Direct ion flux measurements at high-pressure-depletion conditions for microcrystalline silicon deposition

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The contribution of ions to the growth of microcrystalline silicon thin films has been investigated in the well-known high-pressure-depletion (HPD) regime by coupling thin-film analysis with plasma studies. The ion flux, measured by means of a capacitive probe, has been studied in two regimes, i.e., the amorphous-to-microcrystalline transition regime and a low-to-high power regime; the latter regime had been investigated to evaluate the impact of the plasma power on the ion flux in collisional plasmas. The ion flux was found not to change considerably under the conditions where the deposited material undergoes a transition from the amorphous to the microcrystalline silicon phase; for solar-grade material, an ion-to-Si deposition flux of ~0.30 has been determined. As an upper-estimation of the ion energy, a mean ion energy of ~19 eV has been measured under low-pressure conditions (<1 mbar) by means of a retarding field energy analyzer. Combining this upper-estimate with an ion per deposited Si atom ratio of ~0.30, it is concluded that less than 6 eV is available per deposited Si atom. The addition of a small amount of SiH4 to an H2 plasma resulted in an increase of the ion flux by about 30% for higher power values, whereas the electron density, deduced from optical emission spectroscopy analysis, decreased. The electron temperature, also deduced from optical emission spectroscopy analysis, reveals a slight decrease with power. Although the dominant ion in the HPD regime is SiH4+, i.e., a change from H3+ in pure hydrogen at high plasma powers, a higher SiH4 depletion is achieved resulting in increased deposition rates—the dominant SiH4 dissociation mechanism is electron impact induced and as higher plasma powers increase the electron density, the SiH4 dissociation is enhanced. However, high plasma powers also induce ion-film interactions through an increase of the ion density, which, especially in collisionless low-pressure plasmas, can result in an energetic ion bombardment. This energetic ion bombardment possibly causes an amorphization of the crystalline phase (i.e., a reduced crystal fraction,9-12 smaller crystallite sizes,11,12 and increased void fraction12) and an increased defect density.10,13 By moving to high-pressure regimes and/or the application of VHF, energetic ion bombardment can be suppressed; increasing the pressure results in a reduced ion energy due to ion-neutral collisions in the collisional plasma sheath, whereas application of VHF reduces the ion energy via a reduced voltage drop across the plasma sheath in front of the grounded electrode. A combination of high pressures, high powers, and high frequencies has resulted in high deposition rates (2-3 nm/s) while maintaining high solar cell efficiencies (7%-8%).1,14-17

I. INTRODUCTION

Microcrystalline silicon (µc-Si:H) has been extensively used as light absorber in thin-film tandem solar cells. The most commonly used µc-Si:H deposition technique is a capacitatively coupled plasma (CCP) in parallel plate configuration using radio or very high excitation frequencies (RF or VHF, respectively) from silane (SiH4) highly diluted in hydrogen (H2). Empirically, the best µc-Si:H films have been found close to the so-called amorphous-to-microcrystalline transition regime, i.e., where the µc-Si:H films have a crystallinity of about 60%.1 The phase transition can be ascribed to a critical H flux to Si growth flux ratio.2,3

Key issues for µc-Si:H film deposition are high growth rates (>1 nm/s), preferably in combination with large-area roll-to-roll processing, while maintaining solar-grade material quality. Approaches to increase the growth rate include an increase of the precursor gas flow rates and plasma power, moving from a low-pressure to a high-pressure depletion (LPD to HPD, respectively) regime, and/or by increasing the excitation frequency from 13.56 MHz to 27-300 MHz.4-8 At high plasma powers, a higher SiH4 depletion is achieved resulting in increased deposition rates—the dominant SiH4 dissociation mechanism is electron impact induced and as higher plasma powers increase the electron density, the SiH4 dissociation is enhanced. However, high plasma powers also induce ion-film interactions through an increase of the ion density, which, especially in collisionless low-pressure plasmas, can result in an energetic ion bombardment. This energetic ion bombardment possibly causes an amorphization of the crystalline phase (i.e., a reduced crystal fraction,9-12 smaller crystallite sizes,11,12 and increased void fraction12) and an increased defect density.10,13 By moving to high-pressure regimes and/or via the application of VHF, energetic ion bombardment can be suppressed; increasing the pressure results in a reduced ion energy due to ion-neutral collisions in the collisional plasma sheath, whereas application of VHF reduces the ion energy via a reduced voltage drop across the plasma sheath in front of the grounded electrode. A combination of high pressures, high powers, and high frequencies has resulted in high deposition rates (2-3 nm/s) while maintaining high solar cell efficiencies (7%-8%).1,14-17

