

Hot-Wire Chemical Vapor Deposition of Silicon from Silane: Effect of Process Conditions

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We have examined the deposition of uniform polycrystalline silicon films over large surface area for application in photovoltaics and flat panel displays. Depositions were conducted using a commercially available hot wire chemical vapor deposition chamber. We investigated the effect of silane flowrate (4-60 sccm), filament temperature (1550-1850°C), total pressure (25-1000 mTorr), substrate temperature (400-600°C) and hydrogen dilution on the exit gas phase composition, film growth rate, and film crystalline fraction.

Experiments show that the growth rate increases with silane flowrate and is independent of the substrate temperature. The growth rate variation with pressure and filament temperature is observed to change with the axial position of the substrate. A transition from amorphous (a-Si) to polycrystalline (poly-Si) silicon films is observed with increasing total pressure, filament temperature and substrate temperature and

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decreasing silane flowrate. The effect of hydrogen dilution is found to be equivalent to the effect of increasing gas pressure using pure silane. The experiments suggest that interaction of atomic hydrogen with the growing surface leads to the growth of crystalline phase in the silicon films.

(Keyword: Hot-wire CVD, silicon, silane, reactions, crystalline fraction, hydrogen effect)

1. Introduction

A goal of photovoltaic research and development is reducing the cost of photovoltaic modules. The manufacturing cost of modules for large-scale power generation can be significantly reduced by fabricating high efficiency, large area thin film semiconductor on low cost substrates.¹ Thin polycrystalline silicon (poly-Si) films are attractive because they combine the benefits of crystalline silicon performance and stability with the large area manufacturability.

The hot wire chemical vapor deposition (HWCVD) technique has been used to deposit high quality hydrogenated amorphous silicon films at low substrate temperatures.^{2,3} Recently, the HWCVD method has been successfully applied to the deposition of poly-Si films.⁴⁻⁷ The motivation of this work is to evaluate the feasibility of the HWCVD technique to deposit poly-Si films from silane at high deposition rates and to relate process conditions to film properties.

The reaction chemistry of silicon deposition by HWCVD can be divided into four steps as shown in Figure 1. The steps include:

1. Pyrolysis of silane and hydrogen on the filament surface to form radicals (Si & H).
2. Gas phase reactions of the generated radicals to form other species (SiH_x).
3. Adsorption of radicals (H) and film precursors (SiH_x) on the film surface.
4. Surface rearrangement reactions involving H(ad) and $\text{SiH}_x(\text{ad})$ to incorporate the adsorbed Si precursors in the film and release hydrogen.

To understand and optimize HWCVD, one must determine which of these steps is rate controlling under various conditions and which steps control the surface characteristics. To probe these issues, silicon films were deposited on glass substrates by HWCVD using a pure silane feed.

In this paper, we report the effect of various process parameters on the HWCVD process and describe the reaction chemistry to support these observations. We report the effect of process parameters on the concentration of silane in the gas stream exiting the reactor during HWCVD of silicon. This quantifies silane utilization, which is important for evaluating process economics. We also discuss the experimentally observed variations in film properties along the reactor length; this is a critical factor for controlling film uniformity over a large deposition area.

2. Experimental

The cross-sectional view of the deposition chamber used in this study is shown in Figure 2. The deposition chamber along with the load lock, purchased in 1997, is one of the early HWCVD reactors built by M. V. Systems, Golden Colorado. The reactor is a turbo-molecular pumped stainless steel chamber, which reaches a base

pressure of 10^{-8} Torr. Feed gases enter through the bottom flange and are delivered inside the reactor via a vertical, 'T' shaped distributor. Before entering the deposition zone, the gases are circulated through the shutter chamber. The shutter can be moved into the reaction chamber to block deposition on the substrates. The gases then flow across an array of heated filaments maintained at temperatures ranging from 1550 to 1850°C. A pure tantalum wire, 0.5 mm in diameter, 100-200 cm long is used as the filament. It is looped to form an array of parallel strands on a filament holder and placed ~3.5 cm below the substrate holder. A vacuum compatible electrical feedthru is used to supply DC power to the filament from a Sorenson power supply. The filament temperature (T_{fil}) is monitored by a two-wavelength pyrometer placed on a view port on the bottom flange. The resistance of the heated filament is also used to estimate the temperature of a new filament. The filament temperature is controlled manually by changing the applied voltage.

The substrates are heated by two concentric coil resistive heaters placed on the outside of the top flange. The substrate holder is placed ~2 cm below the bottom of the top flange in the reactor. The substrate temperature (T_{sub}) was varied from 400 to 600°C based on a pre-calibrated thermocouple, which accounts for the heat supplied by the heater as well as the radiating filaments. The molar flowrate of silane into the reactor is controlled by MKS mass flow controllers. A throttle valve at the exit controls the reactor pressure by changing the volumetric flowrate of the gases leaving the reactor. Typical silane flowrates (F_{SiH_4}) of 4 to 60 sccm and operating pressures (P_i) of 25 to 1000 mTorr were used.

Silicon was simultaneously deposited on nine 1 in² substrates, arranged in the form of a 3x3 matrix, on a 36 in² substrate holder. The substrate holder is parallel to the plane of the filaments. The matrix dimension parallel to both the filament strands and the gas distribution at the reactor inlet is referred to as columns. In Figure 2, the columns are perpendicular to the plane of the paper. No significant change in film properties is expected along a column because all three substrates in a column are at the same axial position and height above the filament. The observed variation in growth rate along a column is within the experimental error of ~20%. The matrix dimension parallel to the flow direction (reactor length) represents the rows. Axial variation in film properties was documented by analyzing the samples in the middle row of the substrate holder. Based on their axial position relative to the gas inlet, the samples are referred to as the inlet, center and the exit substrates.

The volume between the filament holder and the substrate holder, where the gases interact with the filament, is referred to as the reaction zone. The gases exiting from the reaction zone were analyzed by a Balzers, PPM 400, mass spectrometer. The mole fraction of silane in the gas stream exiting the reaction zone was calculated using the partial pressure measured by the mass spectrometer.

After deposition, the growth rate and the crystalline fraction of the films were determined. The film growth rate was obtained by measuring the weight gain on the substrates and by dividing it by the deposition time. The deposition time was fixed at one hour for all the experiments considered in this analysis. Weight measurements, instead of the thickness measurements, quantify the actual deposition rates because of

the variation in the film density with film structure ($\rho_{c-Si} = 2.33 \text{ gm.cm}^{-3}$, $\rho_{a-Si} = 2 \text{ gm.cm}^{-3}$).

Raman spectroscopy was the primary surface analysis technique used to obtain information on the film structure. A typical Raman spectrum of Si film deposited by HWCVD is shown in Figure 3. The Raman spectrum of an a-Si film shows a broad TO (transverse optical) peak around 480 cm^{-1} and a TA (transverse acoustic) mode around 140 cm^{-1} , while that of c-Si shows a sharp Raman active TO mode at 520 cm^{-1} . For the Raman spectra of poly-crystalline silicon films, a sharp TO peak is observed at a frequency lower than 520 cm^{-1} , the position of which depends on the crystallite size. The contribution of the individual phases can be deconvoluted as illustrated by the solid line in Figure 3. The films were characterized by their crystalline volume fraction, X_c , computed by

$$X_c = \frac{I_{c-Si}}{I_{c-Si} + I_{a-Si}} \quad (1)$$

where I represents the integrated intensities of the TO mode obtained from the baseline corrected deconvolution of the Raman spectra. I_{c-Si} is the sum of integrated intensities for c-Si at 520 cm^{-1} and that for small size crystallite at a lower frequency.

3. Results and Discussion

3.1. Effect of Substrate Temperature

The effect of the substrate temperature was studied for the two different process conditions described in Table 1. In the following discussion, the two process conditions will be referred to as “low pressure” and “high pressure”.

Figure 4 shows the influence of substrate temperature on the mole fraction of silane at the exit. While at high pressure, the silane mole fraction decreases marginally with increasing substrate temperature; the mole fraction is independent of the substrate temperature at low pressure. At high pressure, a larger fraction of silane is converted in the gas phase. In addition, the gas temperature is more sensitive to changes in the substrate temperature at higher pressure due to a larger rate of molecular collision with the heated surface in the reactor. Consequently, the silane mole fraction decreases with increasing substrate temperature at high pressure.

