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MODELING AND ANALYSIS OF THE IMPACT OF TEXTURING ANGLES ON DOPING PROFILES IN ION IMPLANTED N-TYPE SOLAR CELLS

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ABSTRACT

The aim of this paper is to develop an accurate model to study the impact of texturing angles on doping profiles in ion implanted solar cells. This study will help designers and manufacturers choose an optimal angle in texturing the surfaces of innovative solar cells. Using an optimal texturing angle will improve the performance of solar cells. Randomly chosen texturing angles may decrease the absorption of the sun light or introduce excessive defects as clustering or channeling. These defects will represent recombination centers for active electrons and holes. This will contribute seriously to the loss of the active carriers and then to the loss of solar cell efficiency. This loss is known as a recombination loss. This loss alone may reduce the efficiency of a solar cell by 20%. Numerical results showing the effects of texturing angles on doping profiles will be presented, analyzed, and validated.

Keywords: Mathematical models, simulation, texturing angles, solar cells.

1. INTRODUCTION

Numerical modeling and simulation represent a powerful approach that could be used by researchers and manufacturers to understand and investigate the loss mechanisms that are today limiting the efficiency of industrial solar cells. In this paper, we are developing and using an accurate numerical model to investigate, understand, and optimize the effects of texturing angles on the doping profiles and efficiency of modern textured and ion implanted silicon solar cells.

For the past few decades, the workhorse of the terrestrial solar cell industry has undoubtedly been the P-type crystalline silicon solar cells. However, this technology is reaching the limits of its efficiency potential (Bothe 2005), (Ho 2011), (Fabian 2014). Today, there is a need for innovative solar cell designs in order to reach higher efficiencies at lower cost.

N-type substrates and ion implantation are among the candidates of choice for the new silicon-based solar cells in recent photovoltaic market (Bothe 2005), (Ohrdese 2011), (Zimbardi 2012).

Phosphorus doped N-type solar cells present significant advantages over boron doped P-type solar cells. Mainly, N-type solar cells have higher carrier lifetime than P-type cells (Benick 2008, 2009), (Rohatgi 2012). This is primarily caused by the absence of the well-known boron-oxygen defects that exist in P-type cells (Glunz 2001). N-type solar cells do not suffer from light-induced degradation and are insensitive to common contaminants in the fabrication process (Rohatgi 2012); (Geerligs 2004).

Light-induced degradation is a well-known phenomenon in boron doped P-type silicon substrates. During the fabrication of a solar cell, oxygen impurities can be introduced into the bulk. Therefore, under sun light illumination, the minority carrier lifetime of the solar cell is seen to decrease over time. This issue has been caused by the formation of the metastable boron-oxygen complexes (Glunz 2001).

The use of phosphorus doped N-type silicon as substrate material of the new solar cells has the advantage of bypassing this light-induced degradation (Coletti 2012).

Ion implanted solar cells have recently emerged as the best candidates to make low cost and high efficient industrial solar cells (Rohatgi 2012); (Pawlak 2012); (Benick 2009); (Ohrdes 2011); (Zimbardi 2012); (Coletti 2012); (Meier 2010).

Different doping methods are used by different companies to doping industrial solar cells. Some companies use a blanket doping process from the gas phase by using phosphorous-ox-chloride (POCl) or from the paste attached by screen printing (Bateman 2011); (Ryu 2012); (Spitzer 1984). But, blanket doping is very imprecise and does not allow selective doping.

Recently, most of the solar cell manufacturers are using ion implantation technique to doping high efficiency and low cost solar cells. Ion implantation process has many advantages over the blanket doping process. Ion

implantation allows better control of the doping doses, doping depths, doping profiles, and doping-induced defects by adjusting the doping energy of the ion beam and other doping parameters as desired.

Advanced Texturing is one of the best candidates used today in photovoltaic industry to enhance the optical absorption of crystalline silicon solar cells and make lower cost solar cells. Efficient texturing could reduce the sun light reflection losses at the surface of the solar cells by more than 10% (Netsor 2010).
Randomly textured Silicon (001) wafers are used in modern solar cells (Xing 2011); (Netsor 2010). The texturing is fabricated using wet-chemical KOH etch including some special additives. After the application of etching, the textured solar cell surfaces will consist of square pyramids with {111} surfaces of different heights and angles.

Ion implantation on solar cells with textured surfaces is significantly different from ion implantation on solar cells with planar surfaces. This is due to the fact that texturing will increase the surface area of the solar cell and introduce extra defects. The increase of the surface area will lead to a reduction in the effective dose of the implanted ions. This reduction of the effective dose depends strongly on the texturing angle . The texturing angle may also create new types of doping-induced defects.

