PLASMA PROPERTIES OF A NOVEL COMMERCIAL PLASMA SOURCE FOR HIGH-THROUGHPUT PROCESSING OF c-Si SOLAR CELLS

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ABSTRACT

A novel commercial plasma source for high-throughput processing of crystalline silicon solar cells is presented. In this paper, the plasma properties of this so-called Expanding Thermal Plasma (ETP) technique are addressed in detail and its application in an inline PECVD tool for ultrahigh-rate deposition of silicon nitride for anti-reflection coating purposes is described.

INTRODUCTION

Plasma processes are nowadays present in about every state-of-the-art production line of crystalline silicon solar cells, mostly for the deposition of silicon nitride films. These films, deposited generally from a SiH_4-NH_3 reactant mixture, serve as multifunctional antireflection coating as they reduce optical losses and provide surface and bulk passivation (in the case of multicrystalline or ribbon silicon). It is however expected that in the future more plasma steps will be introduced in the production process, for example dry etch processes for wafer cleaning and the removal of saw damage; for surface texturing; and for etching of the phosphorous silicon glass after emitter diffusion. These plasma etch processes can replace the wet etch steps, which are relatively costly due to the use of large amounts of chemicals as well as due to their waste treatment. Dry etching can also be beneficial in terms of throughput and yield, especially when going to thinner wafers or when having different requirements for the front and back side of the wafer (e.g., only front-surface texturing). Furthermore, plasma processes allow the combination of different production steps in, e.g., one vacuum system, such as phosphorous silicon glass etching and anti-reflection coating deposition.

Cost-effective solar cell production requires however plasma sources that can handle a high throughput. For radiofrequency parallel plate reactors or microwave plasmas, this results generally in relatively long reactor chambers and consequently in relatively high investment costs. A more efficient plasma source which can deliver very large fluxes of reactive species (radicals, ions, etc.) is therefore preferred, as it allows for a much smaller footprint of the production equipment. Furthermore, some other important issues are a high-robustness and easy-maintenance of the source, absence of drift of the plasma source in time (preferentially a dc source), large freedom in reactant mixtures, as well as remote operation (i.e., plasma production is geometrically separated from the deposition zone, such that changes in the deposition zone do not affect plasma production). A plasma source that fulfills most of these requirements is the Expanding Thermal Plasma (ETP) source invented at the Eindhoven University of Technology [1]. After an initial period of more than a decade of lab-operation [2,3], this source has recently been commercialized [4,5]. Figure 1 shows the novel commercial version of this plasma source as developed by OTB Solar and used on their DEP_x PECVD tool [5]. In this contribution we discuss the basics of the ETP technique as well as its plasma properties, and we describe the application of the technique for ultrahigh-rate deposition of silicon nitride antireflection coatings.

THE ETP TECHNIQUE: THE BASICS

The ETP technique combines a high-pressure plasma source with a low-pressure processing (deposition) reactor. The cascaded arc plasma source (see Fig. 1 generates a plasma by the application of a dc voltage to one of more cathodes that arc to a grounded anode in a non-depositing carrier gas flowing through a narrow channel. This carrier gas is often Ar but also H_2, N_2 or mixtures of these gases can be used. The pressure in the plasma source is sub-atmospheric (typically 300 Torr), due to the narrow channel, the high gas flows and the plasma itself. The plasma expands through a nozzle into the low-pressure reactor (see Fig. 2). Due to the expansion behavior, the electron temperature is reduced to ~0.1-0.3 eV in the downstream region depending on the gases used. Therefore, electron-induced dissociation and ionization reactions can be neglected in the downstream region, in contrast to conventional plasma techniques. The downstream ion density on the other hand, is relatively high (10^{13} cm^{-3} for pure Ar and down to 10^{11} cm^{-3} for molecular plasmas) compared to other plasma techniques. This can be attributed to the fact that plasma creation takes place in a source at high pressure, with consequently a much higher ionization degree (typically 5%) than low-pressure plasmas. Furthermore, when molecular gases such as H_2 and N_2 are admixed in the source, the frequent electron collisions and the high gas temperature result in a very