The film growth rate is independent of the substrate temperature at all substrate positions and at each total pressure, as illustrated in Figure 5. The growth rate is apparently not affected by the variation in silane conversion at high pressure because the magnitude of this change is small. Previous studies^{3,8,9} have also reported that the deposition rate is independent of the substrate temperature above 400°C. Thus, under the conditions investigated, the reaction kinetics at the surface of the growing film do not determine the deposition rate of silicon during HWCVD.

The effect of changing substrate temperature on the crystalline fraction at three different axial positions is shown in Figure 6. While the crystalline fraction is independent of the substrate temperature at low pressure, the crystalline fraction increases with substrate temperature at high pressure, with lower temperatures required for crystallinity near the reactor exit. The above observations also demonstrate that poly-crystalline silicon films can be deposited from silane without using hydrogen dilution as reported by Dusane *et al.*¹⁰ and Brogueira *et al.*⁴

It is widely believed^{2,9,11-13} that the abundance of atomic hydrogen on or near the growing surface during HWCVD leads to the deposition of poly-Si films rather than amorphous films. Mahan *et al.*² proposed that the interaction of hydrogen radicals with the growing surface, either by breaking or inserting into the weak Si-Si bonds, leads to the deposition of an ordered Si film. Heintze *et al.*¹³ speculated that the surface reaction rate of adsorbed H-atoms has to be faster than the influx of growth precursors (growth rate) to avoid trapping H-atom in voids, which is detrimental to film quality.

It is proposed that a surface rearrangement reaction (step 4 in Figure 1) involving adsorbed H-atoms controls the film crystallinity. Further, the crystalline structure of the film is a function of the ratio of the surface rearrangement reaction rate to the growth rate. This ratio, R_{xc} , is defined as

$$R_{xc} = \frac{r_4}{r_{dep}} \quad (1)$$

where r_d is the rate of surface rearrangement reaction (Figure 1, step 4) which is a function of the surface temperature and the surface concentration of adsorbed H atoms. The rate of deposition, r_{dep} , is proportional to the rate of step 3 in Figure 1, which is a function of the gas phase concentration of growth precursors. A ratio of the surface rearrangement reaction rate to the growth rate greater than a minimum value, Rxc_{min} , is required to deposit crystalline films. This translates to a minimum surface temperature and a minimum surface concentration of H-atoms above which crystalline films are deposited.

At low pressure, Rxc is expected to be greater than the minimum value even at the lowest temperature investigated due to low growth rates. Thus, a polycrystalline film is always observed. However, at high pressure, amorphous films are observed at low substrate temperatures due to high growth rates. The increase in substrate temperature enhances the surface rearrangement reaction rates at a constant growth rate (increases Rxc) leading to the deposition of poly-Si films. The substrate temperature at the onset of crystallinity changes with the substrate position due to a variation in the deposition rate. Crystalline films at the exit sample are obtained at a lower temperature because of lower growth rates compared to the inlet sample.

3.2. Effect of Filament Temperature

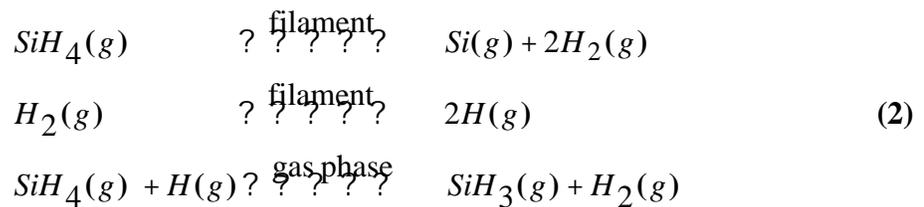
The effect of the filament temperature in the range of 1580°C to 1850°C during hot-wire CVD of silicon was investigated at 500 mTorr using pure silane at a flowrate of 18 sccm. For the range of filament temperatures used, the substrate temperature

varied from 480°C to 520°C. The substrate temperature was assumed to be $500 \pm 20^\circ\text{C}$ during these experiments. As discussed below, this assumption is not critical to the conclusions drawn.

The filament temperature has a significant effect on the exit mole fraction of silane as shown in Figure 7(a). The mole fraction decreases exponentially ($R^2 = 0.94$) with increasing filament temperature. The filament temperature does not affect the growth rate as significantly as it affects the silane mole fraction but it does change the axial growth rate profiles, as illustrated by Figure 7(b). Although, the substrate temperature changes with the filament temperature, the observed behavior is solely an effect of variation in the filament temperature because neither the growth rate (Figure 5) nor the silane conversion (Figure 4) is affected significantly by variations in the substrate temperature.

An axial variation in growth rate is not observed at low filament temperatures because the consumption rate of silane is small. This allows the silane concentration to be high everywhere in the reactor, resulting in uniform growth rates. At high temperatures, the rate of reaction increases, consuming silane more rapidly. This leads to a substantial variation in the silane concentration in the axial direction with silane virtually absent at the reactor exit. The growth rate increases at the inlet where the silane concentration is high, but either remains the same or decreases at the exit where the low concentration of silane dominates the effect of increased filament temperature on the growth rate.

In addition, the growth rate at the inlet sample saturates at high filament temperature. Saturation is not observed at the subsequent substrate positions, where the silane is largely depleted. Saturation in growth rate at high filament temperature has been observed by other workers.¹³⁻¹⁵ However, the filament temperature at the onset of growth rate saturation varied in each study. During HWCVD, silane can be consumed by silane pyrolysis on the filament surface and hydrogen abstraction from silane by H-atoms in the gas phase, as shown in equation (2). The atomic hydrogen is produced by silane or hydrogen decomposition on the filament surface. Saturation indicates that a maximum in the controlling silane consumption rate was achieved. On a tungsten surface, both the rate of silane pyrolysis^{12,16} and the rate of decomposition of hydrogen¹⁷ exhibit saturation under different process conditions. Assuming similar behavior on a tantalum surface, the variation in the observed filament temperature at growth rate saturation is due to a change in the dominant route for silane consumption (either silane pyrolysis or hydrogen abstraction in the gas phase) with process conditions.



As shown in Figure 7(c), the film crystalline fraction increases with increasing filament temperature. The filament temperature can change the film properties either directly, by changing the temperature of the growing surface (substrate temperature)

by radiative heating, or indirectly, by changing the gas phase radical composition. Decreasing the filament temperature from 1850°C to 1580°C reduces the substrate temperature from 520°C to 480°C and changes the film morphology from >80% crystalline to amorphous. Based on the data shown in Figure 6, we can attribute some of the increase in crystallinity with filament temperature to the variation in substrate temperature. However, this direct effect can only account for a 20-30% increase in crystalline fraction. The remaining increase in crystallinity must be due to the effect of filament temperature on the reaction chemistry.

Higher filament temperatures enhance the rate of generation of H atoms¹² increasing the H atom flux to the film surface. Consequently, the surface concentration of hydrogen radicals increases. This enhances the surface rearrangement reaction rate relative to the growth rate, increasing R_{xc} (equation (1)) and thus improves the film crystallinity.

Broqueira *et al.*¹¹ report a decreasing trend in crystalline fraction with increasing filament temperature. They deposited films at 50 mTorr pressure and 50% hydrogen dilution over a 1500-1900°C filament temperature range. Broqueira *et al.* observed that the silicon film growth rate dropped from $\sim 5 \text{ \AA} \cdot \text{s}^{-1}$ at 1900°C to $0.14 \text{ \AA} \cdot \text{s}^{-1}$ at 1500°C, whereas we observe less than two times decrease in growth rate over a filament temperature range of 1850-1600°C. This suggests that the lower growth rate at 1500°C led to higher crystallinity because smaller flux of growth precursors allow sufficient time for surface rearrangement reaction on the film (large R_{xc}).

