Holographic fabrication of periodic structures on silicon as anti-reflective layers for high efficiency solar cells

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ABSTRACT

The paper presents the investigation on the anti-reflection property of 2-dimensional periodic structures on silicon surface for high efficiency solar cells. The characteristics of micron-to-submicron periodic surface-relief structures for broadband anti-reflection silicon layers are studied theoretically and experimentally. Theoretical analysis is carried out to determine the appropriate sturcture period. Hexagonal and cross grating structures were fabricated on the surfaces of silicon wafers using hologrpahic and wet etching techniques. Measurement on the silicon wafers with fabricated structures shows significant reduction of surface reflection for the wavelength from 300 nm to 1100 nm.

Keywords: anti-reflection; periodic structures; silicon, solar cell, holography

1. INTRODUCTION

The photovoltaic technology is well established as a reliable and economical one for small sources of electricity in many applications. The main research activities in the photovoltaic field are related to materials development, which can be obtained at relatively low cost and have the improved conversion efficiency. One of the known ways to increase the conversion efficiency[1] is the reduction of the radiation losses at the front surface of the cell. Lowering surface reflectance of Si wafers by texturization is one of the most important processes for improving the efficiency of Si solar cells. In order to lower surface reflectance of multicrystalline silicon wafers, several texturing methods have been proposed and developed in recent years, such as wet etching of wafers[2-4] by alkaline or acid solutions, mechanical grooving[5], reactive ion etching [6-8], the formation of a layer of porous silicon[9,10] and fabrication of special structures on the surface[11-13].

A holographic technique for fabricating periodic surface structures on Si and the investigation on the optimal structure period are presented in the paper. The purpose of the work is to demonstrate the broadband anti-reflection effect of the structures formed with proposed low-cost method. The periodic surface-relief structures with hexagonal lattice and cross-grating structures have been applied to both single crystal silicon and multicrystalline silicon materials. In the structure formation process, photoresist masks were firstly fabricated with holographic means, then the structures were transferred into the surfaces of silicon wafers through wet etching. By selecting different beam incident angles and controlling the etching time, hexagonal and cross grating structures with different periods and depths on Si were fabricated. Measurement shows that the reflectance of the patterned Si has been significantly reduced. Moreover, the smaller the structure period and the deeper the structure depth, the lower reflectance can be acquired. The reduction of the reflectance of micron-to-submicron periodic structures on Si probably results from significant increase of light radiation area on Si due to diffracted light bouncing between the walls of the structures.

2. MATHEMATICAL EQUATIONS

For a light beam incident vertically to the surface of a grating, the diffraction angle of the grating is expressed by

$$\sin\theta_k = \frac{\lambda}{n_d}\frac{m}{\Lambda}, \tag{1}$$

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where λ is the wavelength in vacuum, Λ is the grating period, m is the diffraction order, θ_k is the diffraction angle for the mth order, n_d is the refractive index of the media, in which the diffracted light waves propagate. For gratings with the periods close to or a few times larger than the wavelengths, diffraction will occur. When light falls on Si with grating relief on the surface, diffracted light beams are bouncing between the walls of the structure, resulting in large increase of light absorption in Si so that the reflection will be reduced. In order to obtain diffractions for all wavelengths within wave band from near ultraviolet to infrared, the choice of Λ must be considered. Substituting the refractive index of silicon as n_d into Eq.(1), diffraction angle varying with wavelength for different value of (Λ/m) is plotted in Fig. 1. It can be seen from Fi.g 1 that only when $\Lambda/m \geq 260$ nm, all wavelengths (300 nm ~ 1100 nm) can have diffraction. Since the majority of light energy concentrates in lower diffraction orders, we can just take the diffraction orders $m = 1, 2, 3$ for consideration. For example, $\Lambda/m = 260$ corresponds to the periods 260 nm, 520 nm and 780 nm for the first, second and third diffraction orders respectively, and $\Lambda/m = 400$ corresponds to the periods 400 nm, 800 nm and 1200 nm for the first, second and third diffraction orders respectively. With these periods, all wavelengths from 300 nm to 1100 nm can diffract. But when $\Lambda/m < 260$ nm, such as the curve for $\Lambda/m = 200$ shown in Fig. 1, wavelength larger than 850 nm will have no diffraction at all.

