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Dependence of intrinsic stress in hydrogenated amorphous silicon on excitation frequency in a plasma-enhanced chemical vapor deposition process

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Intrinsic stress measurements were carried out on hydrogenated amorphous silicon (*a*-Si:H) films deposited with different excitation frequencies (13.56–70 MHz), by plasma-enhanced chemical vapor deposition. It was observed that films deposited at 70 MHz have one order of magnitude smaller intrinsic stress than those deposited at 13.56 MHz. These results have been linked to the estimated variation of the ion impact energy as a function of excitation frequency, deduced from the measured variation of the peak-to-peak voltage between the electrodes. The observation of diminished ion energy at higher excitation frequencies has been interpreted as the cause, both of the decrease in intrinsic stress as well as of the measured increase in surface roughness, of films prepared at higher frequencies.

Over the past decade much progress has been made in the understanding of the material properties, growth characteristics, and the deposition processes of hydrogenated amorphous silicon (*a*-Si:H). Radio frequency plasma-enhanced chemical vapor deposition (PECVD) is normally used for the deposition of *a*-Si:H. Although several other deposition methods have been tried out, at present the most widely used deposition process for growing *a*-Si:H films is still the PECVD method.[1] The technological problems associated with plasma processing at other than the authorized frequencies (13.56, 27.12, 40.68, 915, and 2450 MHz in the USA) has limited the utilization of other frequencies for PECVD. Due to the easy availability of equipment and accessories, the radio frequency generally used for the PECVD process has by and large been restricted to 13.56 MHz, in spite of the promising aspects of very high frequency (VHF) deposition which have been demonstrated by our group[2–4] and others.[5,6]

It has been reported that the ion energy decreases due to a decrease in the sheath field with increasing excitation frequency.[6] In the silane plasma, apart from the neutral species, positively charged ions also exist which bombard the grounded electrode during deposition.[7] Moderate energy (10–100 eV) ion bombardment during the growth of *a*-Si:H films has generally been considered beneficial as it would provide enough kinetic energy for enhancing the surface diffusion processes.[8–11] On the other hand significantly higher ion impact energies could create defects in the films.[7] The effect of ion bombardment during growth of thin films on their final properties has been related to an increase in the intrinsic compressive stress in the films.[9] Another interesting modification generally associated with the effect of increased ion bombardment during growth is the decrease in surface roughness.[12] Studies on the effect of rf frequency on the intrinsic stress of *a*-Si:H films prepared by the PECVD process have been reported by Matsuda *et al.*[13] and others,[14] but the results at frequencies higher than 13.56 MHz cannot be considered to form a complete and well-defined study. In this communication we report on a systematic scan of the frequency, in the range from 13.56 to 70 MHz, on intrinsic stress in *a*-Si:H films prepared under otherwise identical conditions. We corroborate our findings by reporting on the variation of the surface roughness of these films as estimated from simple reflection measurements.

All the films were prepared in a symmetric rf capacitative reactor as described elsewhere.[4] The self bias in our reactor was always negligibly small. The substrate temperature was kept constant at 200 °C and a flow rate of 30 sccm of silane was used at a gas pressure of 0.3 mbar. The reactor consists of two symmetric cylindrical electrodes 130 mm in diameter placed 20 mm apart. One major difficulty with variable frequency operation is that the rf circuit losses are frequency-dependent. Therefore, a frequency scan at constant *source power* does not guarantee constant *plasma power*. Care was taken in this study to keep the true plasma power constant at 5 W during all the depositions; this gives a volume-averaged plasma power density of approximately 19 mW/cm^{-3} as has been described in detail previously.[4] All the films prepared for this study were between 2 and 4 μm thick with the deposition rate increasing monotonously from 3.3 Å/s at the excitation frequency of 13.56 MHz to 10 Å/s at 70 MHz. The intrinsic stress was estimated by the beam-bending method.[15] The stress in the films was determined by taking the difference in the curvature estimated for the glass substrate (Corning 7059) with the film on it and after the film was stripped off. It was checked separately that there was no appreciable deviation in the stress calculated by this method, compared to the general way of determining stress from the bending of crystalline silicon substrates. In both cases films thicker than 2 μm were used to avoid errors due to the thickness depen-