3.3. Effect of Silane Flowrate

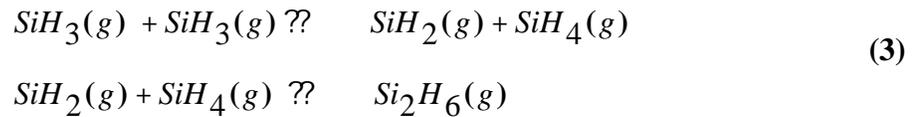
The influence of the silane flowrate on the silane mole fraction at the exit is shown in Figure 8(a). The data was obtained for two different gas pressures, 25 mTorr and 500 mTorr at an average filament temperature of $1870\pm 20^\circ\text{C}$ and $1815\pm 5^\circ\text{C}$, respectively, and a substrate temperature of $505\pm 20^\circ\text{C}$. The exit silane mole fraction increases with silane flowrate due to a decrease in the residence time. The growth rate increases linearly with the inlet flowrate of silane for all substrate positions at 500 mTorr and 25 mTorr as illustrated in Figure 8 (b) and (c), respectively.

In the range of silane flowrates investigated, the conversion of silane is high due to a long residence time in the reactor; thus, the supply of silane to the filament limits the growth rate. Therefore, while the conversion decreases with increasing silane flowrate, the growth rate increases with silane flowrate in this supply-limited regime. At very high flowrates, the kinetics of silane decomposition becomes rate limiting due to a very small residence time. Thus, in this regime, the growth rate is expected to decrease with increase in silane flowrate. This suggests that there should be a maximum in the growth rate variation with silane flowrate. This maximum most likely occurs at flowrates greater than we can obtain. Feenstra *et al.*⁹ observed saturation in the growth rate for silane flowrates greater than 60 sccm at a deposition pressure of ~ 20 mTorr and filament temperature of 1900°C . For the range of silane flowrates used in this study, various workers^{9,10,15} have reported a linear increase in growth rate with silane flowrate.

This supply-limited deposition rate is also responsible for the observed axial variation in growth rate at 500 mTorr. Axial variation in growth rate is not observed at 25 mTorr due to a lower extent of reaction. At lower pressure, both the residence time of the gas and the number of gas phase collisions are small. Consequently, consumption of silane is slow and its concentration is higher downstream in the reactor. Therefore, the growth rate at 25 mTorr is slower at the inlet and faster at the exit compared to 500 mTorr depositions at the same silane flowrate. This implies that lower pressure deposition can lead to better uniformity in film thickness over a larger area.

The variation in the crystalline fraction of the film with silane flowrate is illustrated in Figure 9. At high flowrates, the deposited films are amorphous at both pressures, implying that the crystalline fraction decreases as the growth rate increases. The flux of growth precursors to the film surface increases with silane flowrate whereas the rate of the surface rearrangement reaction does not change due to a fixed substrate temperature and filament temperature. Consequently, the molecules already present on the surface have less time to rearrange resulting in amorphous films. However, poly-Si films obtained at 500 mTorr have higher growth rates compared to a-Si films deposited at 25 mTorr. This implies that the rate of surface rearrangement reaction increases with total pressure. A small axial variation in the crystalline fraction is also observed at 500 mTorr with the crystalline fraction increasing from the inlet to the exit because of a decrease in the growth rate.

At 500 mTorr for silane flowrates above 27 sccm, brown ‘soot’ forms leading to the deposition of Si films with very poor adhesion to the substrate. The brown ‘soot’ formation usually arises from deposition of higher silanes and its presence indicates gas phase polymerization. A possible reaction route leading to the formation of disilane is,



Radical recombination and high concentrations of unconverted silane lead to the formation of higher silanes. Thus, at high silane flowrates, an increase in silane concentration results in the formation of brown powder, especially at higher pressures.

3.4. Effect of Total Pressure

The total pressure inside the reactor was varied by using a throttle valve to change the volumetric flowrate of gases at the reactor exit. The flowrate of silane at the inlet was kept constant at 18 sccm to eliminate its effect on the growth rate. The filament temperature was controlled at $1850 \pm 5^\circ\text{C}$, and the substrate temperature was fixed at $520 \pm 20^\circ\text{C}$.

The effect of the total pressure on the mole fraction of silane at the exit is shown in Figure 10(a). As the reactor pressure increases, the silane conversion increases reducing the exit concentration of silane. The increased consumption of silane is a combined effect of an increase in the rate of gas phase reactions and the

residence time with pressure. The increase in silane conversion coupled with an increase in gas pressure increases the concentration of hydrogen in the reactor.

The growth rate profile as shown in Figure 10(b), indicates that as the pressure increases the axial variation in growth rate increases. While the deposition rate on the inlet substrate increases monotonously with pressure, the deposition rate on the center and the exit samples increases initially and then decreases at high pressures. While some workers ^{11,13} observed that the growth rate increases with pressure, others ^{9,10} observe a maximum in growth rate with respect to total pressure. Our data suggests that the variation in the growth rate is sensitive to the axial position of the substrate relative to the gas inlet. Therefore, variation in the reactor geometry can account for most of the conflicting observations reported in the literature. As the pressure increases, we see that the crystalline fraction of the film also increases as illustrated in Figure 10(c). This behavior is similar to that observed for decreasing silane flowrate (increasing residence time) in Figure 9; however, now crystalline films are obtained at higher growth rates.

At higher pressures, both the residence time and the rate of gas phase reactions increase leading to higher conversions. This consumes silane rapidly at the reactor inlet resulting in a large concentration gradient in the axial direction. The growth rate on the inlet sample increases continuously due to an increase in the silane conversion, but decreases for the center and the exit sample because of reduced silane concentrations.

The higher consumption of SiH_4 with pressure increases the concentration of H_2 in the reactor, which increases the production rate of H-atoms. The resulting increase in the H-atom flux to the growing surface increases the concentration of adsorbed H. The rate of surface rearrangement reaction thus increases, leading to the deposition of poly-Si films.

3.5. Effect of Hydrogen Concentration

Molecular hydrogen is generated during the decomposition of silane. To understand the effect of hydrogen on silicon film deposition, a series of experiments were performed with different hydrogen concentration in the reactor. For these experiments, a fixed silane flowrate of 18 sccm, a filament temperature of $1850 \pm 5^\circ\text{C}$, and a substrate temperature of $520 \pm 20^\circ\text{C}$ were used. The feed concentration of hydrogen was varied at a constant flowrate of silane by changing the flowrate of hydrogen. The total pressure was increased proportional to the increase in total flowrate to maintain a constant feed concentration (partial pressure) of silane and a constant residence time (calculated based on the inlet flowrates) across these experiments.

Figure 11 shows the change in the exit mole fraction of silane with hydrogen concentration. The bottom x-axis represents the hydrogen partial pressure in the feed. The top x-axis represents the corresponding total pressure in the reactor. The silane mole fraction decreases with increasing hydrogen concentration. Additional hydrogen in the reactor enhances H-atom production and thus the silane conversion by hydrogen

abstraction reaction in the gas phase. Figure 11 also includes the effect of reactor pressure (top x-axis) on the silane mole fraction obtained under similar conditions using a pure silane feed. Although the volumetric flowrate through the reactor is higher during the hydrogen dilution experiments compared to pure silane experiments, the silane mole fraction at a given hydrogen dilution is the same as the silane mole fraction obtained at the corresponding total pressure using pure SiH_4 . This implies that the increase in the silane consumption rate at higher hydrogen concentrations dominates over the effect of decrease in residence time. The growth rate profiles, compared in Figure 12, also support this argument. The bottom x-axis represents the hydrogen partial pressure in the feed. The top x-axis represents the corresponding total pressure in the reactor. The growth rate profiles for hydrogen dilution and pressure experiments (top x-axis) using pure silane are similar.

The effect of hydrogen concentration on the film crystalline fraction is depicted in Figure 13. With an increase in hydrogen dilution, the crystalline fraction of the films increases. The increase in crystallinity is similar to that with increasing pressure using pure silane (Figure 10(c)). With higher concentration of hydrogen, the H-atom concentration in the reactor will also increase. As discussed earlier, a higher H-atom flux to the growing surface leads to the deposition of poly-Si films.

