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A fractal-like texture of multicrystalline silicon for enhancing optical performance

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Abstract. Appropriate texturing is one major topic for multicrystalline silicon wafers to improve the cost effectiveness. In this paper, a new fractal-like texture being applied to multicrystalline wafers is introduced. The focus of this paper is the study of the light-trapping ability of the novel fractal-like texture for multicrystalline silicon solar cell. With a simple model of the fractal-like texture, the conditions needed to achieve lower reflectance are discussed first. It is shown how the effect of the micro structure of multicrystalline silicon with the fractal-like characteristics. Finally, in our present work, the finite element method(FEM) is used to simulate the propagation of electromagnetic field in the structure of multicrystalline silicon. We obtain an average reflectivity of 3% in the wavelength range 300–800 nm on the surface of multicrystalline silicon wafer, which has the fractal-like structure feature.

1. Introduction

Multicrystalline silicon has been hailed as the cornerstone of the microelectronics industry and photovoltaic industry, which is widely used in solar cells. However, the photoelectric conversion efficiency of multicrystalline silicon solar cells has been no breakthrough. It is an effective method to improve the absorption rate of the surface by texturing of multicrystalline silicon. Appropriate texturing is one effective way to decrease the reflectance of multicrystalline silicon wafers [1].

In the past few years, in order to optimize the optical properties of multicrystalline silicon wafers, many kinds of texture structure of multicrystalline silicon wafers have been proposed, such as inverted-pyramid texture [2], honeycomb texture [3-5], or random pyramid texture [6,7] on the top surfaces. However, a severe drawback has been observed, these textured surfaces have not obtained a sufficiently low reflectivity. Therefore, how to optimize structure for obtaining lower-reflectance surface is still an important research direction in the field of multicrystalline silicon solar cells.

The aim of this work is to introduce a novel fractal-like texture micro structure which may lead to the development of the PV technology. In this paper, to achieve sufficiently high prediction capabilities, three models of multicrystalline silicon including semi-ellipse texture, inverted-pyramid texture, and fractal-like texture were proposed [8]. Simulations are usually used to analyze a series of parameter variations and to predict effects due to structure changes [9]. The study of surface morphology and reflectance of different textured silicon based surfaces have been analyzed by COMSOL Multiphysics in this paper. Firstly, we give a schematic diagram of the light trapping of three models. Further more, specific discussions are given of reflectivity through the fractal-like texture microstructuring. Finally we derive that a remarkable lowering of the reflectance of fractal-like texture compared to other textures is achieved.



2. Methods

One way to acquire lower reflectivity is to introduce specific structure into silicon base surface. Texturing of multicrystalline silicon wafer means creating an especial surface which may be allowing more of the incident light being absorbed into the solar cell [10].

By previous research, it is not difficult to get only a small part of the study is used to simulate light trapping of texture structure. In order to study the light trapping effect of different surface structures of multicrystalline silicon and the corresponding silicon surface reflectivity. We carried out a ray tracing simulation[11-13] by COMSOL Multiphysics to estimate the light trapping influence in the multicrystalline silicon solar cells with different texture structures.

It is not necessary to research details of the different texture structures in order to understand some basic optical performance parameters. Three different structure models with periodic array were designed: semi-ellipse texture, inverted-pyramid texture, and fractal-like texture as shown in Figure 1. As is known to all, when the incident light from a medium incident to another medium, in the interface of two media, the propagation direction of the light will change, part of the light is reflected back to the original medium, which is named as the reflection ray, another part of the light incident another medium, which is called for the refraction ray. So we can know that the light from air into silicon arriving at the interface is divided ,the refraction light is absorbed, at the same time the reflection light is reflected back into the air.

Figure 1 shows that how the incident light trapping in the fractal-like texture compares with the other two kinds of texture structures. From figure 1(a)-(b),we can know that light can be reflected and reflected on the silicon surface by two times. But if we create a fractal-like texture structure, which has many nanoscale structures on both sides, as shown in figure 1(c). In the ideal case, when the light is irradiated on the surface of the multicrystalline silicon, the light in this fractal-like texture features allowing multiple reflection and refraction to make more photons enter into the multicrystalline, which will greatly reduce the surface reflectivity.

