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Fabrication Techniques for Light Trapping and Capturing Textures in Crystalline Silicon Solar Cell

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solar cells, surface texturing, light trapping, micro electro mechanical systems, crystalline silicon

Abstract: In order to increase the performance/cost ratio of solar cells, new approaches reducing optical and electrical losses are necessary during the absorption of the light and collection of charge carriers. In this work we focused on various textures on silicon surface towards a better light management of the cell surface. The efficiency of a solar cell strongly depends on the properties of the interaction between the incoming light beam and the surface of the device. In order to maximize the absorption and the efficiency of the cell, various light trapping schemes have been proposed. We have applied different lithography techniques such as optical lithography, nanoimprint lithography (NIL), hole mask colloidal lithography (HCL) to generate various periodic micro and nano surface textures. After predefined pattern transfer process steps, either dry plasma etching or wet chemical etching techniques were applied. Structural properties of the features like diameter, pitch size, depth were varied and optimized. With a variety of texturing and etching process types, at the end of the study, periodic and random-introduced-periodic patterns were successfully implemented to solar cell fabrication step. The performances of the solar cells were investigated both optically and electrically.

Kristal Silikon Güneş Hücrelerinde Işık Yakalama ve Hapsetme Desenler için Üretim Teknikleri

Keywords
güneş hücreleri, yüzey desenleme, ışık hapsetme, mikro elektromekanik sistemler, kristal silikon

Özet: Güneş pilinin performans/maliyet oranını arttırmak için, ışığın emilimi ve yük taşıyıcıların toplanması sırasında optik ve elektrik kayıplarını azaltan yeni yaklaşımlar gereklidir. Bu çalışmada silikon yüzeyinin daha iyi bir ışık yönetimine yönelik çeşitli şekillere odaklandık. Bir güneş pilinin verimliliği, gelen ışık ışını ve cihazın yüzeyi arasındaki etkileşimin özelliklerine oldukça bağlıdır. Güneş hücresinin ışık emilimini ve verimliliğini en üst düzeye çıkarmak için çeşitli ışık tutucu şemalar önerilmiştir. Çeşitli periyodik mikro ve nano yüzey dokuları oluşturmak için optik litografi, nanoimprint litografi (NIL), delik maskesi kolloidal litografi (HCL) gibi farklı litografi teknikleri uyguladık. Önceden tanımlanmış desen transfer işlemi aşamalarından sonar, kuru plazma aşındırma veya ıslak kimyasal aşındırma teknikleri uygulanmıştır. Çap, periyot, derinlik gibi yapısal özellikleri değiştirilmiş ve optimize edilmiştir. Çeşitli desenleme ve aşındırma işlem türleri ile çalışmanın sonunda, periyodik ve rastgele-tanıtılmış-periyodik desenler, güneş pili üretim aşamasında başarıyla uygulanmıştır. Üretilen güneş pillerinin performansları hem optik hem de elektriksel olarak incelenmiştir.

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1. Introduction

When we consider the design and the optical trapping and capturing performances of surface texture, there are many patterning types, such as pyramids, rods, wires, holes and inverted pyramids [1, 2].

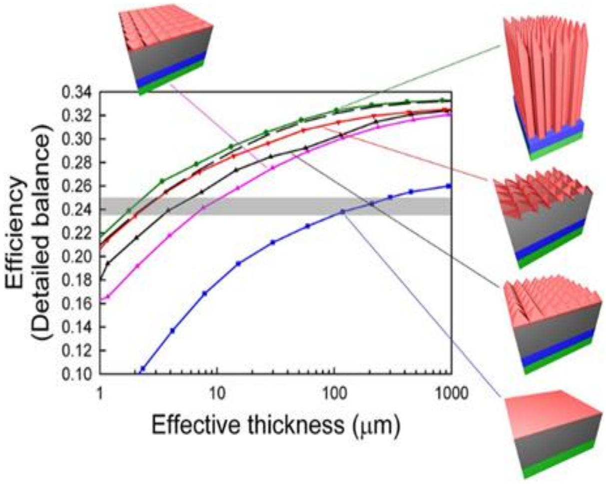

Figure 1. Efficiency values of thin film solar cells with different surface textures (reprinted with permission from [2] Copyright 2010