The above discussion implies that the effect of increasing hydrogen concentration on silicon film deposition is similar to the effect of increasing total pressure using pure silane. Although pure SiH_4 is fed to the reactor, it becomes significantly diluted in hydrogen due to high silane conversion at high pressure. Thus,

the beneficial effect of hydrogen can be obtained at much lower volumetric flowrates by using pure silane and operating under the conditions of high conversion. This can significantly reduce the pumping requirements for depositing poly-Si films.

4. Conclusion

Poly-Si films have been deposited using pure silane as the feed gas. For the conditions investigated, the growth rate increases with an increase in silane flowrate and is independent of the substrate temperature. The variation in the growth rate with the total pressure and filament temperature is dependent on the substrate position relative to the gas inlet. The crystalline fraction of the films increases with total pressure, substrate temperature and filament temperature, whereas the crystalline fraction decreases with an increase in silane flowrate.

The effect of hydrogen dilution on film properties is equivalent to the effect of increasing gas pressure under conditions of high silane conversions using pure silane. The experiments suggest that the direct interaction of atomic hydrogen with the growing surface is essential for depositing an ordered film. Although it is difficult to establish the direct effect of atomic hydrogen solely based on these experiments, it is postulated that the flux of H-atoms relative to the growth rate controls the crystalline fraction of the films. This implies that a critical concentration of H-atoms is required on the film surface to deposit crystalline films.

We have established that poly-Si films can be deposited at substrate temperatures below 600°C using HWCVD, facilitating the use of low cost substrates.

Since, the axial variation in growth rate as well as the crystalline fraction of HWCVD films increases with pressure and filament temperature; the conditions for depositing poly-Si films of uniform thickness over a large surface area have to be optimized. Nonetheless, HWCVD can lead to reduction in the cost of photovoltaic modules by depositing poly-Si films of uniform thickness on a large area, low cost substrates.

Acknowledgments

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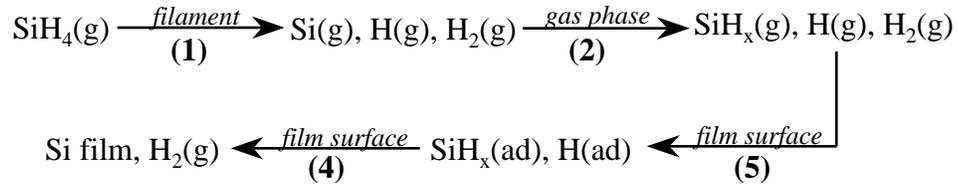


Figure 1: Steps involved in HWCVD of Si films.

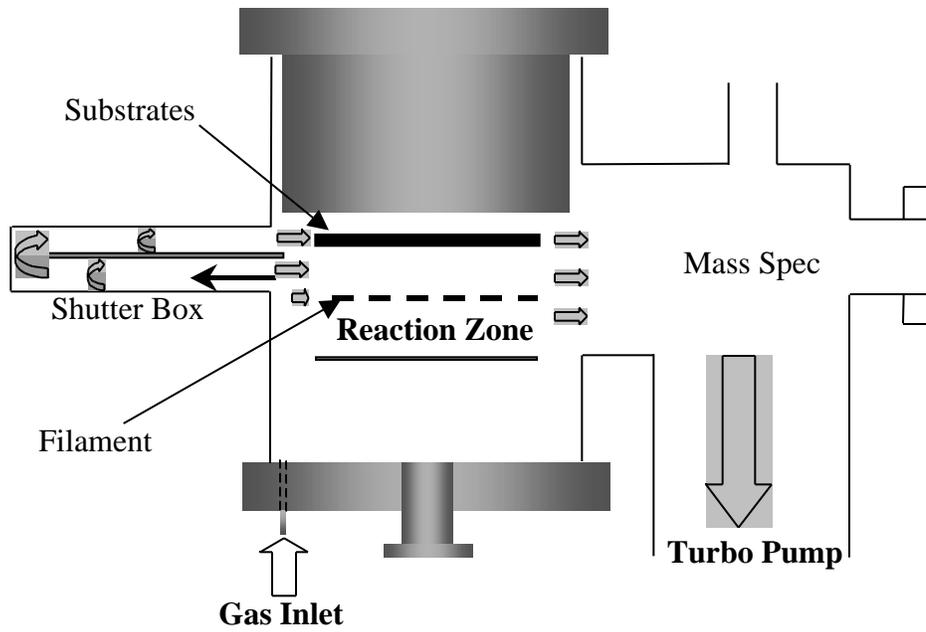


Figure 2: Cross-sectional view of the Hot Wire deposition chamber.

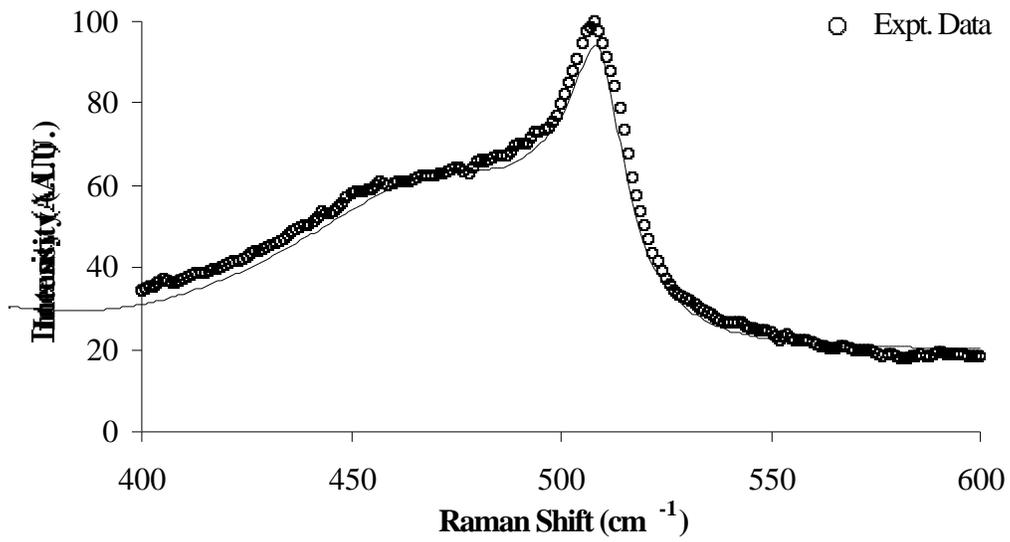


Figure 3: Raman spectrum of a typical poly-Si film.

(a-Si: TO peak around 480 cm⁻¹ and c-Si: TO mode at 520 cm⁻¹. Line represents the contribution of the deconvoluted peaks.)

Table 1: Process conditions used to study the effect of substrate temperature

	Low Pressure	High Pressure
F _{O_{SiH₄}} (sccm)	9	27
Pressure (mTorr)	25	500
Filament Temperature (°C)	1873 ±10	1815 ±5
Reference Temperature (°C)	280-480	280-480
Substrate Temperature (°C)	420-595	415-590

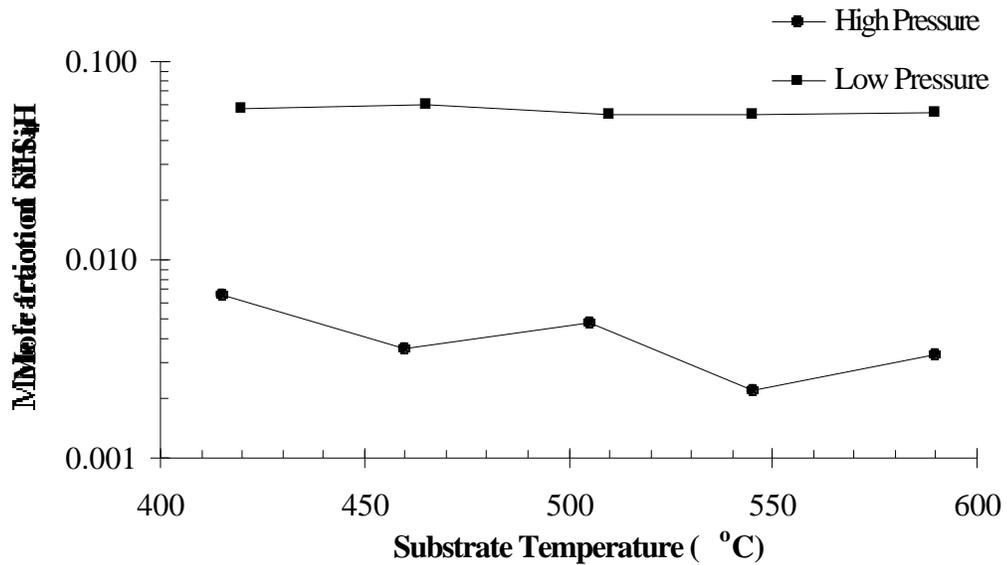


Figure 4: Effect of substrate temperature on the mole fraction of silane at the exit. (Refer to Table 1 for deposition conditions).

