Surface morphology after reactive ion etching of silicon and gallium arsenide based solar cells

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Abstract. This work aims to study the surface morphology of solar cells before and after reactive ion etching (RIE) at two different pressures. Two types of solar cell based on GaAs and polycrystalline Si were processed and compared. Energy Dispersive X-ray spectroscopy (EDS) was used for the composition analysis of the samples. Raman spectroscopy showed a structural fingerprint of materials before and after processing. Atomic Force Microscope (AFM) demonstrated dimensional topography with high resolution. Optical spectrometer detected changing of reflectance the samples. Experimentally, it has been confirmed that GaAs solar cells have a very high endurance to ion bombardment in comparison to Si cells.

1. Introduction
It is known that silicon is the most used material for the fabrication of solar cells. Due to this it is also widely available with an affordable purchase price. On the other hand, GaAs based cells are mainly used in difficult conditions such as space, military or air. We focused on the morphology and structure of the surface of these two types of solar cells to demonstrate their real endurance and compare the differences between them. For surface processing, we chose ion bombardment. It has been shown that in some cases the loss of energy is caused by the reflection of light from the surface, and surface treatment or an antireflective film is required to improve light absorption efficiency [1, 2].

2. Methods
The samples of GaAs and polycrystalline Si solar cells were etched by chemically reactive plasma. This was done using a PlasmaPro 100 Cobra ICP Etch system, where activated reactive gases were made of sulphur hexafluoride ($\text{SF}_6$), chlorine ($\text{Cl}_2$) and oxygen ($\text{O}_2$). Etch conditions strongly depend on gas flow, pressure and RF power. Therefore, we chose two treatments under different conditions. In our case RF power was 200 watts for both processing the same, as well as the gas flow was not changed. However, the difference was in the pressure setting – for the first processing we chose 40 mTorr and for the second processing 10 mTorr. It is also important to note that these two treatments did not follow each other, but was done separately for each new specimen.
3. Experimental results

After etching of silicon at a pressure of 40 mTorr in Figure 1b, it is noticeably visible that the surface differences are up to 2 μm greater than the surface in Figure 1a which was not processed [3]. These changes indicate a significant increase of $S_a$ parameter, up to 576.5 nm, in Table 1. This parameter expresses the absolute value of the difference in height of each point relative to the arithmetic mean of the surface. There is also a much lower occurrence of features than in Figure 1a.

After etching at a pressure of 10 mTorr, Figure 1c shows much sharper features than before etching in Figure 1a. Sharpness is also indicated by coefficient of kurtosis of $-0.386$ in Table 1. In comparison between the two figures we can see the relatively similar roughness of the surface, which is also confirmed by the value of $S_a$ in Table 1.

Differences in morphology of etching GaAs based solar cell compared to the Si based are noticeable from the Figure 2. In particular, there are minimal peak height changes which, after etching at 40 mTorr (Figure 2b) and 10 mTorr (Figure 2c), have a difference of only 5 nm. For silicon based solar cells, the peak height change occurred within 2 μm, as written above.

With decreasing etching pressure, an increasing number of features (Figure 2b and 2c) and higher coefficient of kurtosis can be observed. It can be argued that, at pressure of 10 mTorr, the sharper edges of the features begin to form on both the silicon sample (Figure 1c) and the gallium arsenide sample (Figure 2c). However, the structural changes occurred on the Si cell surface in order of micrometers, but for the GaAs solar cell, it was in nanometer units. Thus, in GaAs sample, much higher reflectivity can be expected in this case. Reflectivity is directly related to surface roughness.
Figure 2(a, b, c). Measurement by AFM; (a) GaAs solar cell before processing; (b) GaAs solar cell after RIE processing with pressure of 40 mTorr; (c) GaAs solar cell after RIE processing with pressure of 10 mTorr.

Compared to silicon in gallium arsenide cells, minor differences were observed with AFM. The heights remained constant at similar sizes around 20 nm [4], while in the second processing with lower pressure, a larger number of features began to appear. Features achieved the highest heights during etching pressure of 10 mTorr.

