Development of antireflective coatings based on SiO$_2$/Si$_3$N$_4$ on textured silicon for heterojunction solar cells

Y Nevenchannyy$^1$, K Khoruzhiy$^1$, D Kudryashov$^2$

$^1$Lyceum "Physical-Technical High School" (PTHS), St. Petersburg 194021, Russia
$^2$St. Petersburg Academic University, St. Petersburg 194021, Russia

Abstract. The technology of antireflective coatings formation on textured silicon by magnetron sputtering was developed. The growth rates of individuals thin films were determined as well as their refractive indexes. According to the results obtained an antireflective coating based on SiO$_2$/Si$_3$N$_4$ on textured silicon with a thickness of SiO$_2$ 68 nm and Si$_3$N$_4$ of 74 nm showed the lowest reflection.

1. Introduction
Silicon-based heterojunction solar cell (SHSC) is one of the most attractive solar cell architectures due to its numerous advantages such as low fabrication temperature, source materials availability, scalable for the mass production, low surface recombination. To realize the whole potential of the SHSC limiting factors are needed to be eliminated such as an optical reflection from the front surface of solar cell. To reduce the reflection, such approaches as texturing the surface of solar cells [1] and the use of antireflective (AR) coatings [2] are known. Due to texturing, the incident light is repeatedly reflected from the faces of the micro-pyramids, thus more light penetrates into the material and the reflection from the solar cell is reduced. AR coatings are based on effect optical interference. Under certain conditions the amplitude of the reflected electromagnetic waves decreases, causing the reflection coefficient to decrease accordingly. The aim of this work is to combine these two approaches and to develop a technology of manufacturing of AR coatings based on SiO$_2$/Si$_3$N$_4$ layers on textured silicon for heterojunction solar cells.

2. Experiment details
SiO$_2$/Si$_3$N$_4$ layers were grown by RF-magnetron sputtering on BOC EDWARDS Auto 500RF Sputter Coater. The deposition was conducted with a magnetron power of 200 W and a chamber pressure of $10^{-4}$ - $10^{-3}$ mbar. Pure argon (99.999 %) was used as a working gas for plasma maintenance. To grow the oxide and nitride layers, oxygen or nitrogen were additionally supplied to the growth chamber. A silicon target with a diameter of 3” was used as a Si source. The layers were deposited on a flat and a textured monocrystalline Si(100) substrates and also on glass slides to check the transmittance of the applied layers. The control of the thickness of the obtained layers was carried out using a profilometer AMBiOS XP-1. The refractive index at a wavelength of 633 nm was determined using ellipsometer HORIBA JOBIN YVON. Total reflection spectra of the polished samples were recorded using a S100 spectrometer. Total reflection spectra of the textured samples were recorded using integrating sphere.

In the first phase of the research one-layer films were grown with different magnetron power to find out the growth rate and the conditions when the refractive indexes of the layers were closest to the monocystal structures of SiO$_2$ and Si$_3$N$_4$ (Fig 1). Rise of magnetron power leads to an increasing of film growth rate. Refractive index of Si$_3$N$_4$ thin film non-linearly depends on sputtering power and after the magnetron power value of 200 W remains nearly constant.
Then using the obtained data, theoretical calculation of the SiO$_2$/Si$_3$N$_4$ pair of thicknesses, which would give the smallest average reflection for wavelengths from 400 to 1000 nm, for two-layer AR coating were carried out.

![Figure 1](image1.png)

**Figure 1.** Silicon nitride growth rate (a) and its refractive index (b) as a function of magnetron power.

A series of films depositions by magnetron sputtering were carried out with different pairs of thicknesses of silicon nitride and oxide, based on theoretical calculations, to find the optimal combination which would give the minimal average reflectance.

Finally, the AR deposition was carried out on textured silicon surface. The following method was used to texture silicon. The polished silicon wafer (100) was divided into several samples (4x4 cm$^2$) and were set in a teflon holder. The samples were placed in an aqueous solution of isopropyl alcohol and KOH. The temperature of the solution was maintained at 85 °C. The samples were kept under such conditions for 60 minutes, after which they were rinsed with distilled water to remove alkali residues. SEM image of textured silicon wafer is shown on Fig 2.