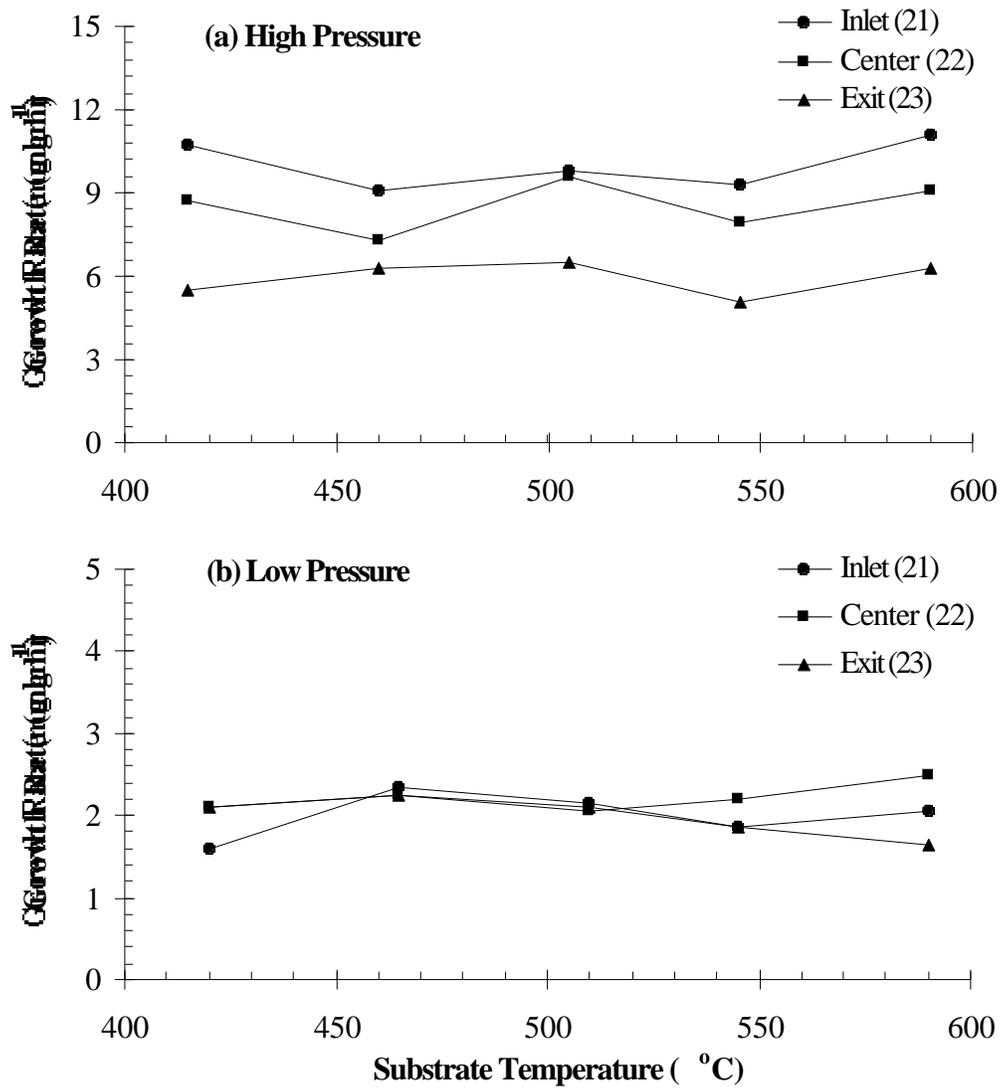


Figure 5: Effect of substrate temperature on Si-film growth rate.

(Refer to Table 1 for deposition conditions).

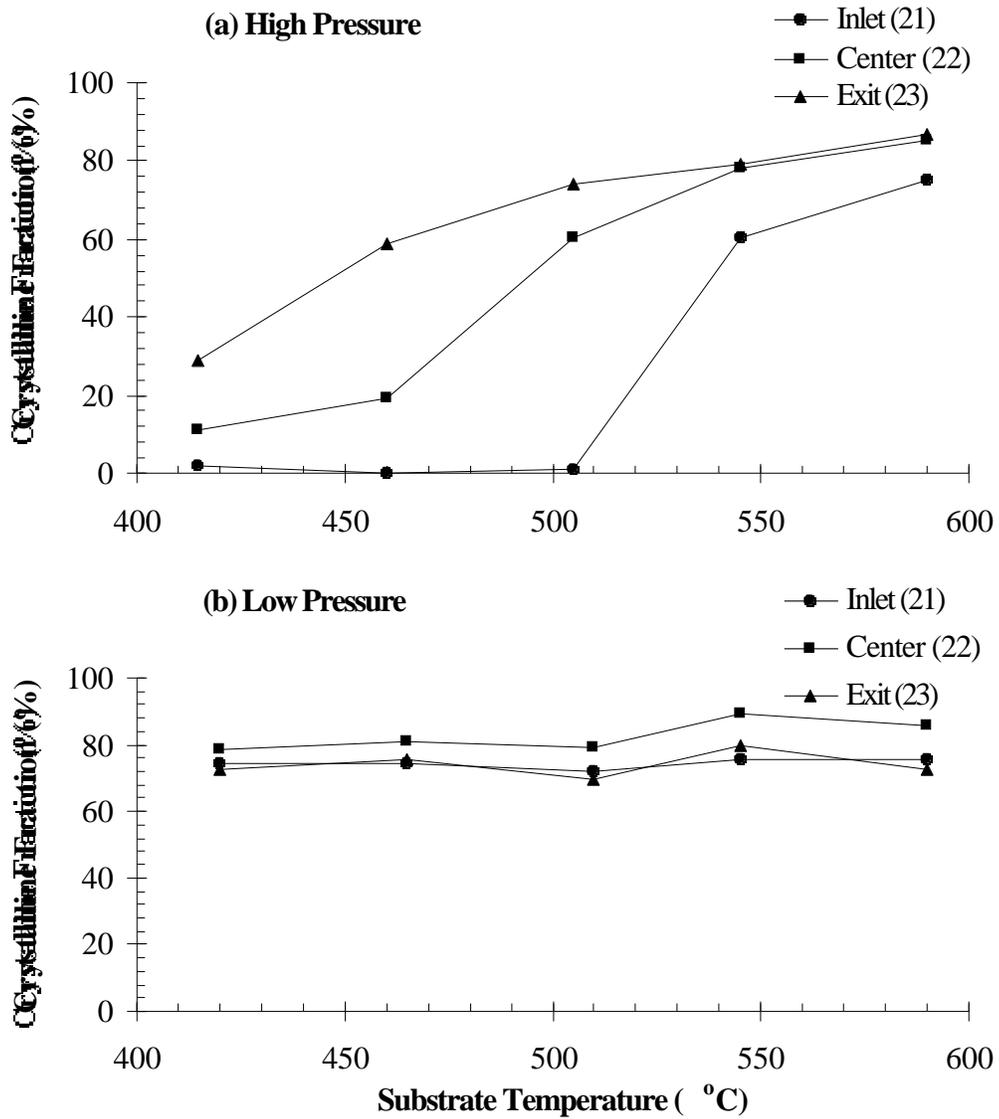


Figure 6: Effect of substrate temperature on the crystalline fraction in the Si-films. (Refer to Table 1 for deposition conditions).

