PLASMA TEXTURING PROCESSES FOR THE NEXT GENERATIONS OF CRYSTALLINE SI SOLAR CELLS

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ABSTRACT: c-Si solar cells made of thin films and thin substrates have to rely on efficient light absorption to ensure maximal conversion efficiencies. We have develop processes that achieve this by texturing using plasma etching. Since plasma etching is essentially a single side process it will be very beneficial for producing thin cells with a dielectric rear surface passivation, which requires decoupling of front and rear surface conditioning. The facts that the presence of surface defect is not necessary for the texturing process, and that only a small amount of silicon is removed makes it very attractive for both thin substrates and c-Si films.

Keywords: texturing, c-Si, Si-Films

1 INTRODUCTION

The deposition of silicon nitride (SiN_x:H) anti-reflection coatings (ARCs) was the first plasma technology to be introduced in c-Si solar cell manufacturing for surface treatment at high throughput. This demonstrated that the use of plasma technology for surface treatment is not fundamentally limited to small surface areas. In this work we argue that the use of plasma etching for surface conditioning might be the next plasma technology used in the c-Si solar cell manufacturing industry. This is because plasma etching is an elegant solution to reduce front surface reflectivity in different solar cell technologies in which classical approaches to texturing are difficult or impossible. Besides plasma texturing of front surfaces in very thin solar cells, the use of plasma texturing for silicon thin film technologies is demonstrated.

1 LIMITATIONS OF CONVENTIONAL TEXTURING PROCESSES

A common way of increasing conversion efficiency (*h*) in silicon solar cells is to reduce reflection and enhance light confinement by texturing the silicon front surface. This texturing can be executed as the first step of the cell process, directly after substrate sawing. A surface texture can be obtained by mechanical grooving of the surface or by a wet chemical etching, either in an alkaline solution or in an acidic solution. The latter process, which is an isotropic etching, preserves the shape of the saw damaged surface. This technology was successfully transferred to the industry. However, wet chemical texturing is problematic if it has to be applied only to the front side of the substrates. This is a constraint for solar cell processes with a dielectric rear surface passivation, which requires that the rear surface is flat [1]. An example of such processes is the *i*-PERC (*industrial* Passivated Emitter and Rear Cells) process, which was recently developed by IMEC [2].

Conventional texturing methods are also ill suited for thin silicon films like epitaxial deposited c-Si and poly-Si silicon films [3]. Such layers have no surface damage to initiate wet chemical texturing. During texturing the amount of silicon removed has to be as low as possible to reduce the costs involved in deposition.

In this work we demonstrate that plasma texturing is a key technology in solving these problems. The principle of texture formation is summarized and various issues on plasma technology are discussed.

2 MECHANISM OF PLASMA TEXTURING

Etching of c-Si occurs by halogen radicals produced by gas dissociation inside the plasma. Hydrogen, fluorine and chlorine atoms are able to etch the silicon surface chemically. The highest etch rates are normally obtained with fluorine atoms, since diffusion into the silicon is easy due to the relative small size of the atom. The back bonds of the Si atom at the surface than react easily with fluorine. This in contrast to chlorine atoms, which need additional energy to reach to silicon back bonds inside the crystalline material. This additional energy can be supplied from the kinetic energy of ions, impacting on the substrate. However, high ion impact rates, as occurring in reactive ion etching, introduce material defects that have a substantial detrimental impact even on bulk minority carrier lifetimes [4]. For this reason the best approach for plasma texturing is to make use of an ion-impact free technology. Micro-wave (MW) plasma excitation provides plasmas with low ion impact rates. Magnetic confinement of the ions even eliminates the ion impact completely. In the technology used at IMEC [5], a magnetic field around MW antennas is used to keep the ions away from the substrate surface.

For the formation of texture, etching should be locally inhomogeneous over the surface. This inhomogeneity originates from unequal etching events at atomic level. Radical impact on the Si surface happens locally as a purely randomized event, causing local removal of atom(s) and thus a microscopic roughness. This initial roughness is then expanded to larger scales through both etching of silicon and redeposition of the etch products. An analytical description of these two competing processes leads to a model for the creation of texturing and can be mathematically formulated with the Kardar-Parisi-Zhang equation. [6]

$$\frac{\partial h}{\partial t} = -\sqrt{1+\left(\nabla h\right)^2} + \nu\nabla^2 h - \kappa\nabla^4 h + \mu$$

(in which $\nabla = \partial/\partial x + \partial/\partial y$.)