With the information obtained from the simulation studies represented in Figure 1, which enable us to make the correct selection of texturing types [2, 3]. With the recent developments in today's micro electro mechanical system (MEMS) technology, it is possible to fabricate anything with desired parameters. For solar cell technology, the more the interaction between light and the wafer, the higher the possibility of ending up with more efficient solar cells. Here in this study we have summarized possible patterning methods to create desired textures ending up with exact dimensions.

2. Materials and Method

In order to obtain a periodic and uniform distribution of structures with specific geometries, pattern transfer is needed. One of the most common ways to make pattern transfer is photolithography. After creating the patterns with desired geometries on transparent plate called mask, we can transfer them to a flat surface via optical printing process. During this printing process a photosensitive polymer, which is called as photoresist, is used to create desired pattern on the surface. When the resist is exposed to UV light, depending on being negative or positive, either the exposed part or unexposed part of the resist is dissolved in a chemical solution called developer [4]. Pattern transfer could be made in basically three ways: 1) optical lithography, 2) nano imprint lithography (NIL), 3) hole colloidal lithography (HCL)

2.1. Basics of Experimental Procedures for NIL

NIL patterning is assumed to be one of the most promising and relatively low cost methods compared to other techniques of surface patterning. As shown in Figure 2 first we should prepare a master stamp and clean it in: H2O2:H2SO4=1:4, H2O: HF: HCl=20:1:1. In order to protect the pillars of the master stamp, we should coat the stamp with Octadecyltrichlorosilane (ODTS). Thanks to ODTS for making the surface hydrophobic and enabling the stamp resist-free.

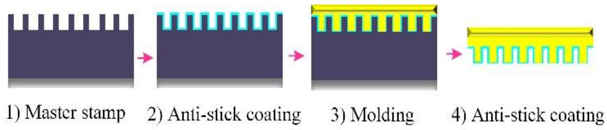

Figure 2. Schematic representation of soft stamp fabrication process step

After obtaining master stamp successfully, now we can make the pattern transfer on our wafer as shown in figure 3. To make pattern transfer successfully resist thickness must be calculated depending on the dimensions of the pillars on top of the soft stamp.

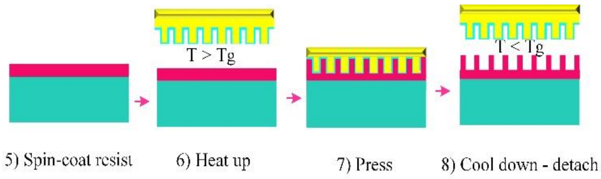

Figure 3. Schematic representation of imprint process

During transfer process, resist must fill the gaps between pillars in such a way that pattern can be transferred to resist, and after that to the wafer surface.

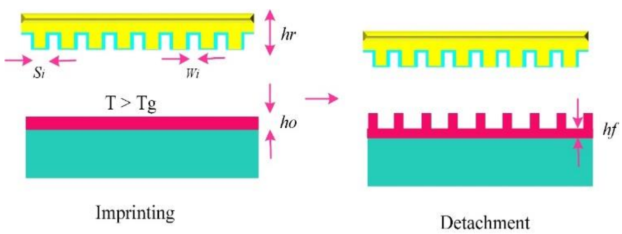

Figure 4. Schematic representation of residual resist layer thickness and master stamp's dimension representation