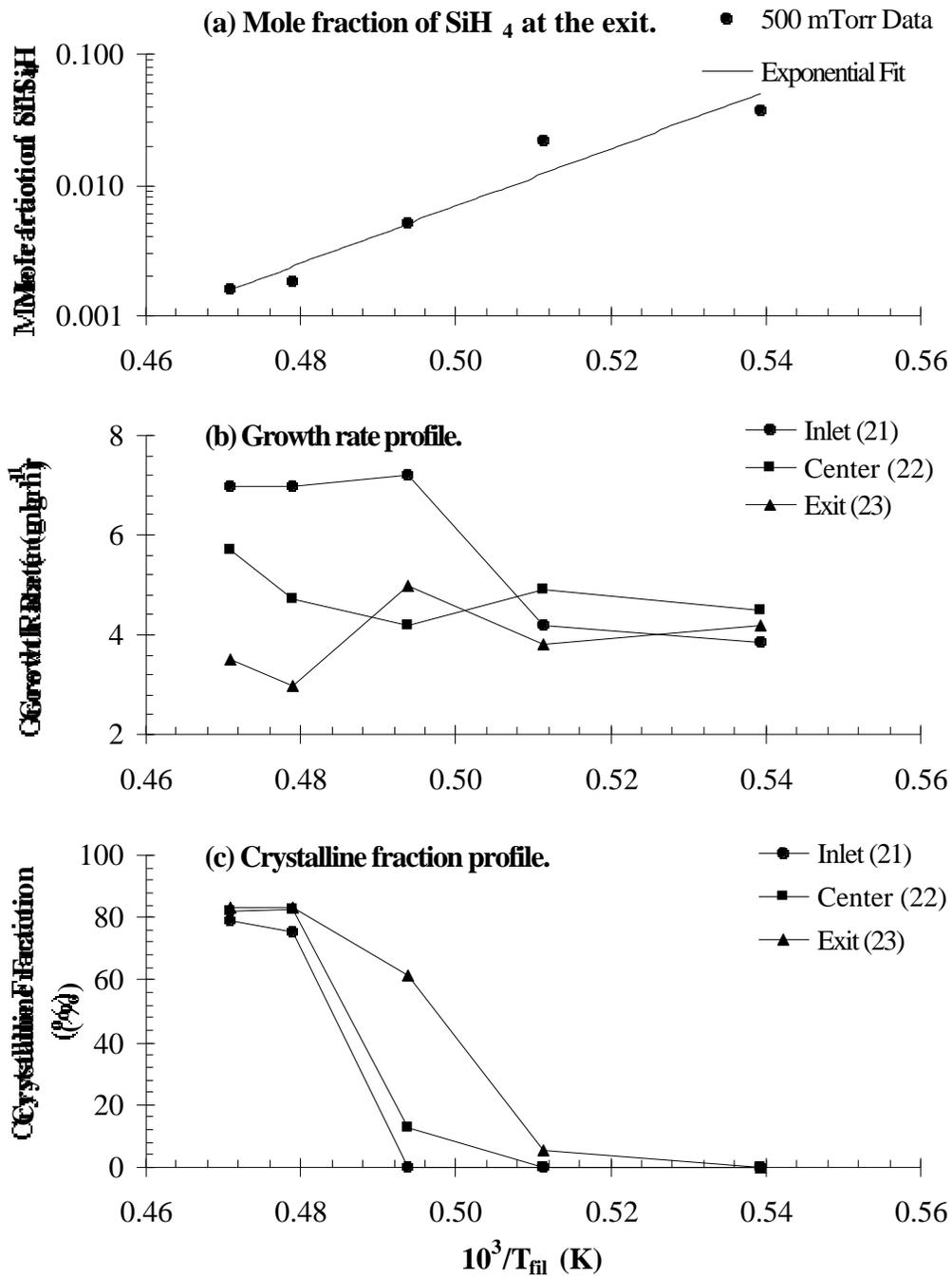


Figure 7: Effect of filament temperature

(Deposition conditions: $P_t = 500$ mTorr, $F_{\text{SiH}_4} = 18$ sccm, $T_{\text{sub}} = 500 \pm 20^\circ\text{C}$)

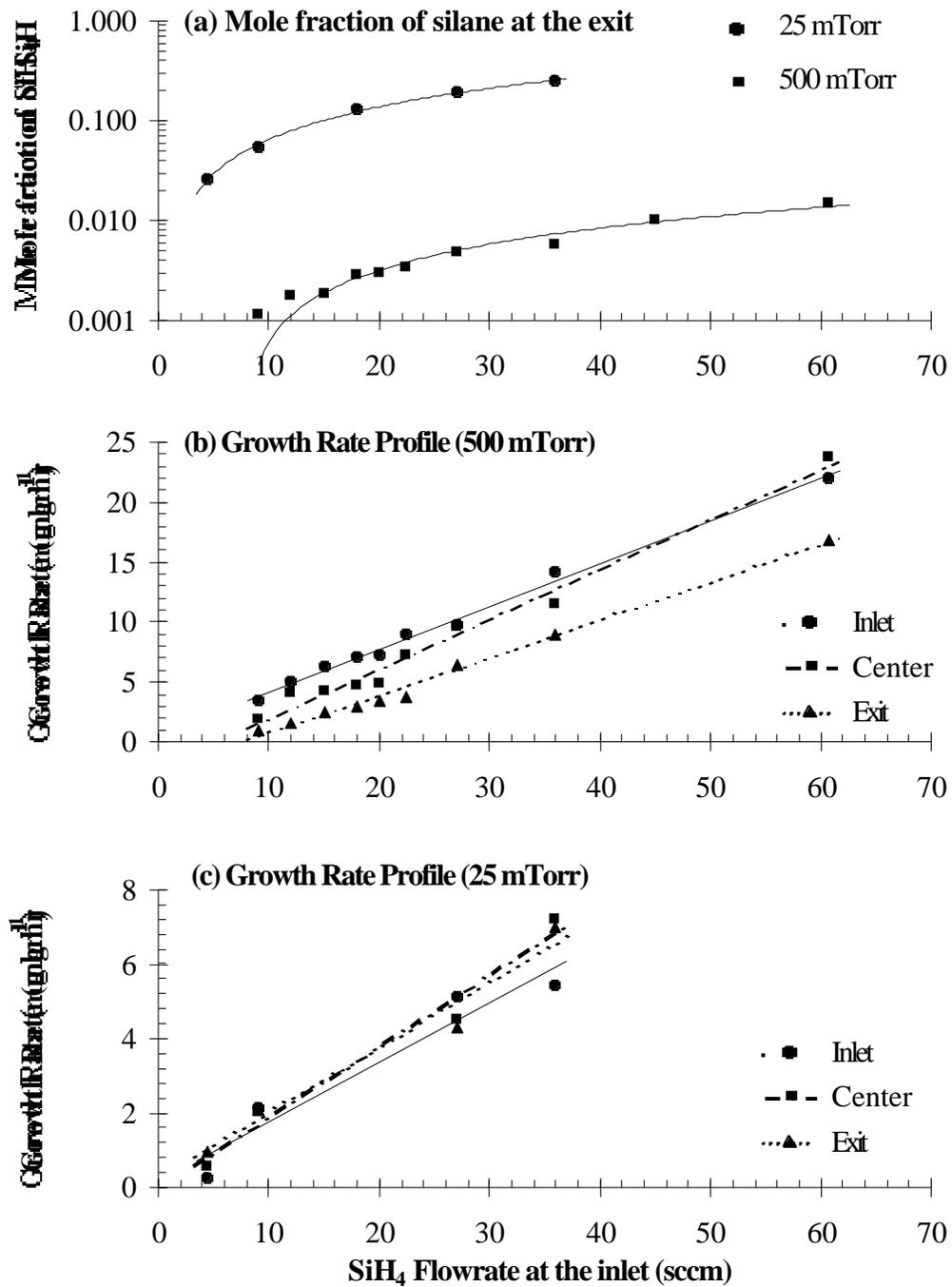


Figure 8: Effect of SiH₄ flow rate (Lines represent least square fit to the data.)