This equation gives the time evolution of the surface profile, given as the etch depth h as function of position (x,y). In this model two processes are considered to take place simultaneously. This are etching and (re)deposition which is included in the model with respectively the etching term $-\sqrt{1+(\nabla h)^2}$ condensation term $\nu\nabla^2 h$, were v is the sticking coefficient. Also the diffusion of etched or redeposited species are taken into account by the diffusion term $-\kappa\nabla^4 h$, with κ the surface diffusion coefficient. For atomically flat surfaces, the onset of the texturing process is generated by a random noise term μ, which represents the random radical impact and localized etching. This noise term is an important term because it is responsible for the formation of a roughness on atomic scale and is the onset for texture formation on shiny flat or mirror polished substrates. If certain equilibrium between etching and redeposition is reached, the texture formation extends to macroscopic scales. Normally this model is applied in the case of ion sputtering [7] and is complicated to apply for plasma technology due to the many chemical reaction kinetics involved. Generally, the texture formation improves if the re-deposition process and etching process keep each other in equilibrium. This can be realized effectively by adding oxygen into the plasma causing the following reaction

$$\mathrm{SiF} + \mathrm{O} \rightarrow \mathrm{SiO} + \mathrm{F}$$

Etchants as SiF_x radicals form silicon oxide clusters which redeposit and cause micro-masking. If the redeposition and etching rates are nearly equal, very rough and dark surfaces can be obtained with reflectivity even below 1%. However, this texture is unsuitable for a good emitter formation and/or surface passivation. Any texture needs to be optimized together with the solar cell process.

3 APPLICATIONS OF PLASMA TEXTURING

3.1 Plasma texturing for *i*-PERC

c-Si cell technologies currently need a rear surface passivation based on dielectrics instead of the classical aluminum BSF [9]. Initially, the problem of using full coverage Al as the metal rear contact involved excessive substrate bowing. This issue can be solved, but still the rear surface recombination velocity (750 cm/s [8]) is not enough to maintain efficiency while going to substrate thicknesses of 100 µm [10]. Dielectric passivation is required to achieve low surface recombination velocities. It appears however that a surface with a texture (as obtained with a classical wet texturing process) gives rise to an excessive surface recombination, even with a good dielectric surface passivation layer [1]. For this reason, texture has to be removed from the rear side or flat substrates have to be textured on the front side. In any case, a specific surface treatment has to be applied only on one side. Single side etching is challenging to implement in a fast and industrially applicable liquid chemical process. Instead, with plasma processing, a decoupling of the front and rear surface treatment is easy. Since plasma processing is essentially a single side process, the texturing can even be applied after the rear surface passivation with dielectric films. Using plasma texturing in combination with rear surface reflection from the dielectric-aluminum stack give typical boost in *Jsc* of 1.5-2.0 mA/cm^2 on both thin Cz-Si as mc-Si solar cells.

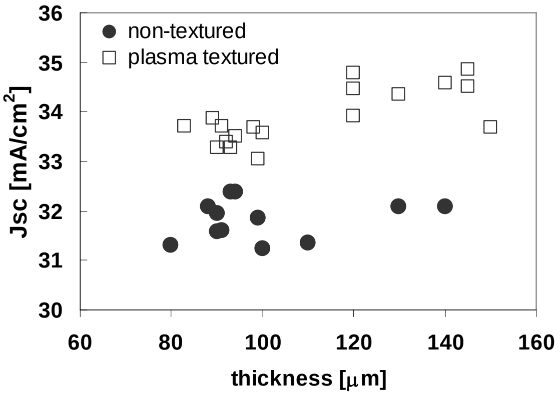

Figure 1, Jsc for different cell thicknesses for screen-printed Cz-Si i-PERC cells with and without plasma texture.

This recently led to high efficiency mc-Si solar cells above 16% on substrates thinner than 160 µm, using industrial technologies [10]. The application of this texturing process is further demonstrated in an *i*-PERC process on mechanically thinned Cz-Si samples. In figure 1 *Jsc* of textured and non-textured cells are given according their final thickness. The cell characteristics of the best cells processed thus far with plasma texturing are summarized in table 1. The thinnest cell was 83 µm thick and was realized on mechanically thinned circular substrates (100 µm). All cells were processed using the classical cell process for metal contacts, including screen-printing. This contacting step integrates the alternative rear surface passivation of the *i*-PERC process. Full coverage screen printed Al forms a local back surface field and contact upon firing on the back at places where the passivation layer was opened (see figure 2). Optimization for higher efficiencies, using thin emitters on even thinner substrates is in progress.

Substrate thickness	Surface area cm^2	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	η [%]
130 µm	100	35.1	633	79.1	17.6
105 µm	100	34.8	630	78.7	17.3
83 µm	78.5	33.7	635	73.0	15.6

Table 1, characteristics of Cz-Si cells using i-PERC integrated with screen-print technology.

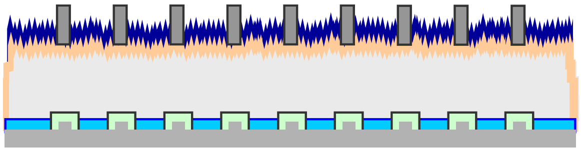

Figure 2, i-PERC structure for thin c-Si cells

4.2 Epitaxial solar cells

The fact that no initial surface roughness is required to initiate texture formation makes plasma texturing an ideal process for flat, mirror like surfaces. Using SF_6 and N_2O enables texturing of mirror-like surfaces leading to a reduction of the reflectivity down to 14.3-16% at 700 nm within 45-60 seconds only. During this short time, an average etching depth $\langle h \rangle$ of maximum 1 μm silicon is removed. This small amount of removed material makes the texturing attractive for application on thin film silicon solar cells since it reduces the total layer thickness to be deposited during the process.

