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AN OVERVIEW OF PLASMA SOURCES SUITABLE FOR DRY ETCHING OF SOLAR CELLS

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ABSTRACT

Characteristic feature of a plasma system is the method of plasma excitation. A parallel plate system, i.e. reactive ion etching (RIE), the atmospheric downstream plasma (ADP) source and two types of microwave plasma sources (slot and linear antenna) are tested regarding their suitability for solar cell processing in terms of high throughput and plasma-induced damage. In silicon etching possibly occurring damage was analyzed by means of solar cells. No decrease of cell parameters is observed if ion bombardment is avoided (slot and linear antenna plasma source, ADP). The parallel plate system and the slot antenna source show insufficient etch rates «1 um/min) while those of linear antennas and ADP are extremely high (>10 µm/min). Therefore, of the analyzed plasma sources the latter represent the most promising systems for solar cell processing.

INTRODUCTION

Although in semiconductor industry plasma etching has been a well established technology for more than 15 years it is not widely used in solar cell production. Only edge isolation is performed by plasma etching in barrel type reactors in some fabrication lines. Recently though, because of increasing water and chemical waste disposal costs, the photovoltaic industry has been showing an increasing interest in other dry etching processes as well, like saw damage removal, surface texturing and cleaning, or phosphorous silicate glass removal [1].

Various plasma systems are available on the market. However, not all of them are suitable for use in solar cell processing. Especially in terms of high throughput and plasma-induced damage [2-5] these systems have to meet other requirements than e.g. in micro technology.

For two years large area plasma chambers for fast SiNx deposition have been available on the market now. Since these machines work in a semi-continuous mode, they are very well suited to meet the requirements of high throughput solar cell production. With the existing knowledge a break-through in the field of high throughput plasma etchers will be achieved soon.

The characteristic feature of a plasma system is the plasma source that creates the plasma. Since a large variety of plasma sources is available on the market we have chosen four representative methods of plasma etching (reactive ion etching (RIE), microwave downstream etching (MWDSE) with the slot antenna plasma source (SLAN), MWDSE with linear antennas, and atmospheric downstream plasma (ADP) etching) that will be described and evaluated in terms of etch rates, i.e. throughput, and of plasma-induced damage.

EXPERIMENTAL

In order to characterize plasma-induced damage 25x25 mm^2 solar cells were made from 0.5 Ω cm p-type float zone silicon. The wafer surface was cleaned by plasma etching. Those wafers that were etched by Tru-Si, Sunnyvale, and Secon, Vienna, received additional wet chemical (RCA) cleaning in order to eliminate any surface contamination due to the shipping of the samples. Since the RCA clean only removes a few nm of the wafer surface it is assumed that is does not affect possible damage of the plasma treated wafer surface. The samples then received an 80 Ω/sq. emitter by $POCl_3$ diffusion, an Al back surfaces field, a photolithographic front metallization and an MgF/TiO_2 antireflection coating (no surface texturing).

The open-circuit voltage is used as a measure of plasma-induced damage, since it reacts very sensitively to defects in silicon. In addition, the short circuit current provides information on possible surface roughness due to the etching process.

Each plasma source was investigated with a different batch of solar cells. Therefore, results within a batch due to etch parameter variation are well comparable, whereas the overall cell performance may vary a little from batch to batch because of slightly different processing conditions.

PARALLEL PLATE SYSTEMS

Parallel plate setups (diode etchers) are widely spread etching systems. The substrate electrode is capacitive powered by RF while the counter electrode and the chamber walls function as a grounded anode. In case of an asymmetric electrode configuration (anode area larger than cathode area) a negative de-bias builds up towards the substrate electrode due to which ions are accelerated onto the sample surface [6] (Fig. 1). If reactive (F, Cl or Br containing) gases are used this etching configuration is called reactive ion etching. Due to the ion bombardment a physical etch component occurs in addition to the chemical etch component. The de-bias is a function of the used etch chemistry, the process pressure and the RF power. It increases almost linearly with RF power [7,8].