(Process conditions: $T_{fil} = 1815^{\circ}\text{C}$ (at 500 mTorr), 1870°C (at 25 mTorr); $T_{sub} = 505^{\circ}\text{C}$)

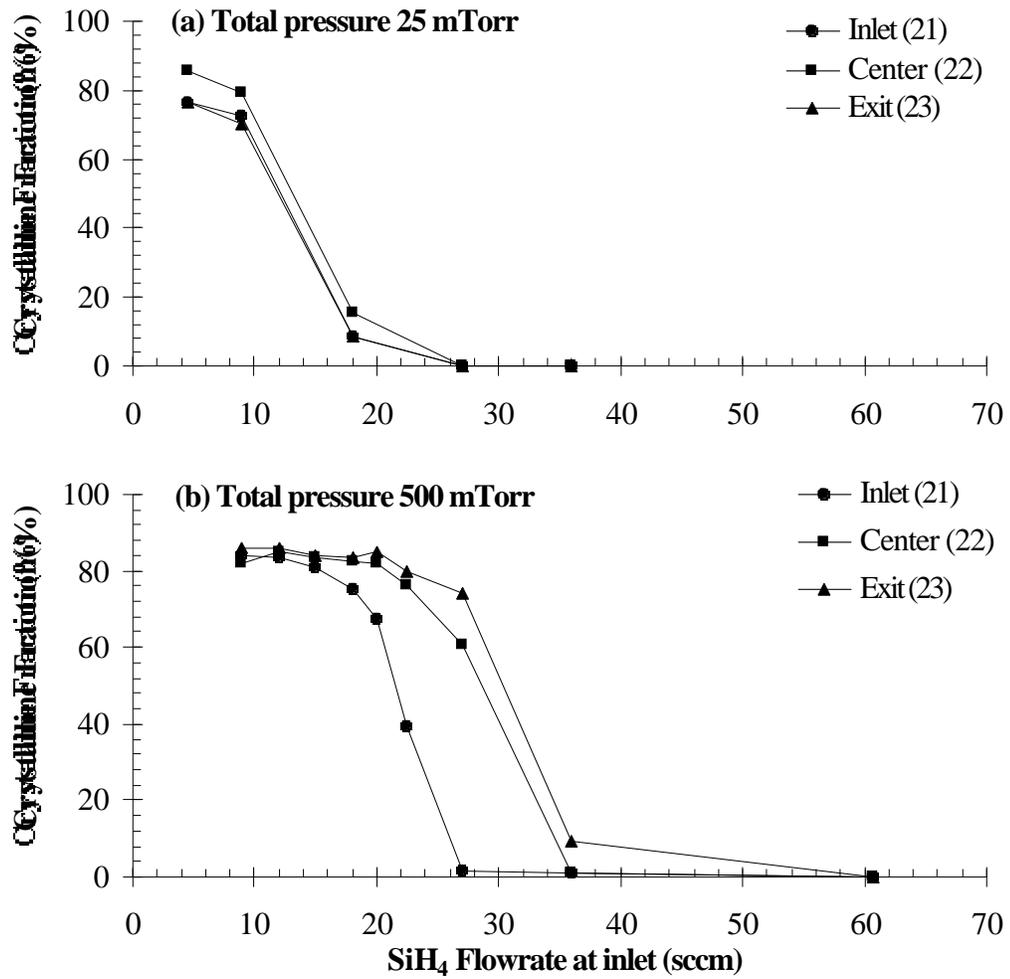


Figure 9: Effect of silane flow rate on the crystalline fraction in the film.

(Process conditions: $T_{\text{fil}} = 1815^{\circ}\text{C}$ (at 500 mTorr), 1870°C (at 25 mTorr); $T_{\text{sub}} = 505^{\circ}\text{C}$)

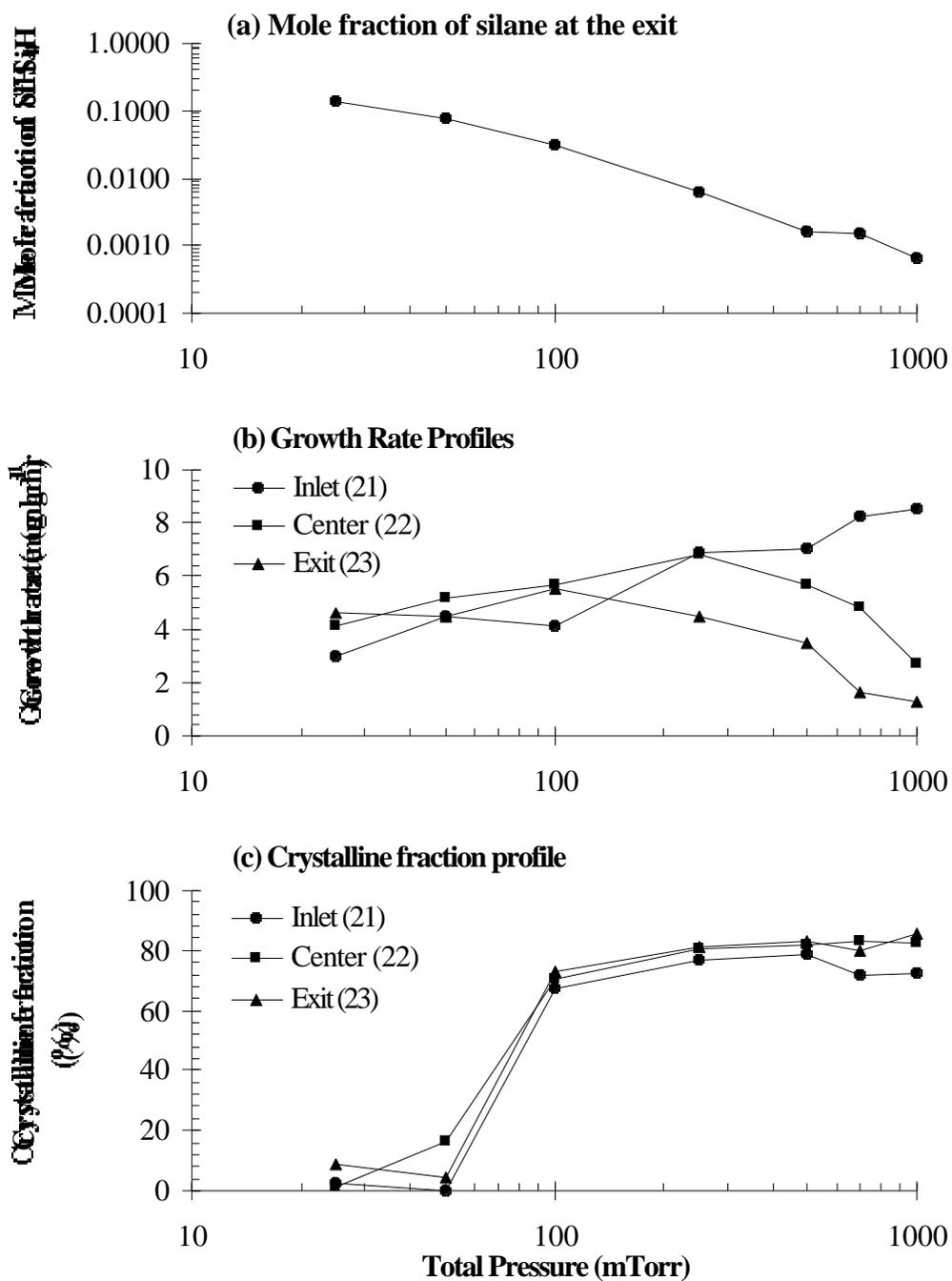


Figure 10: Effect of total pressure.