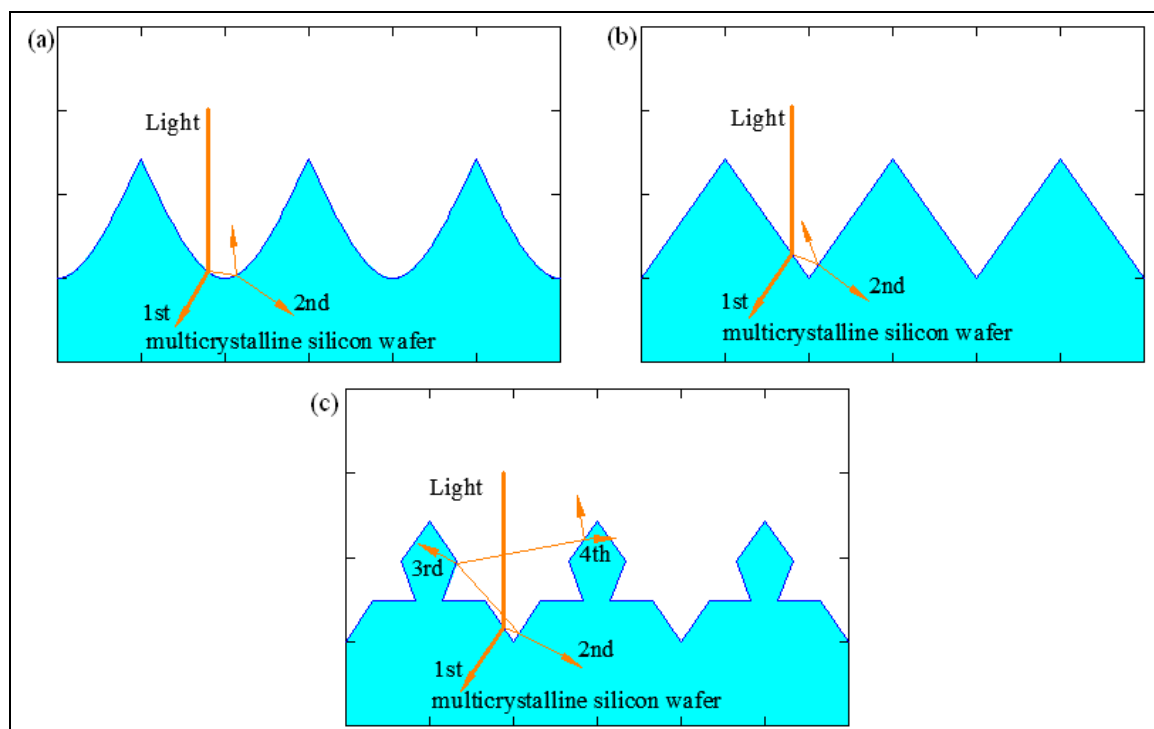


Figure 1. three structures of light reflection and refraction in the trap including semi-ellipse texture(a), inverted-pyramid texture(b) and fractal-like texture(c).

After that, we investigated these texturing structures to determine which produced the lowest reflectance using the RF Module by COMSOL Multiphysics simulation software. Under normal circumstances, the way to use COMSOL is to design the model structure firstly. A 3-D model, as shown in figure 2, is constructed with periodic array.

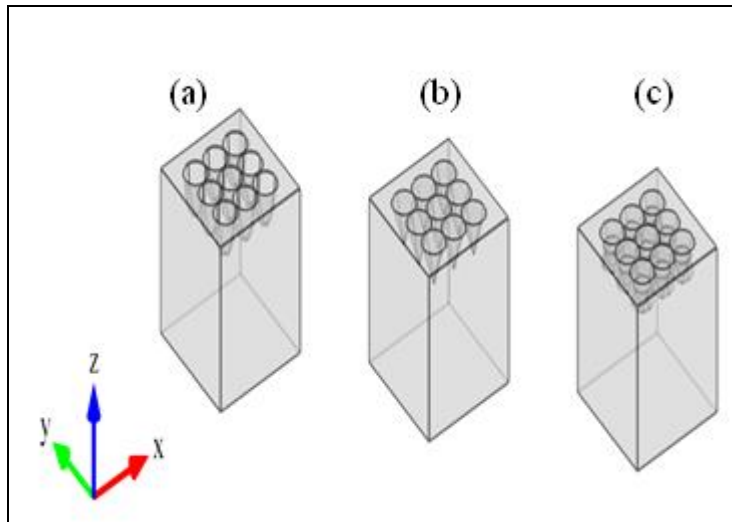


Figure 2. three different models of light trapping geometry of silicon are constructed with periodic array: semi-ellipse texture(a), inverted-pyramid texture(b) and fractal-like texture(c).