Table 1. Calculated $S$ parameters obtained by AFM.

|                  | Average Roughness $S_1$ [nm] | Root Mean Square $S_q$ [nm] | Surface skewness $S_{sk}$ [-] | Coefficient of kurtosis $S_{ka}$ [-] |
|------------------|-------------------------------|----------------------------|--------------------------------|---------------------------------------|
|                  | Si                           | GaAs                       | Si                             | GaAs                                 | Si                                   | GaAs                                 |
| No etching       | 152.1                        | 2.133                      | 186.6                          | 2.716                                | −0.1                                | 0.133                                | −0.487                              | 0.085                                |
| RIE, 40 mTorr    | 576.5                        | 3.327                      | 741.7                          | 4.111                                | 0.077                               | 0.056                                | −0.102                              | −0.28                                |
| RIE, 10 mTorr    | 186.6                        | 2.356                      | 228.9                          | 3.057                                | 0.139                               | 0.207                                | −0.386                              | 0.976                                |

Significant changes in the composition of material can be observed by using of electron dispersion spectroscopy on the cell surface in Figure 3. After etching at pressure of 10 mTorr there was a noticeable influence of SF$_6$ reactive gas, which is characterized by a fluorine peak in the spectrum. In contrast, at a higher pressure of 40 mTorr, there was a decrease of the fluorine peak. However, the intensity of silicon at the 1.75 keV band almost doubled against non-etched sample. This can be also attributed to the loss of silver that is used in silicon as a doped material.

In the case of GaAs sample, a much lower difference in the material composition compared to Si sample can be observed. In particular, the changes at different etch pressure in Figure 4. Here the composition of the material was almost the same. However, the decrease in intensity is noticeable before and after processing.
Using of Raman spectroscopy, the change in intensity for both types of cell was observed on the samples. However, each material has a different behavior within the Raman spectra. Figure 5a shows a typical silicon spectrum with several silicone modes. The decrease in spectrum intensity is evident. The largest drop was observed in the case of etching at pressure of 10 mTorr. A number of factors may lead to this effect. One of them may for example be a different roughness of the surface.

The opposite phenomenon can be seen in GaAs spectrum (Figure 5b). Band shape and intensity are strongly influenced by etching. However, unlike silicon, the intensity of the spectrum has increased after etching. There is also a larger peak with full width at half maximum (FWHM). On a longitudinal mode of GaAs of about 270 cm$^{-1}$, a peak slope can be observed after etching. This also indicates mechanical stresses due to structural damage. Longitudinal mode of AlAs with a value of about 395 cm$^{-1}$ has a much smaller height after etching. Which could be expected because the GaAs sample was doped with aluminum on its surface.
Figure 5(a, b). Measurement using Raman spectroscopy; (a) Si solar cell before and after processing; (b) GaAs solar cell before and after processing.

Measured reflectance of both types of solar cells confirms the intensity drop in both etching pressure of 40 and 10 mTorr. Interestingly, the Si based cell had a higher decline in reflectivity using etching at 40 mTorr (Figure 6a), but in the GaAs-based cell there was higher drop in etching at 10 mTorr (Figure 6b). This confirms the different behavior of the morphology of these materials. It is also noticeable from the figures that the GaAs solar cell has a much greater reflectivity than Si cell which also contributes to a much higher roughness degree as mentioned in Table 1.

Figure 6(a, b). Measurement of reflectance in the ultraviolet region of the spectrum; (a) Si solar cell before and after processing; (b) GaAs solar cell before and after processing.
4. Conclusion
Using various experimental measurements, it has been verified that silicon based solar cells are more susceptible to surface modification than GaAs based solar cells processed by RIE. These differences are particularly noticeable in Table 1, where data were obtained using AFM, where the average values for silicon vary within hundreds of nanometers. An increasing coefficient of kurtosis was also observed for both types of cells with 10 mTorr pressure.

It was found that the material composition significantly differs in silicon after etching analysing by EDS. Compared to that, in GaAs sample was found only decrease in intensity. Any other changes between etching pressures of 10 and 40 mTorr for this cell were not observed.

Raman spectroscopy revealed the different behaviour of both types of cells. With the decreasing etching pressure on the Si specimen, the intensity of the Raman peaks has also decreased. In contrast to GaAs specimens with lower etching pressure, the total spectral intensity increased.

Optical spectrometer confirmed a difference for material modification and reflectance changing for both Si and GaAs samples. The reflectivity dropped after etching in all cases. This was already assumed according to the findings from the measured roughness degree using AFM. However, much higher reflectivity was measured on the GaAs sample surface. This is due to the fact that the features of GaAs surface rise to about 20 nm, on the other hand, the Si surface features differs by up to 3 μm which is a very significant difference.

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