The dimensions of master stamp gives the exact thickness of residual resist layer. From Si and Wi, final residual resist layer thickness (hf) can be extracted from the initial resist thickness (ho) as shown in equations (1) and (2) given below [5]:

$$hf = ho - vhr \quad (1)$$

with fill factor v:

$$: \frac{\sum_i Wi}{\sum_i (Si+Wi)} \quad (2)$$

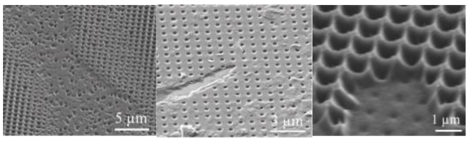

Figure 5. SEM images of partially achieved NIL process

2.2. Basics of Experimental Procedures for HCL

The process building blocks are shown in Figure 6. The polystyrene beads (PS) are adsorbed on top of the surface and the etch mask is deposited. During the adsorption step, Figure 6 a), pattern is defined on Si surface. In order to make a conformal coating, the distribution of PS beads with the position, width and shape of the holes should be optimized. Before spreading PS beads, the surface is coated with three layers: polydiallyldimethylammonium (PDDA), poly sodium 4-styrenesulfonate (PSS), aluminum chloride hydroxide (ACH). These layers are positively charged, and after spreading negatively charged PS beads will cause an attraction between beads and the surface, which is desired. In the system, there will be a repulsive force due to same charged PS beads. With the effect of these repulsive and attractive forces the distribution of beads will be defined. After the removal of PS beads either dry or wet etching technique can be selected [6].

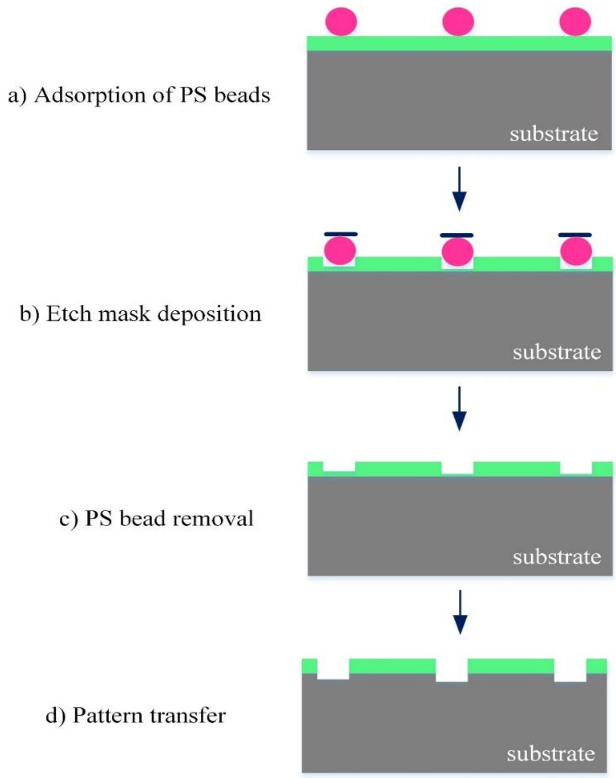

Figure 6. Schematic representation of HCL process: a) adsorption of beads, b) etch mask deposition, c) PS bead removal, d) pattern transfer

The bead size will define the dimension of the features that are intended to be obtained. The smaller the bead size, the easier to control on the surface coverage. When the bead size gets bigger, the probability of agglomeration gets higher, which will end up with larger unexpected features. In order to see the effect of hole colloidal lithography on surface morphology we have used different bead size and etching times. Depending on process parameters we ended up with surface covered with random holes, squares, depending on etching type pyramids with full surface coverage. Figure 7 depicts the surface with PS beads having 270 nm bead size etched for 45 s and 35 s. As the etching time increased, the diameter of the beads increased ending up with larger features.

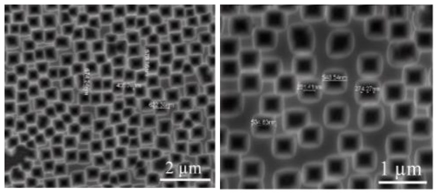

Figure 7. SEM image of HCL applied surface, which was bonded to glass with Al mesh layer in between and PS beads having 270 nm bead size. Dry etching was done for a) 45 and b) 35 s respectively

HCL patterning can also be applied to thinner surfaces. The core part of this study is to work with thin wafers, epifoils. 40 µm thick epifoils were shown to be best selection for solar cell fabrication [7, 8]. It can be seen from SEM images that surface textures are almost similar with periodic patterning achieved with lithography based techniques. The only difference is, for HCL the position of nanostructures is depending on the bead position and diameter. Bead to bead and bead to surface reactions will differ depending on initial bead size. The defining criteria for bead size and position are defined with dry plasma etching conditions. The larger the initial bead size, the larger the final structure size. The sizes of features are depicted in Table 1.