The goal of this paper is to develop and use an accurate mathematical model to investigate, understand, and optimize the effects of texturing angle on the doping profiles in ion implanted N-type solar cells with textured surfaces. The measurement of doping profiles in textured solar cells is still a challenge. Therefore, calculating the doping profiles in textured surfaces using mathematical models is strongly needed.

This model has been implemented in the process simulation software Suprem-IV and has been used to simulate different doping profiles under different texturing angles.
To the best of the authors' knowledge, no theoretical studies exist in literature in two dimensions (2D) about the effects of the texturing angle on the doping profiles in 2D textured solar cells.

This paper is organized as follows. Section 2 presents the theoretical models we have developed. Section 3 presents the numerical results and validation.
Section 4 presents the concluding thoughts and future work.

2. MATHEMATICAL MODEL

To improve efficiency of the novel solar cells, the reflection of the sunlight should be reduced. Surface texturing is used to reduce light reflections and enhance light trapping. When the photons of the sunlight hit the surface of the solar cell, some lights are reflected, some are passed through, and some are absorbed by the p-n junction region. Absorbing the light produces current by creating electron-hole pairs. Roughening the surface is called texturing. Texturing can be done by different ways.

Moncrystalline silicon solar cells are generally processed in an alkaline texturing solution to produce a random set of upright pyramids on the etched surface (Singh 2001); (Vazsonyi 1999); (Nishimoto 2000); (Marrero 2007) as shown in Figure 1 from (Jan 2014). It is the anisotropic nature of such an etchant that drives the formation of a repeated pyramidal geometries with different sizes and shapes as in Figure 1. This anisotropy is due mainly to the fact that the etch rate in the <100> direction is several times greater than that in the <111> direction. Many different etchants have been investigated, including aqueous solutions of NaOH (Singh 2001); Na2CO3 (Nishimoto 2000); KOH (Marrero 2007) and TMAH (Papet 2006).

The final geometry of the obtained pyramids depends strongly on the texturing techniques, texturing temperatures, composition of the solution, and on the pre-etch properties of the silicon surface. The geometry and the size of the obtained pyramids depends on the texturing angle and width (w) and height (h) of the pyramids as shown in the Figure 1.

To help designers and manufacturers of industrial solar cells find and use the values of , w, and h that will lower cost and improve efficiency, we should use mathematical models and numerical simulations.

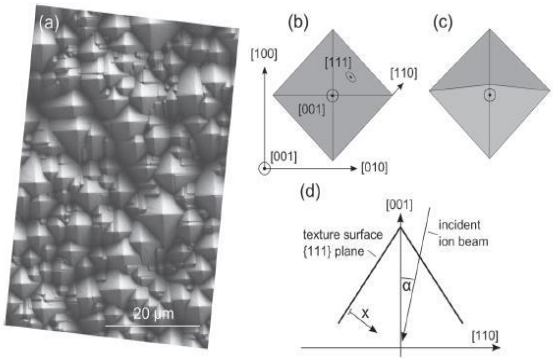

Figure 1: SEMS images of random pyramids.

Let ϕ be the dose of the incident ions from the ion implantation process. Let ϕ_{eff} be the effective dose of the ions that will penetrate the silicon substrate. Because of texturing ϕ_{eff} is smaller than ϕ. Let's define the texturing angle to be the angle between the incident ions and the normal to the substrate as

shown in Figure 1. Using simple vector analysis, we get the relation between ϕ, ϕ_{eff}, and as follows:

$$\phi_{eff} = \phi.\cos(\alpha) \quad (1)$$

When no texturing is applied, $\alpha = 0$, and $\phi_{eff} = \phi$.

Ion implantation is a random process. In literature (Betemann 2011); (Ryu 2012) the distribution of ions in the silicon substrate has been represented by Gauss probability density function C(x) for symmetric distributions and by Pearson IV probability density function f(x) for asymmetric distributions. Here, x represent the ion penetration depth. The Gaussian density function C(x) is given by:

$$C(x) = \frac{\phi}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(x-R)^2}{2\sigma}\right], \quad (2)$$

where, R is the projected range, σ is the standard deviation. Let υ_i represents the ith moment of C(x). Then, we have:

$$\upsilon_i = \frac{\int_0^\infty (x-R)^i C(x)dx}{\int_0^\infty C(x)dx} \quad (3)$$

Let γ, β represent the skewness and the kurtosis of C(x) respectively. Then, R, σ, γ, and β are calculated from the four moments of C(x) as follows:

$$R = \upsilon_1; \sigma = \sqrt{\upsilon_2}; \gamma = \frac{\upsilon_3}{\sigma^3}; \beta = \frac{\upsilon_4}{\sigma^4} \quad (4)$$