However, in order to reduce the computational difficulty, in this paper we use the floquet periodicity as a boundary condition to replace the periodic array structure model. In addition, Perfectly Matched Layers (PML) are set in the incidence and output port, which can effectively absorb into the perfect match Layer area of the incident light. So we can see that a 2-D geometry with creating the cross section is described which is shown in figure 3.

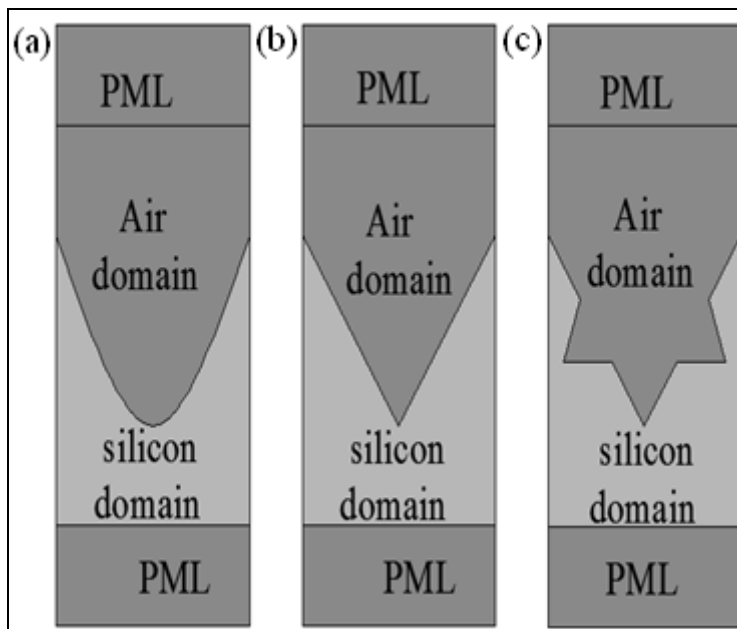


Figure 3. 2-D profile geometry depicts the various domains of the different texture models: semi-ellipse texture(a), inverted-pyramid texture(b) and fractal-like texture(c).

In the geometry which is described above, each region needs to be configured for the corresponding materials. The refractive index of the air domain is assumed to 1. But base material is multicrystalline silicon, which refractive index is different in different wavelengths. Therefore, it is necessary to use interpolation function set silicon refractive index of real and imaginary parts. Then the propagation of the electromagnetic field on the multicrystalline surface is simulated by the finite element method

(FEM), which is known that the solution converges to a given boundary value problem. Therefore, the finite element method is a good method to verify the solution. The constitutive equation is

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0^2 \epsilon_r \mathbf{E} = 0, \quad (1)$$

where $\mu_r = 1$, $\epsilon_r = n^2$, $k_0 = 2\pi / \lambda$; λ is the wavelength of the incident light, n is the refractive index of the material.

Finally, to evaluate the effect of the light trapping, we carried on the simulation of the light trapping effect in the wavelength range from 0.3 to 0.8 μm using the model above as shown in figure 3. The reflectance and surface electrical field intensity are compared in the same size with the ideal case, with the case of the inverted-pyramid texture, with the case of the semi-ellipse texture, and with that of the fractal-like texture.

3. Results and Discussion

In order to test and verify the effect of the fractal-like texture surface compared with the other two structures, the results of surface electrical field intensity and reflectivity for three structures previously mentioned are measured. And it should be noted that the results being simulated from a finite element model with the same size, materials, boundary conditions except for shape.

Figure 4 shows the distribution of surface electrical field intensity of the semi-ellipse texture, inverted-pyramid texture and fractal-like texture at the wavelength of 600 nm from a beam incident at the vertical angle. It can be seen from the figure 4, when the multicrystalline silicon texture morphology is different, the electric field intensity z component distribution is also different. And also it shows that the semi-elliptical textured surface electric field intensity z component shows stripe evenly distributed.