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Although the ion energy, the ion flux, and the nature of the ions have been the topic of a wide range of studies reported in the literature, the HPD conditions specifically used for \( \mu \)-Si:H film deposition have not yet been explored in terms of ion (energy and flux) contribution to the growth. It is rather challenging to study the ion energy and ion flux under HPD deposition conditions, i.e., at high pressures (>1 mbar) and in depositing plasmas. Retarding field energy analyzers (RFEAs) have been used to determine the ion energy. However, the application of this technique is restricted to conditions in which the ion mean free path is larger than the path an ion traverses inside the device, typically 0.6–2.0 mm, and, hence, the use of an RFEA is limited to a low working pressure regime. Horvath and Gallagher\(^\text{21}\) and Nunomura \textit{et al.}\(^\text{22,23}\) used a threshold ionization mass spectrometer (TIMS) to measure the chemical nature of the ions (and radicals) in H\(_2\)/SiH\(_4\) discharges. This technique can be applied at high working pressures, because the TIMS is differentially pumped, although Horvath and Gallagher\(^\text{21}\) still reported data at relatively low pressures (i.e., 2 mbar), which is not typical for high-quality \( \mu \)-Si:H deposition regimes. They found a considerable fraction of positive (Si containing) ions contributing to the growth, i.e., 8% and 30% to the growth of amorphous silicon (\( a \)-Si:H) and \( \mu \)-Si:H, respectively.\(^\text{21}\) Nunomura \textit{et al.}\(^\text{22,23}\) studied the HPD regime using VHF of 60 MHz, measuring poly-silicon hydride groups with ion energies in the range of 3–40 eV. Note, however, that these measurements were performed at the plasma edge rather than the substrate position, and no direct correlation with deposited material was made. Hamers \textit{et al.}\(^\text{24}\) found when using VHF (in a pressure range of 0.6–2.0 mbar) even higher fractions, i.e., an ion contribution of 60%–70% to the growth of \( \mu \)-Si:H. This higher ion contribution may be due to their use of a higher excitation frequency, which results in higher ion fluxes.\(^\text{20}\)

Thus, there seems to be consensus on the ion-to-Si deposition flux, with values reported in the range of 0.3 to 0.7. Remarkably, no direct ion flux measurements under HPD conditions (2-20 mbar pressure range) have been reported so far. Here, we report on the use of a capacitive probe\(^\text{25,26}\) to measure the ion flux at the position of the substrate holder in the HPD regime. This probe, which is developed in-house for the purpose of measuring ion fluxes in depositing plasmas,\(^\text{25,26}\) is tolerant towards film deposition and can easily be applied in RF excited discharges. In addition, we correlate these studies with the obtained material properties.

In agreement with earlier reports,\(^\text{21,24}\) we find an ion per deposited Si atom ratio of 0.30-0.60. It is rather remarkable that solar-grade material can be deposited under these relatively high ion flux conditions, because of their high sticking probability and related low surface mobility. Therefore, we will discuss our findings on the ion-to-Si deposition flux ratio obtained under HPD conditions as employed for the deposition of solar-grade \( \mu \)-Si:H. Our conclusion is that despite the high flux ratio, the ions have a low kinetic energy (less than 19 eV), which is outside the regime in which significant Si surface or bulk displacement can occur;\(^\text{27}\) although, locally, the low-energetic ion bombardment can still lead to enhanced surface diffusion.

II. EXPERIMENT

The experiments were performed in a capacitively coupled parallel plate reactor (Fig. 1). The reactor design was based on a similar reactor located at the Institute of Photovoltaics (IPV) at Forschungszentrum (FZ) Jülich (Germany) with which \( a \)-Si:H and \( \mu \)-Si:H tandem solar cells have been developed with efficiencies up to 12.5%.\(^\text{28,29}\) A grounded, upper electrode serves as substrate holder, and was heated to 200°C. A powered, lower electrode is of a shower head configuration; the power being capacitatively coupled via a 13.56 MHz generator. Both electrodes have an area of 150 cm\(^2\). The inter-electrode distance is set at 1 cm, unless stated otherwise. The hydrogen gas (H\(_2\), 360 standard cubic centimeters per minute, sccm) and silane gas (SiH\(_4\), 0-10 sccm) were injected into the chamber through the shower head electrode. The pressure, regulated via a throttle valve, was kept at 14 mbar. Depositions were performed using a plasma power \( (P) \) of 80 W.