The above discussion is for 1D grating, but it can be extended to more complicated periodic structures. 2D hexagonal lattice structure can be regarded as consisting of several superposed 1D gratings. Lining up the lattice points along different orientations, equivalent gratings with different periods can be determined accordingly. The schematic of 2D hexagonal structure with lattice constant a and gratings with periods Λ_1, Λ_2 and Λ_3 is depicted in Fig. 2. The periods of the gratings are smaller than lattice constant a and have the expressions

$$\Lambda_1 = \sqrt{3}a/2\,, \tag{2}$$

$$\Lambda_2 = a/2\,, \tag{3}$$

and

$$\Lambda_3 = \sqrt{21}a/14\,.\,. \tag{4}$$

The grating with period Λ_1 is the largest among all superposed gratings. With Eq. (2) to (4), the diffraction phenomena of hexagonal structures can be predicted.

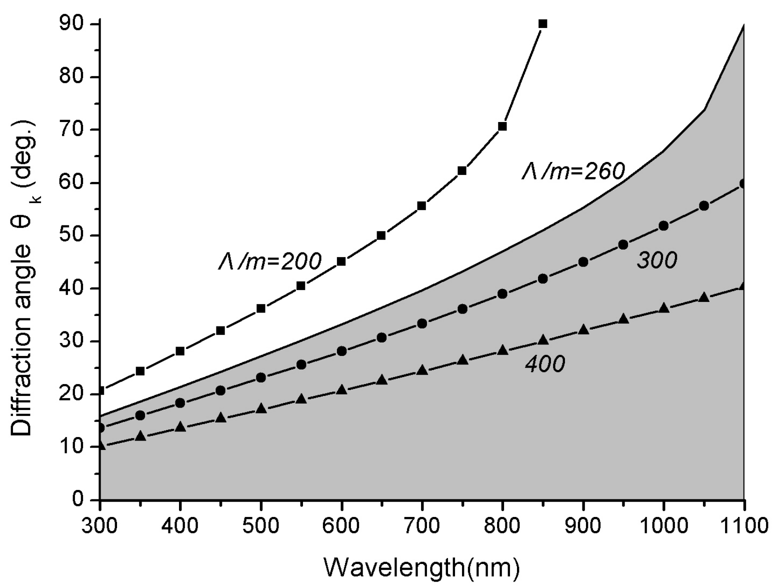

Fig. 1. Diffraction angles in Si for several values of (Λ/m) at the normal incidence, plotted as a function of wavelength for several values of (Λ/m)

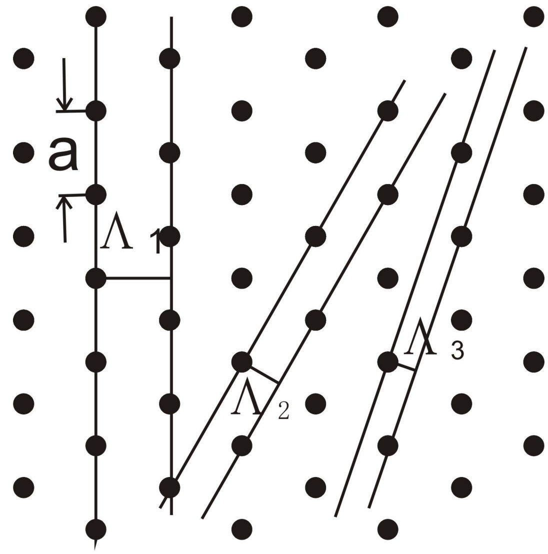

Fig. 2, Schematic showing three different gratings with periods Λ_1, Λ_2 and Λ_3 in hexagonal structure with lattice constant *a*.

3. EXPERIMENT AND RESULTS

3.1 Fabrication of periodic structures on silicon

In the experiment, the periodic surface-relief structures were fabricated in Si by utilizing holographic and wet etching techniques. In the first step the periodic structures were recorded in photoresist layers coated on Si wafers, then the wafers were put into acid solution to transfer the structures into Si..

In the first step, cross-grating and hexagonal lattice structures were recorded in photoresist layers, which were spin coated on Si wafers, using holographic 2-beam dual-exposure method and 3-beam interference technique respectively. Fig. 3 shows the optical setups for forming the two kinds of periodic structures. For recording cross-gratings, as shown in Fig. 3(a), the two coherent beams have the same incident angle β. After one exposure, the sample is rotated 90^{o} about the normal and then is exposed again. In the setup for recording hexagonal lattices, as shown in Fig. 3(b), three beams have the same incident angle β but are separated by 120^{o} between each other. Selecting different beam incident angle β in the two setups, structures with different periods or lattice constants can be obtained. In photoresist patterning processes, laser beam with 457.9 nm wavelength and 200 mW power was used.