high dissociation degree of these molecular gases. This leads to large fluxes of H and N atoms from the source and, due to very effective dissociative ion-electron recombination reactions, the plasma source operates under these conditions predominantly as an atomic H or N source (the atom density is typically a factor 10 – 100 higher than the ion density). Consequently, the high-pressure plasma source delivers very large flows of ions (Ar^+) or atoms (H, N) to the downstream region and, therefore, a large amount of "reactivity" to precursor gases (such as NH_3 and SiH_4) that are injected downstream in the reactor. Due to the low electron temperature, these precursor gases are mainly dissociated by these ionic and/or atomic reactive species. Furthermore, the large amount of "reactivity" allows much larger flows of precursor gases [the flows are typically in the order of 1 standard liter per minute (slm)] to be dissociated than in conventional low-pressure plasmas. Two other important advantages of the ETP technique are that a relatively selective chemistry can be chosen in contrast to electron-collision dominated plasmas and the fact that the source operation is not influenced by the downstream region (i.e., the ETP is the ultimate "remote plasma"). The latter aspect enables independent optimization of the upstream and downstream plasma region. The low pressure in the downstream region - generally 0.15 Torr, similar to typical pressures in rf parallel plate reactors - prevents excessive gas phase polymerization reactions and therefore abundant dust formation. Furthermore, the low electron temperature leads to very low substrate self-bias voltages (ion energy < 2eV), although additional rf substrate biasing can be applied to generate a controllable level of ion bombardment. On the other hand, the gas temperature in the plasma is relatively high (1000 – 2000 K) leading to a thermal load on the substrate of 0.3-0.6 W/cm^2. In Table I, the most important plasma properties of the ETP technique are summarized including the diagnostics used to study the plasma properties.

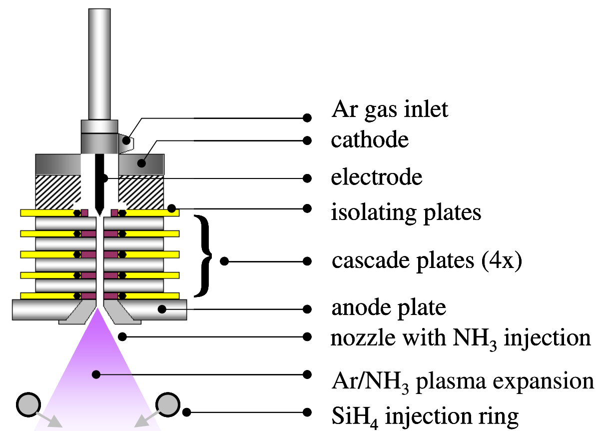

Fig. 1. Schematic of the novel commercial Expanding Thermal Plasma (ETP) source used for silicon nitride deposition at ultrahigh rates.

Fig. 2. Picture of an expanding Ar plasma from the ETP plasma source. The injecting ring is visible at 7.5 cm from the plasma source exit.

Table I: Summary of the ETP plasma properties including the diagnostic techniques used.

Plasma properties	Parameter range	(Plasma) diagnostics	Ref.
Electron temperature	0.1-0.3 eV	Thomson scattering; Langmuir probe	[6,7]
Ion density	~10^{13} cm^{-3} (pure Ar plasma) 10^{11}-10^{12} cm^{-3} (molecular plasmas)	Thomson scattering; Langmuir probe	[6,7]
Metastable density	<10^{12} cm^{-3} (pure Ar plasma)	Absorption spectroscopy	[8]
Radical density	10^{11}-10^{14} cm^{-3} ~10^{14} cm^{-3} (N in Ar-N_2 plasma) 10^{11}-10^{12} cm^{-3} (H in Ar-H_2 plasma) ~10^{12} cm^{-3} (NH_x in Ar-NH_3 plasma) ~10^{13} cm^{-3} (SiH_3 in Ar-H_2-SiH_4 plasma)	Threshold ionization mass spectrometry; cavity ring down spectroscopy; laser-induced fluorescence	[9-11]
Ion energy at substrate	1-2 eV	Langmuir probe; ion mass spectrometry	[7]
Gas temperature	1000-2000 K	Cavity ring down spectroscopy; laser-induced fluorescence	[12,13]
Heat load on substrate	0.3-0.6 W cm^{-2}		[14]