Amorphous and microcrystalline silicon films were simultaneously deposited on \( c \)-Si (\( n \)-type, (100) crystal orientation) and glass (Corning 7059). The film thickness is about 200 nm, as determined with a step profiler. The film crystallinity \( (X_c, \text{for films deposited on glass only}) \) was determined by Raman spectroscopy (Renishaw, 514.5 nm Ar ion laser) following the method described by Smit \textit{et al.}\(^\text{30}\). The material quality was “graded” using Fourier transform infrared (FTIR) spectroscopy as reported by Smets \textit{et al.}\(^\text{31,32}\). Only the highly crystalline film \( (X_c = 70\%) \) was found to be of poor quality, based on the presence of so-called narrow high stretching modes (NHSMs) in the absorption spectra. The \( \mu \)-Si:H films with an ideal phase mixture\(^\text{1} \) \( (X_c = 60\%) \) were rated to be of solar-grade quality due to the absence of NHSM in the absorption spectra. The growth flux \( (F_{Si}, \text{number of deposited Si atoms per cm}^2 \text{per second}) \) was calculated
from the Si density, as determined from Rutherford backscattering (RBS) analysis using 2 MeV $^4$He$^+$ ions and the deposition rate.

The ion flux was measured using a capacitive probe built in the substrate holder (Fig. 1), under the growth conditions as described above and for various plasma powers (5-200 W) using a fixed H$_2$/SiH$_4$ flow ratio (360/3 or 360/0). The working principle of the capacitive probe has been described in detail by Petcu et al. $^{25,26}$ Basically, the ion flux ($\Gamma_{\text{ion}}$) can be determined from the voltage drop across an external capacitor ($C = 1.5 \text{ nF}$)

$$C \frac{dV}{dt} = eA \Gamma_{\text{ion}}, \quad (1)$$

in which $dV/dt$ is the time derivative of the voltage drop across the external capacitor, $e$ is the elementary charge ($1.6 \times 10^{-19} \text{ C}$), and $A$ is the area of the probe (2 cm$^2$).

This technique has already proven to be tolerant towards insulating film deposition on the probe surface.$^{25,26}$ Amorphous and microcrystalline silicon films, which will be deposited on the probe surface under the above-mentioned experimental conditions, probably behave more like a semiconductor than an insulator. Deposition of these Si films may result in a voltage drop between the probe surface and the capacitor. If we approximate the electrical behavior of these Si films with a resistor, and assuming that the deposited material has a conductivity in the range of $10^{-4}$–$10^{-8} \text{ S/cm}$, the maximum allowed film thickness lies in the range of $10–10^{3} \text{ nm}$. A second requirement, to ensure a constant probe surface potential, is that the film thickness should not change fast with respect to the measurement time. With current deposition rates below 1 nm/s, a fast change is not expected.

Typically, a measurement takes less than 180 s, with deposition rates below 1 nm/s 180 nm is deposited at maximum per measurement. To verify the influence of a film deposited on the probe surface in H$_2$/SiH$_4$ plasmas, a procedure analogously to the one used by Petcu et al.$^{25}$ was followed in which before and after every measurement performed in an H$_2$/SiH$_4$ plasma a measurement in a pure, non-depositing H$_2$ plasma was carried out. The ion fluxes obtained in the H$_2$ plasma before and after SiH$_4$ addition (denoted $\Gamma_{\text{ion, before}}$ and $\Gamma_{\text{ion, after}}$, respectively) are shown in Fig. 2. The one-to-one relationship between the fluxes indicates that the film deposited during the measurements in an H$_2$/SiH$_4$ plasma is thin enough as not to influence the ion flux determination.