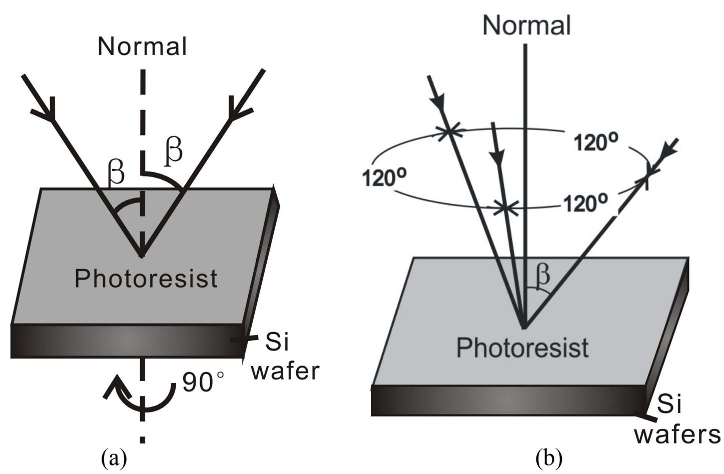

Fig. 3, Optical setups for forming two kinds of periodic structures in photoresist: (a) 2-beam dual-exposure to formcross gratings; (b) Holographic 3-beam interference configuration to form 2D hexagonal structures.

In the second step, the samples were dipped into acid solution for etching. The depth of the structures on Si depends on the etching time. Fig. 4 illustrates the micrographs of silicon wafers with micron-to-submicron periodic surface-relief structures: (a) cross-grating with 500 nm period; (b) (c) and (d): hexagonal structures with lattice constants 600 nm, 900 nm; and 1300 nm respectively. According to Eq. (2) to (4), the hexagonal structures with the three lattice constants can be regarded as consisting equivalent gratings with the periods shown in table 1.

Table.1, Equivalent grating periods in hexagonal lattices.

Hexagonal lattice constant	Λ_1	Λ_2	Λ_3
600 nm	520 nm	300 nm	196 nm
900 nm	780 nm	450 nm	295 nm
1300 nm	1126 nm	650 nm	425 nm

It can be seen from table 1 that, according to Fig. 1, all the equivalent gratings can diffract the light with wavelengths from 300 nm to 1100 nm, except the grating with 196 nm period.

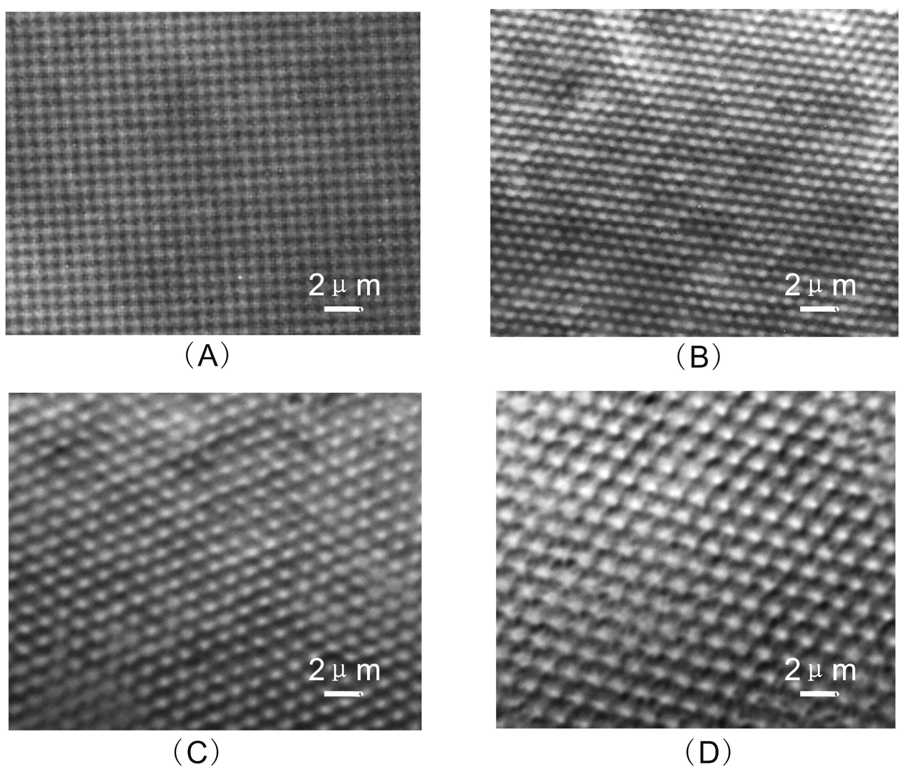

Fig. 4. Micrographs of silicon wafers with micron-to-submicron periodic surface-relief structures: (a) cross-grating with 500 nm period; (b) (c) (d): Hexagonal structures with latticeconstant 600nm; 900nm; and 1300 nm respectively. Scale bar, 2μm..