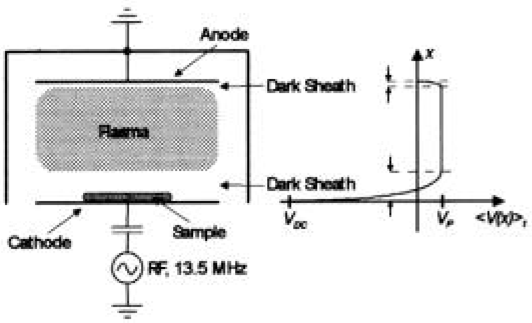

Fig. 1: Schematic of reactive ion etching: The sample lies on the powered electrode of a parallel plate reactor. The asymmetric chamber geometry and capacitive power coupling leads to a de-bias which results in ion bombardment of the sample.

Naturally, higher ion bombardment leads to higher etch rates. At the same time, it causes more severe damage, which strongly affects solar cell performance [2,3]. Hence, the best compromise between fast processes and low damage has to be found, i.e. process speed is limited by plasma-induced damage. In SF_6 RIE the etch rates can also be increased by oxygen addition. By this, etch rates between 0.5 and 1 µm/min can be achieved. But O_2 addition, too, affects plasma-induced damage.

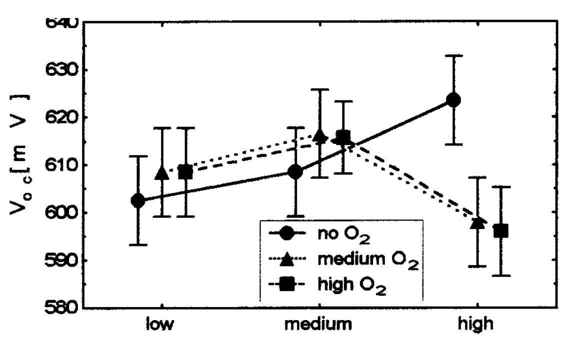

Fig. 2: Open circuit voltage of plasma etched solar cells as a function of RF power and oxygen addition to SF_6 RIE (2.5 urn Si removal).

The plasma etched solar cells (2.5 µm Si removal) show that for oxygen containing SF_6 plasmas the open circuit voltages go through a maximum of 615 mV at medium RF power [Fig. 2]. V_{oc} > 620 mV are only achieved by oxygen free SF_6 RIE at high RF power.

The short circuit current shows the same dependency on RF power and O_2 addition as the open circuit voltage. The fill factor however seems not to be affected significantly by the investigated parameters.

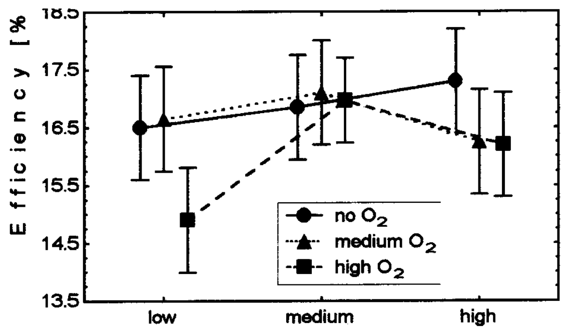

Fig. 3: Solar cell efficiency of plasma etched solar cells as a function of RF power and oxygen addition to SF_6 RIE (2.5 µm Si removal).

Hence, maximum solar cell efficiencies of 17% are obtained at medium RF power for oxygen containing SF_6 plasmas whereas the absolute maximum of 17.3% is achieved by O_2 free plasmas at high RF power (Fig. 3).

It is therefore possible to develop very low-damage silicon etch processes by SF_6/O_2 RIE. However, due to the ion bombardment a small amount of damage still remains, which prevents high efficiency cells from reaching the performance that is obtained by the wet chemically treated reference cells (632 mV and 17.8%).