Next to ion flux measurements, the plasma emission was monitored by means of an Avantis optical emission spectrometer (150-1300 nm range, 1.3 nm resolution, 2000 ms integration time). Using a two lens system, the emission about 2 mm below the probe was focused onto the optic fiber. The emission lines of interest are H$_g$ (656.308 nm) and H$_p$ (486.276 nm). The emission intensity depends on the density of the electron-excited species (i.e., H$_g$ and H$_p$) and the electron energy distribution function (EEDF). Under constant H$_2$ density conditions and with the reasonable assumption that electron impact dissociative excitation of H$_2$ is the main path delivering excited H, the H$_g$ (and/or H$_p$) emission intensity can be used to monitor changes in the EEDF. The H$_p$/H$_g$ emission intensity ratio can be used as a qualitative indication of the electron temperature behavior.$^{33}$ In line with previous results, we consider that these assumptions to be still valid with small additions of silane under HPD conditions.$^{29,34,35}$

With a Balzers QMS 300 Prisma residual gas analyzer (RGA), located in the pump line, the background gas was sampled through a $\sim$50 $\mu$m pinhole with the aim to determine the SiH$_4$ depletion.$^{36,37}$ The SiH$_4$ depletion ($D$) is defined as the relative flow rate of dissociated SiH$_4$ and given by

$$D = \frac{I(i)_{\text{SiH}_4, \text{off}} - I(i)_{\text{SiH}_4, \text{on}}}{I(i)_{\text{SiH}_4, \text{off}}}, \quad (2)$$

in which $I(i)_{\text{SiH}_4, \text{off}}$ and $I(i)_{\text{SiH}_4, \text{on}}$ are the channeltron current signals measured with the plasma off and on, respectively, and $i$ denotes the different mass/charge peaks of the SiH$_4$ cracking pattern. In this work, the parent ion (SiH$_4^+$) is used in the calculation, i.e., $i = 30 \text{ amu}$.

The ion energy distribution (IED) was determined in a pure H$_2$ plasma (15 sccm), using a plasma power of 80 W, at low pressures (0.30-0.50 mbar), and an increased electrode gap of 3 cm, needed to sustain the plasma at these low pressures, using an Impedans Semion retarding field energy analyzer. The RFEA has been built in the substrate holder at the same location as the capacitive probe. Under these low-pressure conditions, the plasma sheath is evaluated to be collisionless, in contrast to the HPD conditions described above which are typically employed for the deposition of $\mu$-c-Si:H. Therefore, the IED measurement provided an upper-estimate of the ion energy. In the remainder of the paper, the mean ion energy is used as upper-estimation. This mean ion energy is obtained by fitting the IED of with two Gaussians (as the IED is bimodal, Fig. 5), using the weighted average of the (two) median ion energies as mean ion energy.

III. RESULTS

A. Ion flux contribution in the transition regime

Fig. 3(a) shows the ion and growth fluxes as a function of the SiH$_4$ flow rate and Fig. 3(b) the ion-to-Si deposition flux ratio ($\Gamma_{i,\text{ion}}/\Gamma_{\text{Si}}$); Fig. 3(c) shows the crystal fraction ($X_c$)
of the corresponding films. The ion flux increases slightly with increasing SiH₄ flow rate, but does not change considerably in the $a \rightarrow \mu c$ transition regime (i.e., where the crystal fraction changes from 0% to 60%); Fig. 3(c) shows that a reduction of the SiH₄ flow rate results in a phase transition from amorphous (>2.7 sccm) to microcrystalline films (<2.5 sccm). The growth flux slightly increases with increasing SiH₄ flow rate in agreement with the increase in deposition rate (0.2 nm/s at 1 sccm SiH₄ to 0.7 nm/s at 7 sccm SiH₄), since the Si density remained constant ($4.9 \times 10^{22}$ at/cm³). From the ion and growth flux presented in Fig. 3(a), the ion-to-Si deposition flux ratio can be determined, which is presented in Fig. 3(b). It is ~0.30 for the solar-grade films (SiH₄ flow rate ≥2 sccm, where the grading is based on FTIR spectroscopy following Smets et al. 31,32), while it is ~0.60 for the highly crystalline, poor-quality film (SiH₄ flow rate = 1 sccm, i.e., poor quality based on the presence of NHSMs in the IR absorption spectra). More importantly, these results illustrate that the $\Gamma_{ion}/\Gamma_{Si}$ is relatively high and does not change significantly with the SiH₄ flow rate.

