Excitation of plasmas using non-sinusoidal waveforms: Applications in photovoltaics

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The use of non-sinusoidal RF "Tailored Voltage Waveforms" to continuously excite capacitively coupled plasmas has proven to be an effective technique to study fundamental physical phenomena involving plasma processing, such as thin-film growth by plasma enhanced chemical vapour deposition (PECVD). In particular, using TVW's to study the growth of silicon films at low temperatures (<250°C) has been used to reveal interesting underlying phenomena that are not directly accessible otherwise.

In the most easily envisioned form, the use of waveforms resembling "Peaks" or "Valleys" enable one to maximize or minimize the ion bombardment energy (IBE) seen by a growth surface, with little impact on the plasma density, as shown in Figure 1. This is achieved by changing how the potential drop is split between the two sheaths, without changing the peak to peak voltage (V_{PP}).

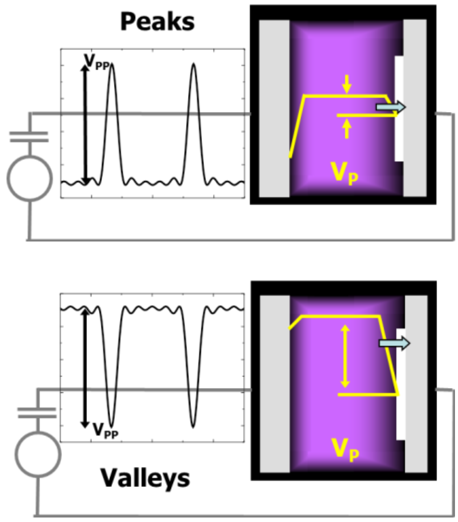

Figure 1

Initial studies focused on these processing extremes, and observed the impact on the resulting hydrogenated microcrystalline silicon (µc-Si:H) thin films [1,2]. As expected, the IBE did have an effect on how amorphous were the films grown, but the impact went beyond this intuitive result. For example, the bonding configuration of the hydrogen in the film was also modified to an important degree, even for films of equivalent crystalline content. As these Si-H configurations are known to be coupled to material density and quality, this was an important outcome. Justifying the importance of these results, these materials differences indeed translated into photovoltaic device performance [3].

More recent work has exploited the fact that TVW's provide not just access to these process extremes, but also enable one to sweep through the range of IBE's, by using a spectrum of waveforms. This allows one to determine critical threshold values of IBE for specific growth processes, such as the nucleation step during µc-Si:H growth [4,5], observable in-situ using spectroscopic ellipsometry. As a further measurement, ex-situ atomic force microscopy can be used to observe macroscopic differences in growth morphology.

Figure 2 summarizes such results for two different process gas mixtures consisting of hydrogen diluted silane. The quantity plotted in the upper graph is the bulk film thickness at which amorphous-to-microcrystalline silicon transition is observed (by in-situ SE). The presence of two threshold energies at ~30eV and ~70eV are apparent, both in this bulk film thickness, and in the surface roughness as measured by AFM. We have presented a coherent model for the role of ions during growth that explains these two phenomena, and a key aspect of the model is the assumption that ions of a certain energy cause a re-nucleation step to occur, and prevent smooth epitaxy-like growth on top of existing crystallites.

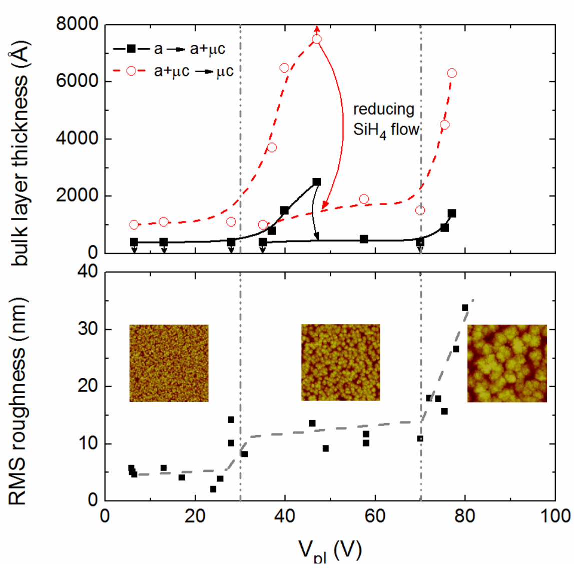

Figure 2 (from Ref.5)

To test the above theory, and as a point of interest on its own, the TVW technique has been applied to the growth of epitaxial silicon [6] by PECVD on HF-dipped monocrystalline silicon wafers at temperatures close to 200°C. In such a perfect growth system, the ability to decouple IBE and plasma density (and presumably pre-cursor flux) is a powerful tool. Again, we can observe the breakdown of epitaxial growth using spectroscopic ellipsometry. As shown in the upper part of Figure 3, under low IBE conditions, the original spectrum of crystalline silicon is preserved while the growth is ongoing. When ions have energies up to 47eV (actual threshold energy of around 30eV), they are able to disrupt the epitaxial growth, and a more microcrystalline/amorphous spectrum evolves with time. This is confirmed by cross-sectional TEM images (lower half of Figure 3) showing the preservation/breakdown of epitaxy under low/high IBE conditions.

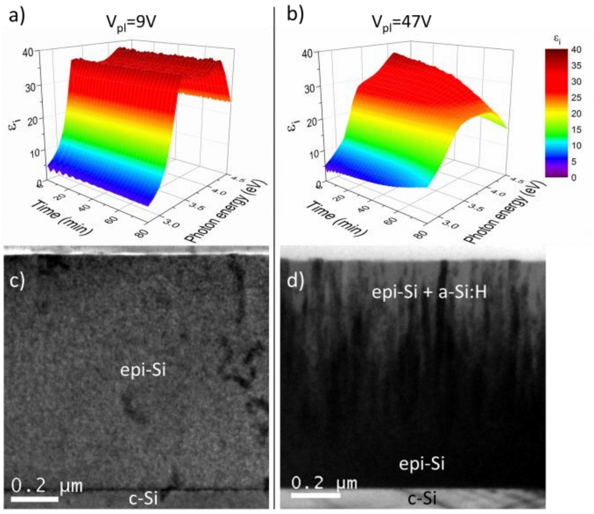

Figure 3 (from Ref. 6)

These examples demonstrate the use of TVW's as an investigative tool for processes useful for thin-film growth in general and photovoltaic devices more specifically. We continue to use such novel waveforms to achieve better device performance, and to understand the role of IBE in all aspects of thin-film growth and plasma processing.

Références

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