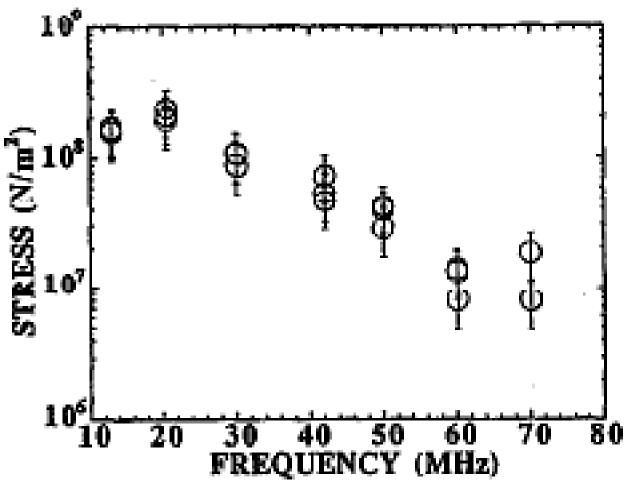

FIG. 1. Variation of intrinsic stress in a-Si:H films with respect to varying frequency prepared at otherwise similar conditions. The fluctuations in the estimation of stress is included in the figure.

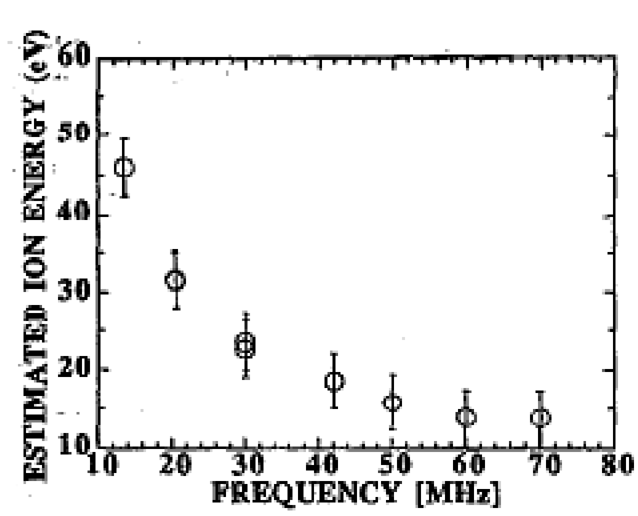

FIG. 2. Variation in the maximum ion energy during deposition with respect to frequency as estimated from $V_{pp}/4$. Standard errors designate the fluctuations in the observed values.

dence of stress in very thin films.[16] The substrate curvature and the thickness of the films were measured by a Tencor stylus-profiler.

The root mean square (rms) surface roughness was determined utilizing the technique developed by Cunningham and Braundmeier.[17] A thin layer (< 1500 Å) of silver was evaporated onto the silicon surface and then the specular reflection at an angle of 7° was monitored in the wavelength region of surface plasmon excitation of the silver film, i.e., at a wavelength of 3500 Å. The loss in the reflectance ΔR due to the coupling of incident light to the surface irregularities, when compared to the reflectance of a smooth silver surface, gives a direct estimate of the rms roughness (∂), based on a correlation of ∂ with ΔR obtained by an interferometric method.[17]

In Fig. 1 we have plotted the intrinsic stress of the a-Si:H films prepared with different frequencies in the range of 13.56–70 MHz. The intrinsic compressive stress decreases steadily from $\sim 10^8$ N/m^2 at 13.56 MHz to $\sim 10^7$ N/m^2 at 70 MHz frequency. Previous studies of Nakamura *et al.*[14] also show a decrease in the stress of the films when they raised the excitation frequency from about 10 KHz to 13.56 MHz. This decrease in the stress of the films at higher frequencies can be linked to the decreased ion bombardment energy.[9,11] In order to support our argument we estimated the maximum ion bombardment energy from the measured rf electrode voltage as follows:

In the capacitative sheath approximation for a symmetric discharge, the maximum ion energy at the substrate surface is given by $(eV_{pp})/4$ (where V_{pp} is the peak-to-peak rf voltage and e the electronic charge), as shown by Köhler *et al.*[18] Since the discharge can be considered in the simplest approximation as a resistive bulk plasma bounded by capacitative sheaths, the sheath voltage diminishes at higher frequencies at constant plasma power. In effect, the impedance of the discharge is reduced as the frequency increases. This leads to a decrease in the maximum ion energy at the substrate for higher frequencies, as shown in Fig. 2, where the measured values of $(V_{pp})/4$ are plotted. The maximum ion energy decreases from ~46 eV at 13.56 MHz to ~14 eV at 70 MHz frequency. This decrease in ion energy at higher frequencies will result in lower energy ion bombardment on the growing surface, thereby effectively decreasing the intrinsic stress of the films (Fig. 1).

In Fig. 3. we have plotted the change in the rms surface roughness in the films with respect to the rf frequency. The rms surface roughness increases from ~4.5 Å for the films deposited at 13.56 MHz to ~11 Å for the films prepared at 70 MHz. It has been shown by ellipsometric measurements that the surface roughness of a-Si:H films decreases when these films are subjected to ion bombardment by applying external potential on the substrate electrode during PECVD deposition from silane.[12] Kasdan *et al.* have also reported that the intentional bombardment by He^+ ions during the deposition of a-Si:H films results in a smoother surface morphology of the films than when the films were grown without any ion bombardment.[19] Thus, the observation of increased roughness at higher frequencies (Fig. 3) further substantiates the conclusion that the ion bombardment decreases as we increase the operating frequency from 13.56 to 70 MHz.

The finding of lower intrinsic stress at higher frequencies agrees well with other observations made with VHF plasma deposition: (1) Using VHF plasma at 70 MHz, very thick layers of a-Si:H films ($\sim 100\ \mu$m) can be easily prepared;[20] this is, however, very difficult at the standard plasma excitation frequency of 13.56 MHz as the film peels

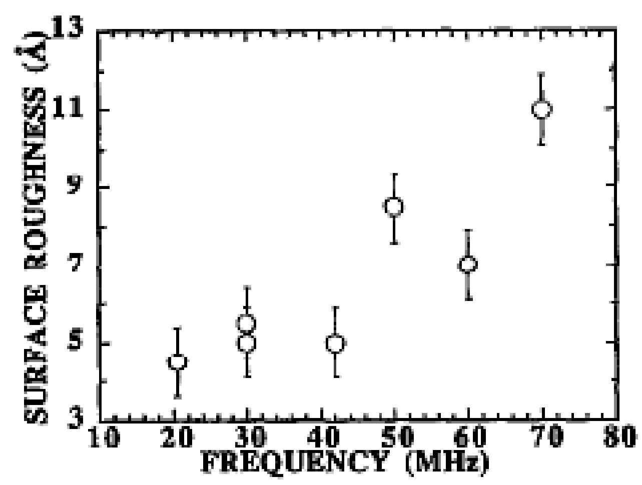

FIG. 3. Variation in the surface roughness of the a-Si:H films prepared at various frequency. The standard fluctuations are shown in the figure.

off. (2) Using VHF-plasma CVD it is possible to grow high-quality μc-Si:H (hydrogenated microcrystalline silicon) layers.[21] This points to a lower energy ion bombardment during deposition, since strong ion bombardment inhibits the growth of the crystallites in μc-Si:H.[22] (3) There is also some evidence showing a different microstructure (void size and distribution) of VHF deposited *a*-Si:H as compared to the films deposited at 13.56 MHz.[23,24] This again may possibly be a consequence of the lower ion energies involved at VHF, resulting in low energy ion bombardment during growth. It is generally expected that this low energy ion bombardment will result in better film quality due to the momentum imparted by these ions during growth, effectively enhancing the diffusion of the radicals at the surface of the growing film.[8] Further work relating to the structural properties of these films is in progress and should throw more light on the microstructural differences between 13.56 MHz and the VHF-deposited *a*-Si:H films. In conclusion, very high frequency PECVD strongly reduces the intrinsic stress of hydrogenated amorphous silicon films. It is suggested that this is related to a reduced ion bombardment energy experienced by the growing films.

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