While RIE might be interesting for the removal of phosphorous silicate glass [1], it is not well suited for fast silicon etching because of the small etch rates. In order to obtain high throughput reaction chambers may not simply be scaled up since large electrode areas counteract the asymmetry of the setup, which is necessary in RIE.

SLOT ANTENNA MW PLASMA SOURCE

Microwave plasmas may be excited by various methods. One of these is the so called slot antenna (SLAN), in which the MW power is coupled from a cavity through slots into the reaction chamber [9,10]. The reactive species then passes by the wafer surface purely due to diffusion. Therefore, the parameters by which the etch rate is controlled are the diffusion length of the reactive species, i.e. process pressure, and the distance between the plasma and the wafer surface. In the system used in this work the minimum distance between plasma and wafer is about 50 cm which results in etch rates of about 0.5 µm/min.

The plasma may be excited by MW power of varying magnitude. However, no significant dependency of solar cell parameters on the MW power between 600 W and 800 W is observed (Tab. 1). The open circuit voltage of the plasma etched samples (2.5 µm Si removal) lie with 625 mV very close to the wet etched reference cells. Short circuit currents at 800 W MW power seem to be larger than that of the reference cells, whereas the fill factor of the same samples is lower. This is probably due to some sort of surface roughness, which can not be accounted for, though.

Tab. 1. Results of plasma etched solar cells after MWDSE (slot antenna) with varying MW power (2.5 µm Si removal).

MW Power [W]	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	η [%]
Reference	627±4	34.7±0.4	79.7±0.6	17.4±0.5
600	625±2	35.1±0.1	80.3±0.6	17.6±0.3
800	625±3	35.7±0.0	78.6±0.7	17.6±0.2
1000	624±2	34.6±0.0	79.4±1.0	17.1±0.3

Hence, maximum efficiencies of 17.8% are obtained by plasma treatment which is equal to wet etched cells. Damage free processing is therefore possible. Although, the obtained silicon etch rates are much too low for an industrial implementation, the SLAN is a very flexible plasma source that can easily be attached to almost any kind of plasma chamber and might therefore be interesting for lab type applications.

LINEAR ANTENNA MW PLASMA SOURCE

A second type of microwave plasma source consists of conducting rods (e.g. made from copper) into which either from one end or from both ends the MW power is coupled [11-13] (Fig. 4). The plasma builds up around the rod and along its entire length. Several of these antennas can be used simultaneously in order to obtain homogeneity over a large area. Additionally, the substrate electrode can be biased and thus the etch rates enhanced by ion bombardment. However, even without substrate biasing etch rates >10 µm/min are achieved in a system by Secon.

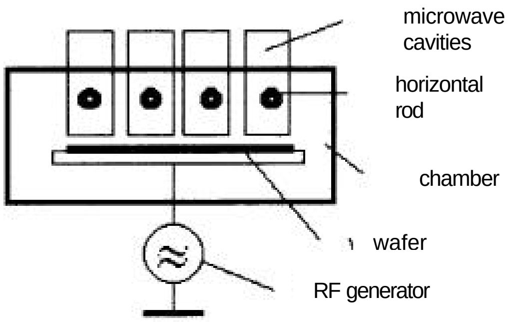

Fig. 4: Schematic of the linear antenna microwave plasma setup. The plasma builds up around the antenna (copper rod) along its entire length.

Solar cells etched in a system like this show no degradation in open circuit voltage even after removal of 19 µm of silicon of the wafer surface (Tab. 2). Maximum efficiencies of >18% are obtained. Plasma-induced damage is only observed if the substrate electrode is biased by additional RF power. Voc drops by more than 15 mV due to the ion bombardment. At the same time, though, J_{sc} increases by almost 0.5 mA/cm^2 due to some sort of surface texturing.

Tab. 2. Results of plasma etched solar cells after MWDSE (linear antenna) with varying silicon removal.

