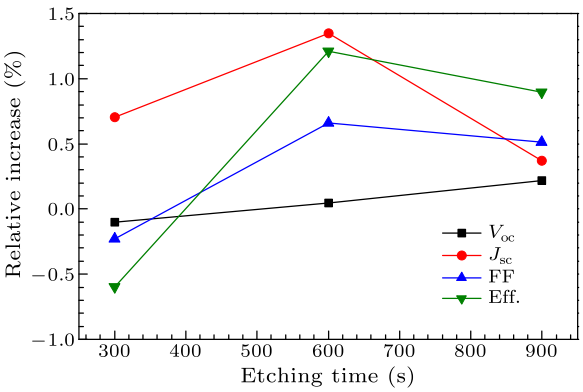

Fig. 5. The relative increase of the current–voltage characteristics as a function of etching time for mc-silicon solar cells by SF_6/O_2 plasma etching with acidic-texturing samples as a reference.

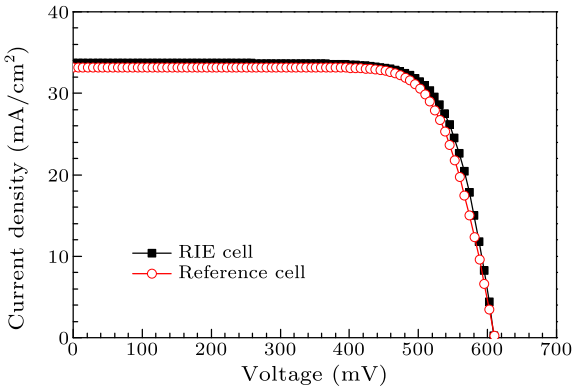

Fig. 6. The illuminated current–voltage characteristics of mc-silicon solar cells by SF_6/O_2 plasma etching with acidic-texturing samples as a reference (AM 1.5 G, 1000 W/m^2, 25℃).

Figure 5 presents the relative increase of the

current–voltage characteristics as a function of etching time for mc-silicon solar cells by SF_6/O_2 plasma etching with acidic-texturing samples as a reference. With the increase of etching time, V_{oc} increases all along, while J_{sc} and FF increase and then decrease. The increased etching time enhances light trapping properties, while it also causes the surface damage to some extent. The surface damage by SF_6/O_2 plasma etching slows down J_{sc}. The optimal values of V_{oc}, J_{sc}, FF and Eff of mc-silicon solar cells by SF_6/O_2 plasma etching are 611 mV, 33.6 mA/cm^2, 76.5% and 15.7%, as shown in Fig. 6. Figure 7 presents the QE as a function of wavelength of SF_6/O_2 plasma texturing mc-silicon solar cells at the SF_6/O_2 flow ratio of 3:1 and at the plasma power of 100 W. The integral currents of RIE cell and reference cell are 34.4 mA/cm^2 and 34.1 mA/cm^2, respectively. In the blue-wave range, the QE spectra are slightly lower than that of acidic texturing due to the surface damage caused by the RIE process. In the range of 500–1000 nm, the QE curve of plasma texturing samples becomes higher, which is due to the fact that the damage layers have been removed. The optimized texturing brings about a high visible and infrared response.

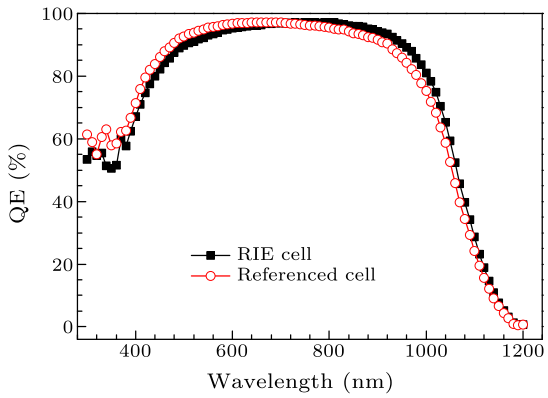

Fig. 7. The QE as a function of wavelength of SF_6/O_2 plasma texturing mc-silicon solar cells at the SF_6/O_2 flow ratio of 3:1 and the plasma power of 100 W.

In summary, the optimized texturization for mc-silicon solar cells by mask-free SF_6/O_2 plasma etching has been specifically studied. In the measurement of current–voltage characteristics, the cell electrical performance is improved, especially J_{sc}, although there is some damage in the surface. By using the optimized plasma power of 100 W, the flow ratio of 3:1 and etching time of 600 s, the optimal efficiency of 15.7% on 50×50 mm^2 RIE textured mc-silicon silicon solar cells is obtained. Additionally, the features of low cost and high performance make it possible to carry out large-scale industrial fabrication of silicon solar cells by SF_6/O_2 plasma etching.

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