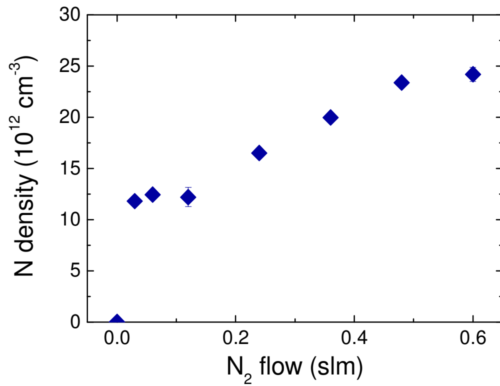

Fig. 3. The density of atomic nitrogen N in the ETP plasma as a function of the N_2 flow in an Ar-N_2 plasma. The N density has been measured by threshold ionization mass spectrometry at the position of the substrate.

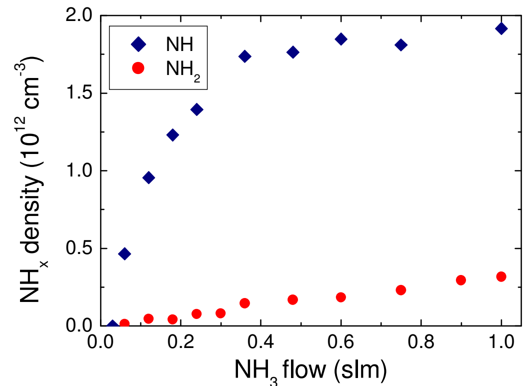

Fig. 4. The density of the NH and NH_2 radicals in the ETP plasma as a function of the NH_3 flow in an Ar-NH_3 plasma. The radicals have been measured by cavity ring down absorption spectroscopy at 10 cm from the nozzle of the plasma source.

THE ETP TECHNIQUE FOR ULTRAHIGH-RATE SILICON NITRIDE DEPOSITION

For the deposition of silicon nitride antireflection coatings, the plasma source can be operated on an Ar-N_2 mixture or on pure Ar with NH_3 injected into the nozzle. In both cases SiH_4 is injected downstream through the injection ring [15]. The reactive species generated from these Ar-N_2 and Ar-NH_3 mixtures lead to the dissociation of SiH_4 creating new species that can contribute to the silicon nitride growth. Therefore, the reactive species (ions, radicals, etc.) emanating from the plasma source have been studied extensively. As an example, a few results obtained in such studies are shown in Figs. 3 and 4. From this kind of experimental data on the densities of radicals, the plasma chemical processes as well as the surface reactions ruling silicon nitride film growth have been unraveled [9,16].

Furthermore, by the implementation of ETP sources in the DEP_x PECVD deposition tool, silicon nitride deposition rates up to 20 nm/s have been reached, while the nominal deposition rates range from 3 to 7 nm/s [3,5,18]. With the application of three ETP sources in one single deposition chamber an excellent uniformity of ±2.5% over the carrier width of 30 cm is obtained. This has resulted in a nominal throughput of the DEP_x of 960 cells/hour (15.7×15.7 cm^2). For multicrystalline silicon solar cells these silicon nitride films have lead to a solar cell efficiency of 15.3%, compared to a top efficiency of 15.5% using silicon nitride deposited at low rate (<<1 nm/s) by a state-of-the-art conventional technique. These high solar cell efficiencies reached for multicrystalline silicon can be attributed to a high level of bulk passivation induced by the a-SiN_x:H films after the “firing” of the screen-printed contacts [18,19]. Furthermore, it has recently been shown that the a-SiN_x:H films also yield a high level of surface passivation, as evidenced by the relatively high lifetimes of minority charge carriers in low-resistivity silicon wafers coated by the a-SiN_x:H [19]. Besides high-rate deposition of silicon nitride antireflection coatings, in the future also dry etch processes using the ETP technique [20] will be studied for solar cell manufacturing purposes.

CONCLUSIONS

A novel commercial plasma source based on the so-called Expanding Thermal Plasma (ETP) technique has been presented and the associated plasma properties have been summarized. The application of this ETP source for ultrahigh-rate (~5 nm/s) deposition of high quality silicon nitride antireflection coatings in an inline PECVD deposition tool is described. In the future, this source will also be applied for other solar cell processing steps.

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