3.2 Experimental results and discussion

Optical reflection measurements have been carried out using an UV/Vis/NIR Spectrophotometer (from Perkin-Elmer ''lambda900''). Fig. 5 shows the graphs of measured reflectance for cross-grating with 500 nm period illustrated in (a), and for hexagonal structures with lattice constant 600 nm; 900 nm; and 1300 nm illustrated in (b) (c) and (d) respectively. In each graph, the solid line represents the sample without any structure, marked as ‘original’, while dashed line and dotted line represent structures with different depth.

It can be seen from Fig. 5 that the reflectances of all structured Si have been reduced. Fig. 5(b)-(d) also show that for hexagoanl structures with the same lattice constant, deeper depth brings about not only lower reflectance but also flatter reflectance curves, i.e., less reflectance variation with wavelength. The result suggests that further increase the depth of the structures, even lower and further flattened reflctance can be acquired.

Comparing Fig. 5(a) and (b) it can be realised that the reflectances for the cross grating with 500 nm period and 260 nm depth (dashed line in (a)) and the hexagonal structure with lattice constant 600 nm and depth 280 nm (dotted line in (b)) are rather similar. The possible reason is that the hexagonal structure with 600 nm lattice constant has an equivalent grating period Λ_1 = 520 nm (see table 1), which is very close to the period of the cross grating (500 nm). Moreover the two structures have the similar depth. Similar period and depth result in similar reflectance variation curves. This further proves that the reflection of a structure is mainly determined by the structure’s period and depth.