A first thin-film application is on epitaxially grown thin film silicon solar cells. Texturing 18 μm thick single-crystalline epitaxial grown films leads to a boost in J_{sc} of typically 2 mA/cm^2. Plasma texturing in combination with porous Si Bragg reflectors for light confinement made it possible to achieve cell efficiencies above 13.5%. [11]

Texture	time	$\langle h \rangle$	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	η [%]
no	-	-	24.9	614	66.4	10.3
yes	45 s	0.76 μm	26.3	613	77.5	12.5

Table 2, characteristics of thin film epitaxial cells with and without texturing.

4.3 Thin-film polysilicon solar cells

Another material on which plasma texturing was successfully applied is polycrystalline silicon thin films. Thin poly crystalline films with a final thickness of 2.0-3.0 μm were made with and without plasma texturing. Thanks to plasma texturing, the current increased by 2 mA/cm^2 which lead to a conversion efficiency of 7% [12]. (see table 3)

Texture	time	$\langle h \rangle$	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	η [%]
no	-	-	17.2	483	69	5.7
yes	60 s	1.0 μ	19.6	506	71	7.0

Table 3, characteristics of poly-c Si cells with and without texturing.

5 ASPECTS FOR INDUSTRIAL IMPLEMENTATION

Applying plasma technology in the c-Si solar cell industry implies the upscaling of the existing technology towards large throughput, i.e. large areas which have to be treated uniformly. This can be achieved by obtaining a very rough surface with using SF_6/N_2O plasma as a first step, creating a texture with varying quality over the whole area. A second step uses Cl_2 based plasma etching. With a Cl_2 plasma, the texture can be made pyramid like, since [111] planes are etched much more slowly than in the [110] and [100] directions, due to the different packing density of the Si atoms. Using this second step transforms all surface roughness induced in the first step into a similar texture. In areas with a 'sponge' structure formation, a texture consisting of flat facets is formed (figure 3), yielding a uniformity equal to that of wet chemical texturing.

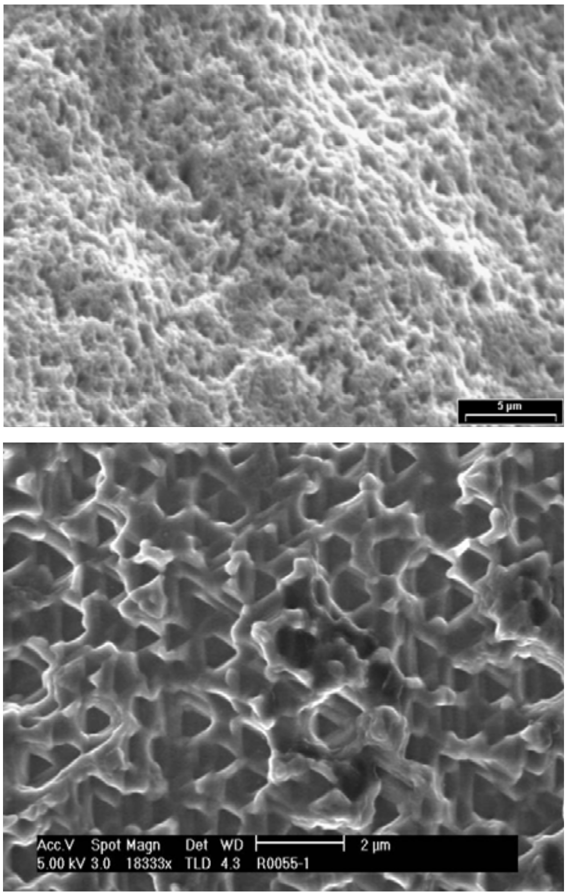

Figure 3, *top: a sponge-like texture using fluorine plasma chemistry. bottom: ordered texture with triangular shapes etched in [111] oriented Si surfaces due to Chlorine based plasma chemistry.*

6 CONCLUSION

With the ongoing decrease of substrate thickness to save material costs, plasma texturing might play an important role in the manufacturing of thin c-Si bulk or thin-film Si film solar cells. Several examples in which plasma texturing was applied demonstrated a significant efficiency increase, meanly through an increased J_{sc}, induced by lower reflectivity. Plasma texturing can be applied in a fast process with a minimal amount of silicon removal. This makes it attractive for thin cell technologies. It is to be expected that plasma texturing will be introduced in commercial solar cell manufacturing in the near future.

7 ACKNOWLEDGEMENTS

This Work was partially funded by the European Commission under the FP6, project CRYSTAL CLEAR, contract SES6-CT-2003-502583.

We thank Fraunhofer ISE for mechanical thinning Cz wafers for the thinnest cells.

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