Table 1. Initial bead size and final dimension of features obtained with dry plasma etching

Bead size (nm)	Etching time(s)	Final dimension (nm)	Depth (nm)
270	50	550	450
410	55	760	550
510	55	900	600

2.3. Comparison of HCL and NIL in Terms of Optical and Electrical Properties

When we investigated surfaces patterned with HCL and NIL we can say that some surfaces had reflection values lower than pyramid texturing. Process details were analyzed depending on substrate type, bead size for HCL, stamp dimensions for NIL and either dry plasma or wet chemical etching selection.

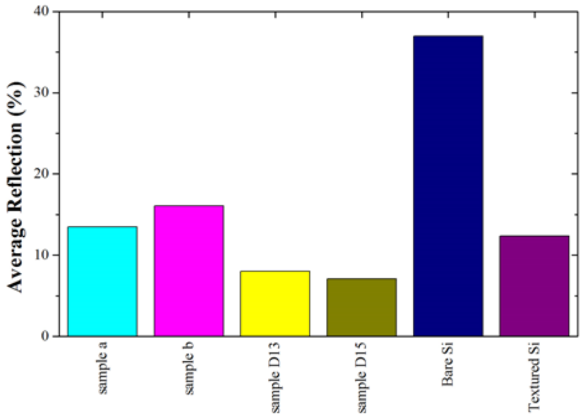

Figure 8. Average reflection comparison of samples patterned with NIL having different pitch sizes and etching conditions

We can see from Figure 8 that the lowest reflection value was obtained from the sample having 680 nm pitch size subjected to wet chemical etching, D15. D13 had also lower reflection value than standard pyramid textured surface. For NIL, both dry and wet etching process showed remarkable optical performance. With SiNx coating, these results can be further improved.

Table 2. Performance of patterned surfaces with NIL and HCL

Texturing	Jsc (mA/cm2)	Voc (mV)	FF (%)	η (%)
*900 nm Dry-NIL	15.3	435	72	4.8
*600 nm Dry-NIL	15.4	403	56	3.5
*Dry-HCL	17.2	444	58	4.5
Flat	20.9	564.9	75.8	9

(*Results are taken from [9,10])

3. Results

The interaction between coming sunlight and the surface is the most crucial part for the efficiency value of a solar cell. The aim is to maximize the effect of light with capturing that occurs at the top surface and trapping, which occurs after the entrance of light to the deeper portions of the substrate. In order to keep the light inside the substrate as much as possible, the dimensions of the texture should be in the order of the wavelength of light. If we can design and fabricate a mask with desired dimensions, there is no limitation for us to multiply it as much as we wish. Each dimension behaves like a unique character, and requires specific process optimization. With the correct process parameters, we could successfully obtain whatever the shape of the texture and the dimensions are.

4. Discussion

The smaller the textures, the more difficult the process development is. The most crucial part for pattern transfer is the resist thickness, especially for NIL. During NIL process, prior to pattern transfer to wafer surface, we start with the pattern translation to the top of the substrate, which is resist. As shown in Figure 4, in order to achieve exact dimensions, process optimizations should be carried out meticulously. If we choose to pattern the surface with HCL, the bead size, like the resist thickness, should be selected depending on future process steps.

5. Conclusion

To conclude each mask requires unique process optimizations to end up with desired surface patterns, if not fulfilled, process ends up with undesired surface morphology. Apart from process trials at first stage, we could manage to provide a good control over the distribution of textures with intended depths.

Acknowledgment

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