(Process conditions: $T_{fil} = 1850^{\circ}\text{C}$, $F_{\text{O}_{\text{SiH}_4}} = 18 \text{ sccm}$, $T_{\text{sub}} = 520^{\circ}\text{C}$)

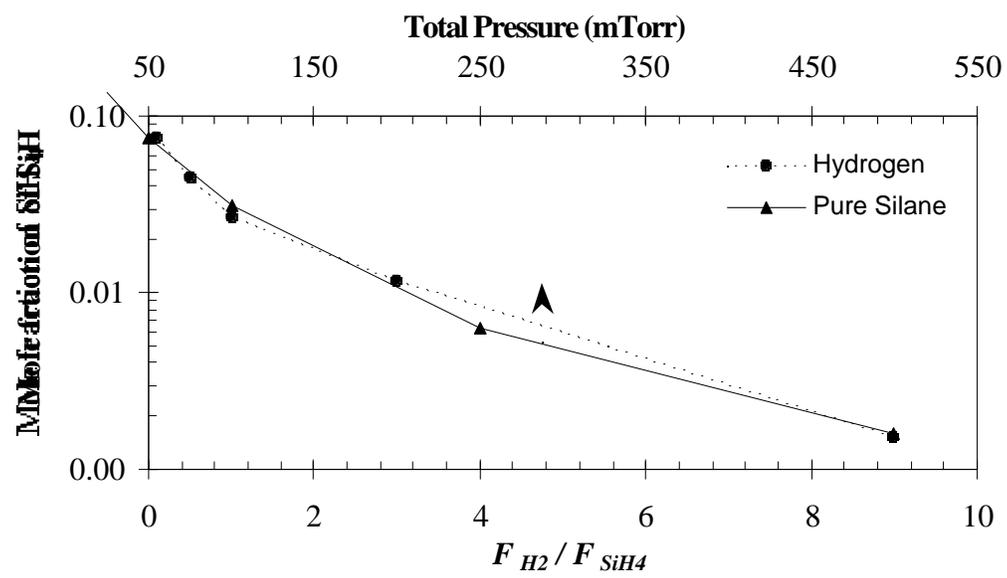


Figure 11: Effect of dilution on the partial pressure of silane at the reactor exit.

(Process conditions: $T_{fil} = 1850^{\circ}C$, $F_{O_{SiH_4}} = 18$ sccm, $T_{sub} = 520^{\circ}C$)

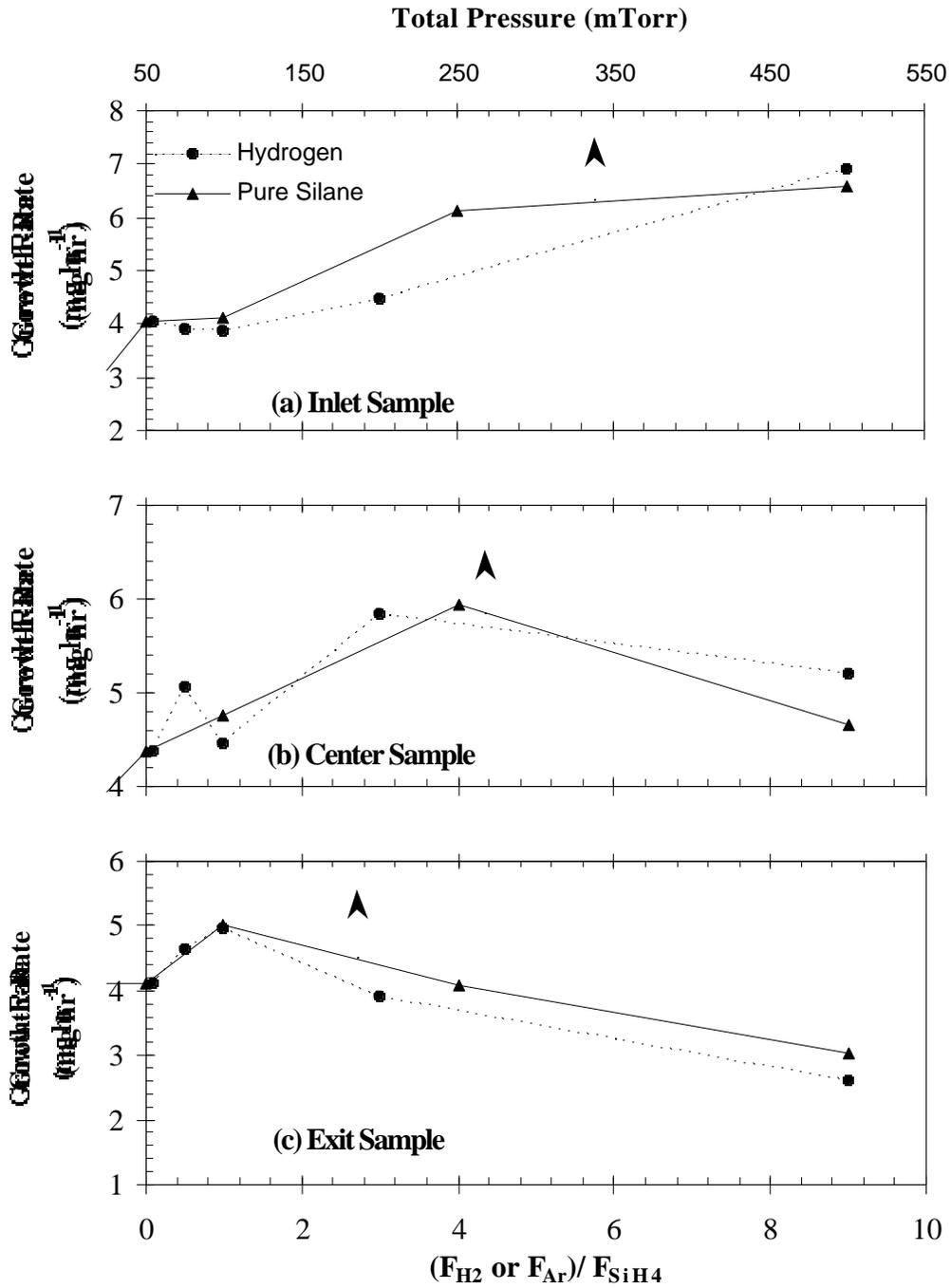


Figure 12: Effect of dilution on the film growth rate on the substrates in the center row. (Process conditions: $T_{fil} = 1850^{\circ}\text{C}$, $F_{\text{SiH}_4} = 18$ sccm, $T_{\text{sub}} = 520^{\circ}\text{C}$)

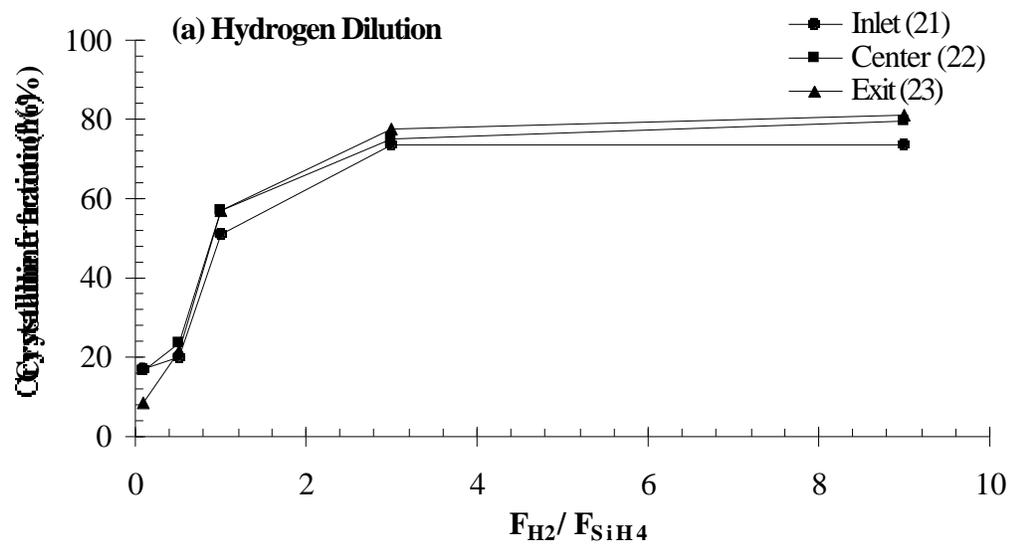


Figure 13: Effect of hydrogen dilution on the crystalline fraction in the film.

(Process conditions: $T_{fil} = 1850^{\circ}C$, $F_{O_{SiH_4}} = 18$ sccm, $T_{sub} = 520^{\circ}C$).