The Pearson IV probability density function f(x) is the 4th solution of the following first-order linear differential equation:

$$\frac{f'(s)}{f(s)} - \frac{s-a}{b+cs+ds^2} = 0; s = x - R \quad (5)$$

This differential equation has 7 solutions. The 4th solution is given by:

$$f(x) = \phi E \exp\left[F \times G\right]. \quad (6)$$

Where,

$$E = \left|b + cs + ds^2\right|^{\frac{1}{2d}} \quad (7)$$

$$F = -(\frac{c}{2d} + a)\frac{2}{\sqrt{4bd - c^2}} \quad (8)$$

$$G = \arctan(\frac{2ds + c}{\sqrt{4bd - c^2}}) \quad (9)$$

The coefficients a, b, c, d are calculated from the four moments of C(x) as follows:

$$a = c \quad (10)$$

$$b = \frac{4\beta - 3\gamma^2}{10\beta - 12\gamma^2 - 18}\sigma^2 \quad (11)$$

$$c = -\frac{\beta + 3}{10\beta - 12\gamma^2 - 18}\gamma\sigma \quad (12)$$

$$d = -\frac{2\beta - 3\gamma^2 - 6}{10\beta - 12\gamma^2 - 18} \quad (14)$$

The originality in this paper is that the dose ϕ in the equations (2) and (6) used to calculate the Gaussian and the Pearson IV densities C(x) and f(x) is replaced by the effective dose ϕ_{eff} which includes the texturing angle . In the new models we are proposing, the ion densities C(x), and f(x) are be replaced by the ion densities $Cn(x,\alpha)$ and $fn(x,\alpha)$ given by:

$$\begin{aligned} Cn(x,\alpha) &= \phi\cos(\alpha)C(x) \\ fn(x,\alpha) &= \phi\cos(\alpha)f(x) \end{aligned} \quad (11)$$

We have implemented these novel densities in the open source process simulator Suprem-IV (Hansen, 1993). We have used them to investigate the effects of the angle on the doping profile of Boron in ion implanted and textured silicon (001) solar cell shown in Figure 2.

3. NUMERICAL RESULTS AND VALIDATION

We use an N-type silicon (001) solar cell textured with identical pyramids of faces (111) as shown in Figure 2. The texturing angle was varied from 20° to 64° degrees. The height of pyramids is 0.12um. The width of the pyramids is 0.05um. The dose of Boron is $2\times10^{15} cm^{-2}$, implant energy is 10 KeV, the implant model is $fn(y,\alpha)$. The depth, y, of the cell is 0.37 um and the length, x, is 0.3 um. Figure 2 also shows the 2D Boron doping profile on textured solar cell for =36°. Figure 3 shows the cut of the Boron doping profile at x=0.15 and =36° and y between 0 um and 0.15 um. Figure 4 shows the cut of the Boron doping profile at x=0.15 and =64° and y between 0 um and 0.15 um. Figure 5 shows the cut of the Boron doping profile at x=0.15 and y between 0 um and 0.15 um when the surface of the solar cell is not textured. By comparing Figure 5 with Figures 3 and 4, we see that the texturing of the solar cell changes significantly the doping profile. This will affect significantly the efficiency of the textured solar cell. From Figures 3 and

4 we see the significant effects of the texturing angle on the doping profile. Two effects are visible: (i) reduction of the doping values with increasing . (ii) reduction of the implantation depth with increasing . The first effect could be explained by the reduction of the effective dose due to the angle as shown by the Equation (1). The other effect (ii) could also be explained by the reduction of the effective dose due to the angle . Small ion doses will produce shallow doping profiles seen in ii). For =36°, the maximum value of the doping is 1.2e+20 (atom/cm-2) (see Figure 3). For =64°, the maximum value of the doping is 7e+19 (atom/cm-2) (see Figure 4). These 2 values are smaller than the maximum value of the doping on non-textured surface which is 4e+20 (atom/cm-2) (see Figure 5). The implantation depth on textured surface for =36° is about 0.06 um and on non-textured surface for =0° is about 0.08 um. From these simulation results, we could suggest to use smaller texturing angles for ion implantation on textured surfaces if shallow profiles are not needed. On the other hand, it has been shown in (Zahi, 2018), that with smaller angles around 36°, the measurements of doping profiles in textured solar cells using the secondary ion mass spectrometry (SIMS) technique are more accurate than with larger angles. We should note that the measurements of doping profiles using SIMS technique are strongly depending on the texturing angles as well. The doping profiles obtained in this simulation are in a good agreement with SIMS measured profiles obtained in (Zahi 2018).