Si Removal [µm]	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	η [%]
Reference	635±0	35.9±0.2	80.0±0.6	18.2±0.0
6	630±2	36.0±0.0	79.9±0.1	18.1±0.0
19	632±2	35.7±0.2	79.4±0.3	17.9±0.2
19 (RIE)	614±1	36.4±0.3	79.2±0.6	17.7±0.3

Linear antenna MW plasma sources are very appropriate for use in solar cell processing because the etching is damage free as long as additional substrate biasing is avoided. The etch rates are very high (~10 µm/min) and the use of several antennas allows for homogeneous large area plasma excitation.

ATMOSPHERIC DOWNSTREAM PLASMA SOURCE

The atmospheric downstream plasma (ADP) is an inert gas thermal plasma generated by DC discharge at atmospheric pressure in the process chamber (Fig. 5) [14]. The reactant is injected into the plasma stream outside the plasma source. Due to the high temperature of the plasma, the reactant is fully decomposed.

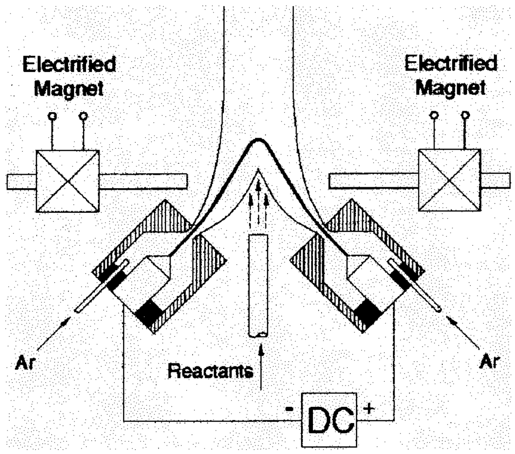

Fig. 5: Schematic of the Atmospheric Downstream Plasma Source (ADP). Reactant gases are injected at atmospheric pressure into an inert gas dc arc-plasma discharge where they are fully decomposed.

By deploying the plasma in a downstream configuration ADP prevents ion impact damage. Batch-mode processing of 13 4" wafers results in single-wafer equivalent etch rates of >40 µm/min in Si.

All of the plasma etched solar cells show the same results as the wet etched reference cells (Tab. 3). No significant difference between removal of 5 µm and 20 µm of silicon is observed. Maximum open circuit voltage is 632 mV and maximum efficiency 18.1%, The fill factor is slightly increased due to smaller contact resistances.

Tab. 3. Results of plasma cleaned solar cells after ADP etching with varying silicon removal.

Si Removal [µm]	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	η [%]
Reference	627±5	35.7±0.1	79.0±0.0	17.7±0.1
5	625±4	35.4±0.2	80.2±0.4	17.8±0.3
20	624±2	35.4±0.1	80.1±0.5	17.7±0.1

Hence, APD proves to be a method that allows damage free and fast thinning of wafers with etch rate of >10 pm/min. However, the reactive region on a wafer is currently in the order of a few 10 µm². Thus, in order to realize a throughput of 1000 wafers/min an array or a line of several of these plasma sources is necessary.

CONCLUSION

Of the investigated plasma sources the atmospheric downstream plasma (ADP) source and the linear antenna microwave plasma source show the highest potential of implementation in dry silicon etch processes in an industrial solar cell fabrication. Both plasma sources allow damage-free etching and achieve etch rates > 10 µm/min. ADP has the advantage of atmospheric operating pressure and, thus, makes vacuum equipment unnecessary. The linear antenna microwave plasma source represents a typical large area plasma source. At the present stage this source seems to be more likely to be implemented first. It is easily up scalable so that large areas of silicon can be treated and the requirements of throughput can be met. In addition, similar plasma systems are already in use in PV production for the deposition of silicon nitride.

The slot antenna MW plasma source is a very flexible toot that is well suited for lab type applications. Although it allows damage free silicon etching it lacks in etch rate (0.5 µm/min). Reactive ion etching is not completely damage free due to ion bombardment. In parallel plate systems etch rates or 0.5-1 µm/min are obtained. However, parallel plate systems are not easily scaled up since large electrode areas counteract the asymmetry of the set up which is necessary in RIE.

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