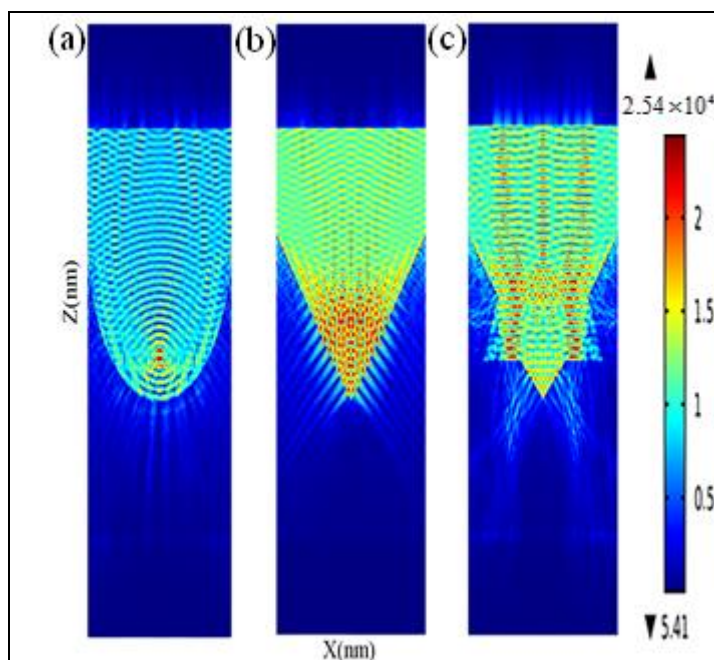


Figure 4. Distribution of surface electrical field intensity of the semi-ellipse texture(a), inverted-pyramid texture(b) and fractal-like texture(c) at the wavelength of 600nm.

The reflectivity of the fractal-like texture multicrystalline silicon is compared with the other texturings in figure 5, which has significantly reduced reflectivity. This is attributed to this fractal-like texture effects which can make a large number of photons into the inside of the multicrystalline silicon far above the other texturing. Simulation of reflection based on the fractal-like texture assumption show that it can obtain lower surface reflectance, is superior to the other two textured surfaces. The reflectivity may be further improved by optimizing the structure.

The result states clearly that a obvious light trapping effect can be obtained using the fractal-like texture, which is better than the other texturings.

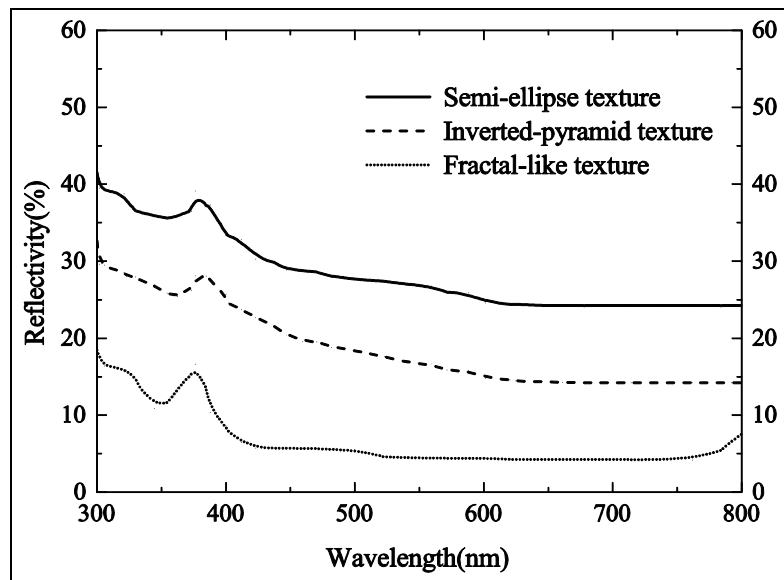


Figure 5. The reflectivity distribution of the semi-ellipse texture, inverted-pyramid texture and fractal-like texture at the wavelength range of 300-800 nm .

4. Conclusions

In summary, the fractal-like texture provides better optical properties than the other texture structures. Figure 1 shows the different light trapping effect between the fractal-like texture and the other two structures under ideal conditions. In accordance with the above simulation results, the fractal-like texture designed shows extremely good reflection results. The resultant multicrystalline silicon with a fractal-like structure as a solar cell can absorb more solar photon energy, and consequently has higher efficiency. The conclusion is that the fractal-like texture used in this work is very effective for enhancing optical performance. The novel "fractal-like texture" structure is introduced in this letter that may continue to increase the cost effectiveness of solar cells and extend the application of multicrystalline silicon.

Our further work will relate to model and optimize the other textures that could be manufactured through new processing technology.

Acknowledgments

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