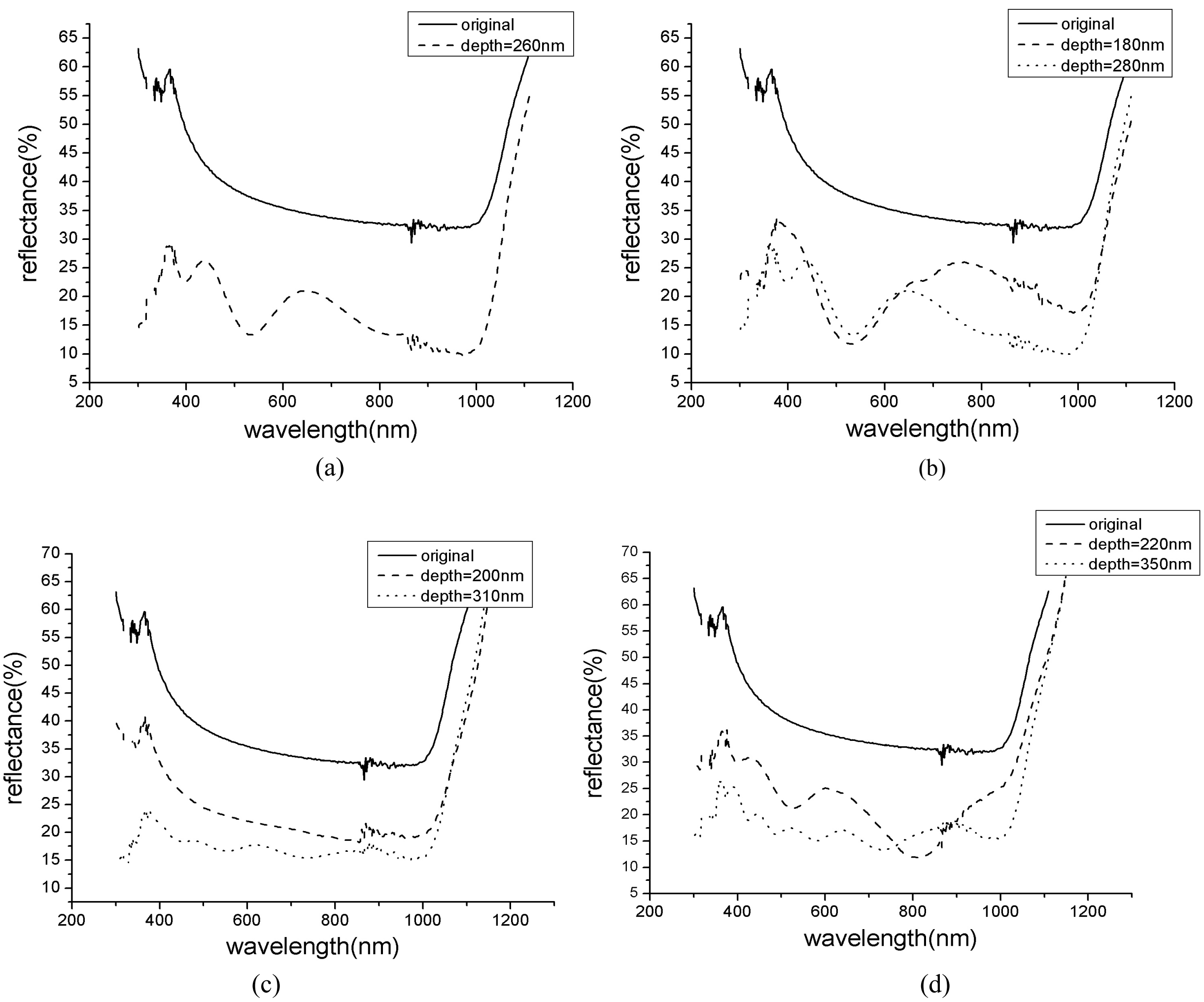

Fig. 5.Measured reflectances of the silicon samples. (a): Cross-grating with 500 nm period; (b) (c) and (d): Hexagonal structures with lattice constant 600 nm, 900nm and 1300 nm respectively. Solid line – Si without structure, dashed line and dotted line – Si with the structures for different depth.

4. CONCLUSION

The anti-reflction effect of micron to submicron periodic structures on Si surfaces has been studied in the paper. Theoretical analysis indicates that if the grating on Si satisfies $\Lambda/m \geq 260$, diffraction will take place for all the wavelengths in the range from 300 nm to 1100 nm. Cross grating and hexagonal lattices were fabricated in Si wafers using holographic and wet etching techniques. The measured result shows that the fabricated structures have effectively reduced the reflectance, and deeper structure depth can result in lower reflectance and less reflectance variation with wavelength.

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REFERENCES

[1] Zechner C, et al, "Systematic study towards high efficiency multicrystalline silicon solar cells with mechanical surface texturization, " Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference, 243–246(1997).

[2] E. Vazsonyi, et al, "Improved anisotropic etching process for industrial texturing of silicon solar cells," Sol. Energy Mater. Sol. Cells **57**,179-188 (1999).

[3] R. Einhaus, et al, "Isotropic texturing of multicrystalline silicon wafers with acidic texturing solutions, " Proceedings of the 26th IEEE Photovoltaic Specialists Conference, Anaheim, CA, 167(1997).

[4] K. Tsujino,et al, "Texturization of multicrystalline silicon wafers for solar cells by chemical treatment using metallic catalyst," Sol. Energy Mater. Sol. Cells **90**,100–110(2006).

[5] H. Nakaya, et al, "Polycrystalline silicon solar cells with V-grooved surface," Mater. Sol. Cells **34**, 219-225 (1994).

[6] Y. Inomata, et al, "Surface texturing of large area multicrystalline silicon solar cells using reactive ion etching method," Sol. Energy Mater. Sol. Cells **48**, 237-242(1997).

[7] D.S. Ruby, et al, "Rie-texturing of multicrystalline silicon solar cells," Sol. Energy Mater. Sol. Cells **74**, 133-137 (2002).

[8] W.A. Nositschka,et al, "Texturisation of multicrystalline silicon wafers for solar cells by reactive ion etching through colloidal masks," Sol. Energy Mater. Sol. Cells **76**, 155-166 (2003).

[9] Yerokhov VY, et al, "Cost-effective methods of texturing for silicon solar cells," Solar Energy Materials and Solar Cells **72**, 291–298(2002).

[10] I. Divliansky, T. S. Mayer, K. S. Holliday, et al. " Fabrication of three-dimensional polymer photonic crystal structure using single diffraction element interference lithography, " Appl.Phys.Lett., **82**: 1667-1669(2003).

[11] Rajesh Kumar, et al, "Macro and microsurface morphology reconstructions during laser-induced etching of silicon," Micro **39**,287-293(2008).

[12] Kensuke Nishioka, et al, "Antireflection subwavelength structure of silicon surface formed by wet process using catalysis of single nano-sized gold particle," Solar Energy Materials and Solar Cells **92**, 919-922(2008)

[13] Udaibir Singh, et al, "Single layer homogeneous model for surface roughness by polarized light scattering, " Optics and Laser Technology **40**, 315-324(2008).