### B. Ion flux vs. plasma power

Fig. 4(a) shows the effect of plasma power on the ion flux in H₂ and H₂/SiH₄ plasmas (left axis) and on the $H_a$ and $H_b$ emission intensities (right axis). The ion flux is found to increase by two orders of magnitude for lower plasma powers and increases more slowly for higher plasma powers ($P > 70$ W). Even at these high-power conditions, characterized by an ion flux in the range of $0.8–2.0 \times 10^{15}$ ions/cm²s, solar-grade µc-Si:H material can in principle be grown by optimizing the SiH₄ flow rate, indicating that, contrary to other reports, a high ion flux is not detrimental for the material quality. It should be noted (data not explicitly shown) that in H₂/SiH₄ plasma, the ion flux is higher by approximately 30% for the higher powers than in H₂ plasmas, suggesting a higher ion loss under these conditions.

The $H_a$ emission intensity, which depends on the density of excited H ($n_3$) and the EEDF, is also found to increase with power. Under constant H₂ density conditions and with the reasonable assumption that in pure H₂ as well as highly H₂ diluted H₂/SiH₄ plasmas electron-impact dissociative excitation of H₂ is the main path delivering excited H (in line with previous work 29,34,35), the $H_a$ emission intensity depends only on the EEDF. Fig. 4(b) shows that the $H_b/H_a$ emission ratio decreases slightly with increasing plasma powers, reflecting a slight decrease in the population of the high energy tail of the EEDF. Since the $H_b/H_a$ emission ratio varies only slightly with power, the $H_a$ emission intensity mainly reflects the electron density ($n_e$) behavior. The results indicate a higher electron density in the case of a pure hydrogen plasma. For low plasma powers (low $n_e$ conditions), the $H_a$ emission intensity increases at the same rate as the ion flux, indicating that spontaneous emission is the dominant de-excitation mechanism. For higher electron densities, however, electron-induced de-excitation becomes important. The point where this process becomes important can clearly be seen in Fig. 4(a), from this point onwards ($P > 40$ W) the increase in $H_a$ emission intensity lags behind with respect to the increase in ion flux.

![Fig. 3](image-url)  
**Fig. 3.** (a) Ion flux and growth flux, (b) ion to Si deposition flux, and (c) the Raman crystallinity versus the SiH₄ flow rate. Note: the Si density has not been measured for films deposited at 2 and 3 sccm SiH₄. However, since the Si density was found to be constant in the studied range, the growth flux (and ion-to-Si deposition flux ratio) for these films, represented by the closed symbols, has been calculated by using this constant Si density.

![Fig. 4](image-url)  
**Fig. 4.** (a) Ion flux and the $H_a$ and $H_b$ emission intensities in a pure H₂ and H₂/SiH₄ plasma, (b) the $H_b/H_a$ ratio, and (c) the SiH₄ depletion versus plasma power.
In Fig. 4(c), the depletion of SiH$_4$ is shown. As can be seen, under high power condition about 40% to 80% of the injected SiH$_4$ is consumed.

**IV. DISCUSSION**

To summarize the results for varying power for a H$_2$ and H$_2$/SiH$_4$ plasma, we observe a higher ion flux and a lower electron density in H$_2$/SiH$_4$ plasmas, whereas the electron temperature only shows a slight decrease with increasing plasma power. The electron density and electron temperature are linked to the ion flux following the Bohm flux relation, i.e.,

\[
\Gamma_i \propto n_e u_B \propto h_i n_e u_B \propto h_i n_e \sqrt{T_e/M_i},
\]

in which $M_i$ is the ion mass, $n_e$ and $n_i$ are the electron density in the center of the plasma and at the sheath edge, respectively, $u_B$ the Bohm velocity, and $h_i$ an inverse gradient length of the electron density profile.\(^\text{40}\) Due to the very high reaction rate of hydrogen ions (H$^+$, H$_2^+$, and H$_3^+$) with silane,\(^\text{41,42}\) the dominant ion in H$_2$/SiH$_4$ plasma is the SiH$_3^+$ ion, even under HPD conditions for a measured depletion of up to 80%, as confirmed by Horvath et al.\(^\text{21}\) and Nunomura et al.\(^\text{22,23}\) Horvath and Gallagher\(^\text{21}\) reported that “the addition of 3%-8% silane to the H$_2$ did not significantly change the total ion current,” which is in agreement with our findings, and report on a Si$_n$H$_m^{+}$ ($n=1$-3) dominant ion flux; Si$_3$H$_m^{+}$ ($n=1$-3) contributes for ~90% to the ion flux, whereas H$_3^+$ contributes for less than 10% to the ion flux. In addition, Nunomura et al.\(^\text{22,23}\) reported that the dominant ion changes from H$_3^+$ in a pure H$_2$ plasma to Si$_3$H$_m^{+}$ ($n \geq 2$) in a H$_2$/SiH$_4$ plasma (for pressures > 1.0 mbar). The dominance of the SiH$_3^+$ results in a lower Bohm velocity $u_B$ with respect to a pure H$_2$ plasma, and since the electron density is lower and the electron temperature only slightly changes in H$_2$/SiH$_4$ plasma this evidently leads to the conclusion that $h_i$ must be higher. Amanatides et al.\(^\text{43}\) indeed confirmed a change in $n_e$ density profile as illustrated by the measured H$_2$ emission profiles under HPD conditions. This shorter gradient length in H$_2$/SiH$_4$ plasma is the result of higher ion loss processes, most probably because the Bohm velocity is lower leading to a higher probability of dissociative recombinations of the silicon containing ions with electrons. Alternatively, the presence of dust particles may induce an increase of ion losses, as well.