![Figure 2](image2.png)

**Figure 2.** SEM image of silicon surface after texturing process.

The textured wafer along with a polished one were used as substrates for AR coating deposition. The samples were mounted on a substrate holder. The deposition was conducted without additional substrate heating.

3. Results and discussion

Figure 3 demonstrates calculated integral reflection coefficients for SiO$_2$/Si$_3$N$_4$ AR coating formed on silicon as a function of the layers thickness.
Figure 3. Calculated integral reflection coefficients for SiO$_2$/Si$_3$N$_4$ AR coating formed on silicon as a function of the layers thickness.

The lowest reflection is observed at thicknesses of silicon oxide and nitride of 80 nm. Increasing of both layers thicknesses over 80 nm leads to a rising of integral reflection. Experimental data for measured total reflection spectra of polished samples with AR coatings are presented on figure 4, while the average reflectance coefficients are presented in table 1.

Figure 4. Measured reflection spectra of polished silicon samples with and without AR coatings.

Flat silicon sample without any deposited thin films show an average reflectance of a 37% in a wavelength range of 300-1100 nm. This is a very large value for the top surface of solar cell. For this reason an AR coating is needed to reduce optical reflection. Deposition of silicon oxide and nitride thin films leads to a changing of reflectance spectra. In one wavelength region the reflectance is decreasing but in other – on the contrary – it tends to get close to initial, corresponding to the bare silicon.

Experimental data for measured total reflection spectra measured on textured samples with AR coatings are presented on figure 5, and the average reflectance coefficients in table 2.
Table 1. Characteristics of grown AR coatings formed on polished silicon surface.

| Thickness of Si$_3$N$_4$ layer (nm) | Thickness of SiO$_2$ layer (nm) | $R_{av}$ (%) |
|-------------------------------------|---------------------------------|-------------|
| 0                                   | 0                               | 36          |
| 73                                  | 73                              | 15.3        |
| 83                                  | 83                              | 11.7        |
| 90                                  | 100                             | 10.3        |
| 105                                 | 115                             | 10.9        |
| 130                                 | 130                             | 17.7        |
| 140                                 | 155                             | 13.5        |
| 163                                 | 179                             | 18.3        |

The lowest reflection from textured samples is observed at the thickness of SiO$_2$ 68 nm and Si$_3$N$_4$ of 74 nm. Small deviation from the simulated earlier values could be connected with the effect of thinning of film thickness while depositing on inclined surface like textured pyramid.

Figure 5. Measured total reflection spectra of textured samples with AR coatings.

The reflectance spectra for the textured silicon show more smooth form without very pronounced peaks. Its form is more suitable for solar cells fabrication.

The lowest reflection from polished samples was observed at the thickness of SiO$_2$ 90 nm and Si$_3$N$_4$ of 100 nm with the average reflectance of 10.3%.

Table 2. Characteristics of an AR coating formed on textured silicon surface.

| Thickness of Si$_3$N$_4$ layer (nm) | Thickness of SiO$_2$ layer (nm) | $R_{av}$ (%) |
|-------------------------------------|---------------------------------|-------------|
| 0                                   | 0                               | 14.7        |
| 68                                  | 74                              | 3.64        |
| 83                                  | 83                              | 4.3         |
| 90                                  | 100                             | 3.95        |
| 105                                 | 115                             | 3.76        |

The technology of AR coatings formation on textured silicon by magnetron sputtering was developed. According to the results obtained an antireflective coating based on SiO$_2$/Si$_3$N$_4$ on textured silicon with a thickness of SiO$_2$ 68 nm and Si$_3$N$_4$ of 74 nm showed the lowest reflection.
Acknowledgements
This work was carried out with the support of the grant of government of the Russian Federation (16.2593.2017/8.9)

References
[1] Kudryashov D, Gudovskikh A, Rodin A, Pinaev N. 2018 J. Phys: Conf. Series 1124 041010
[2] Kotlikov E N 2009 Design, Manufacturing and Investigation of Interference Coatings: Tutorial (St. Petersburg: GUA Press) p 188