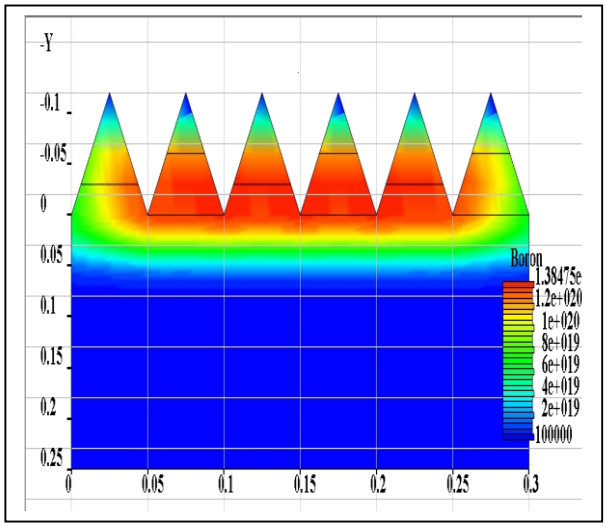

Figure 2: 2D sample textured solar cell.

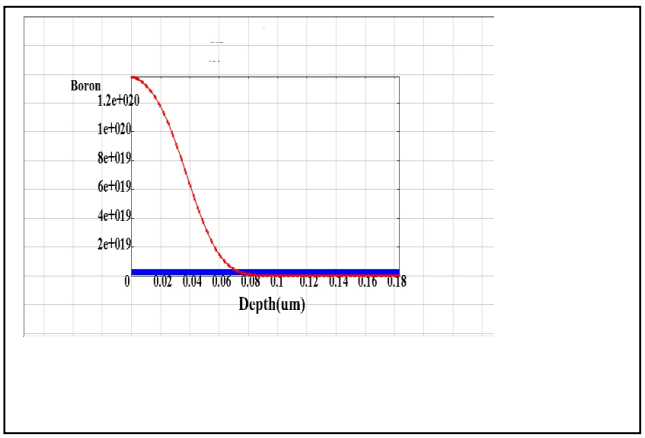

Figure 3: Boron doping profile on textured surface for α =36°.

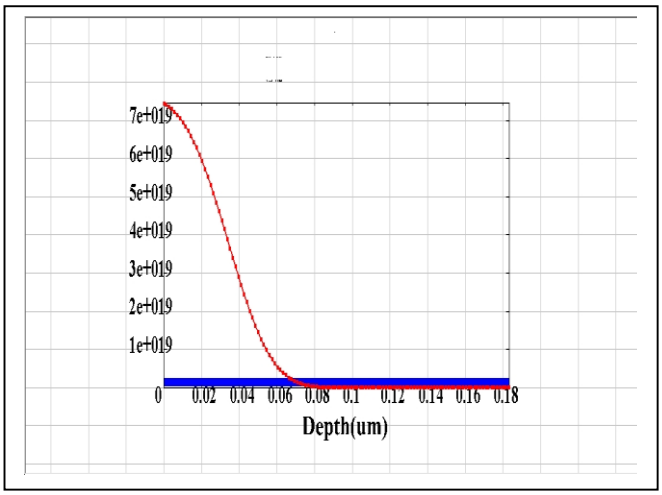

Figure 4: Boron doping profile on textured surface for α =64°.

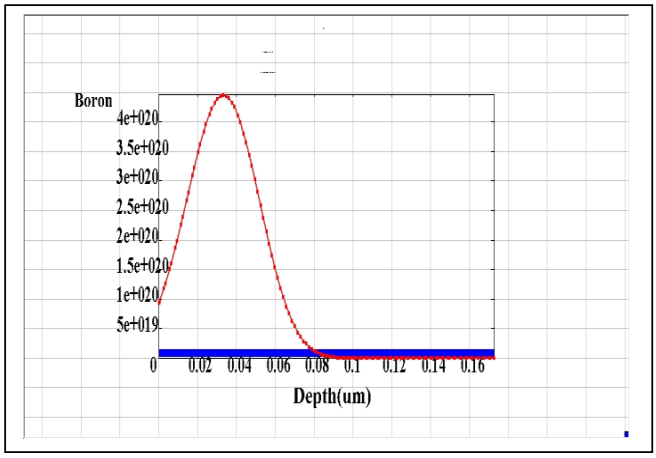

Figure 5: Boron doping profile on non-textured solar cell (for α =0°).

4. CONCLUSIONS

We have shown that the texturing angle affects significantly the doping profiles in textured solar cells. The values of the doping and the implantation depth are decreasing with increasing . By comparing the doping profiles on planar surface shown in Figure 5 with doping profiles on textured surfaces shown in Figures 3 and 4, we see that the shape of the doping profiles are also affected by the texturing angle . In future work, we will investigate the effects of the size of the pyramids on the doping profiles.

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