The extent to which ions contribute and/or affect the film growth depends on the ion flux, the chemical nature of the ion, and the ion energy. The ion energy has not been measured (yet) under these HPD conditions. However, retarding field energy analyzer measurements, performed under collisionless sheath conditions in an H$_2$ plasma, provided an upper-limit of the ion energy, i.e., a mean ion energy of ~19 eV (Fig. 5). Similar values have been reported by Hamers \textit{et al.}\(^\text{44}\) in a similar pressure range, and were found to decrease with increasing pressure. Nunomura \textit{et al.}\(^\text{23}\) reported even lower ion energies, i.e., ~3 eV at 13 mbar, which were measured at the plasma edge with a differentially pumped energy-filtered mass spectrometry which enabled measurements at high pressures. Note, both Nunomura \textit{et al.}\(^\text{23}\) and Hamers \textit{et al.}\(^\text{44}\) used higher excitation frequencies which typically lead to lower ion energies.\(^\text{19}\)

Combining the upper-estimation of the ion energy (~19 eV) with an ion-to-Si deposition flux ratio of 0.30, less than 6 eV is available per deposited Si atom. For significant Si surface or bulk displacement to occur, ion energies >18 eV and >40 eV are required.\(^\text{45}\) With expected ion energies below 19 eV under collisional HPD conditions, ion-induced Si surface and/or bulk displacement are rather unlikely to occur.

The extent to which ions contribute to the growth of $\mu$-Si:H in the HPD regime will most likely be as an H flux in disguise, albeit accompanied with an energy transfer to the surface (thermal spike). At (or actually a few Angstroms above) the surface, SiH$_3^+$ neutralizes and dissociates into silicon containing radicals, H$_2$ and H (or three H atoms). It can, therefore, be considered as an addition to the H flux. Compared to estimated H fluxes,\(^\text{2}\) it contributes for 1% to 10% to the atomic H flux. Such a small contribution will not affect the critical H flux to Si growth flux ratio, which induces the phase transition and therefore do not conflict with our earlier findings.\(^\text{2}\) However, since atomic H is generated most probably at every SiH$_3^+$ impact, it may assist in mitigating the detrimental effects of the high sticking probability and, associated, low surface mobility of the SiH$_3^+$. In effect, it has no influence on the $\mu$-Si:H film properties nor phase transition which is still ruled by the much higher atomic H to deposition flux ratio.\(^\text{2}\) Molecular dynamics modeling might provide here the final answer.

**V. CONCLUSIONS**

The contribution of ions to the growth of $\mu$-Si:H thin films deposited in the HPD regime has been studied. The ion flux, determined by means of a capacitive probe, did not change considerably under the conditions where the material undergoes a transition from the amorphous to the microcrystalline silicon phase. The ion-to-Si deposition flux ratio was determined to be ~0.30 under solar-grade deposition conditions. However, the impact of this high ion-to-Si deposition flux ratio is limited because the average ion energy is rather low (less than 19 eV), making surface and bulk Si
displacement unlikely. Thus, under HPD conditions as employed for $\mu$-Si:H deposition, the kinetic energy of the ions is too low to induce significant bulk (and surface) damage.

Moreover, as the relatively large $\text{Si}_i\text{H}_{m+}^+$ flux, compared to the deposition flux, can be considered as an H flux in disguise, the hydrogen present in these silicon containing ions possibly mitigates the detrimental effect of the impinging ion.

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