Tailored Voltage Waveforms

Introduction

In the classical configuration of capacitively coupled plasmas (CCP), there is a strong link between the plasma density and the ion energy flux to a surface. This places certain limitations on the accessible process conditions, as the plasma chemistry, process rate, and process quality become inextricably linked.

The use of **Tailored Voltage Waveforms** allows one to break this link. By using multiple harmonics of the RF base-frequency of 13.56 MHz, one can create voltage waveforms resembling "Peaks" or "Valleys" (Figure 1), or any arbitrary shape, and decouple the **ion flux from the ion bombardment energy (IBE)**.

This technique provides many opportunities to improve material processing and understand the underlying processes; we have applied it to amorphous and nanocrystalline silicon growth, low-temperature epitaxy, silicon wafer etching, graphene cleaning/doping, as well as fundamental plasma studies.

We have been developing the use of TVW's in close collaboration with the Laboratoire de Physique des Plasmas (LPP, www.lpp.polytechnique.fr), also located at the Ecole Polytechnique.

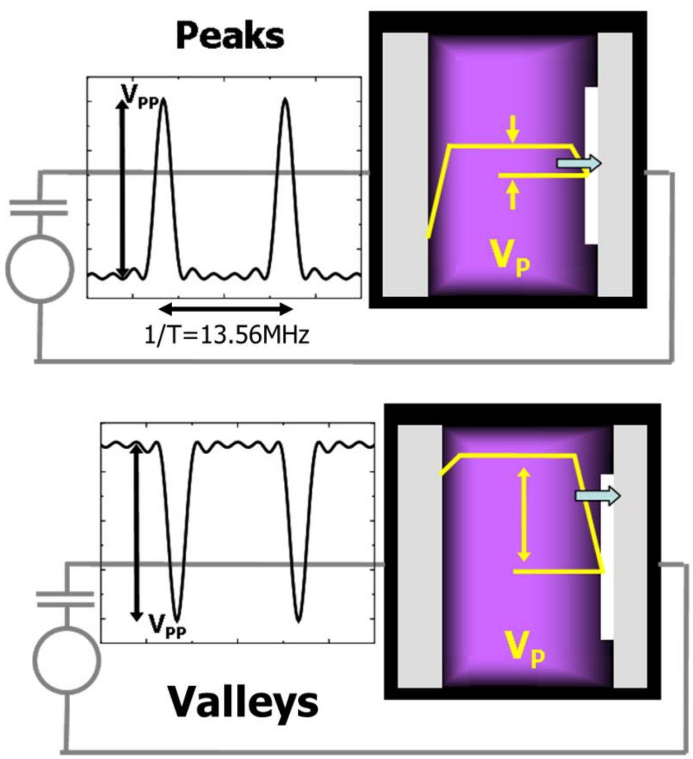

Figure 1

We have directly observed the impact of the use of such waveforms on the Ion Flux Distribution Function (IFDF), as shown in Figure 2. Compared to the use of a sinusoid (one harmonic, "1H"), the use of the sum of two or four harmonics (2H or 4H) allows one to create a greater range of maximum ion energies at the surface (measured in Ar). This is a direct demonstration of the tuning of plasma density with independent control of the IBE.

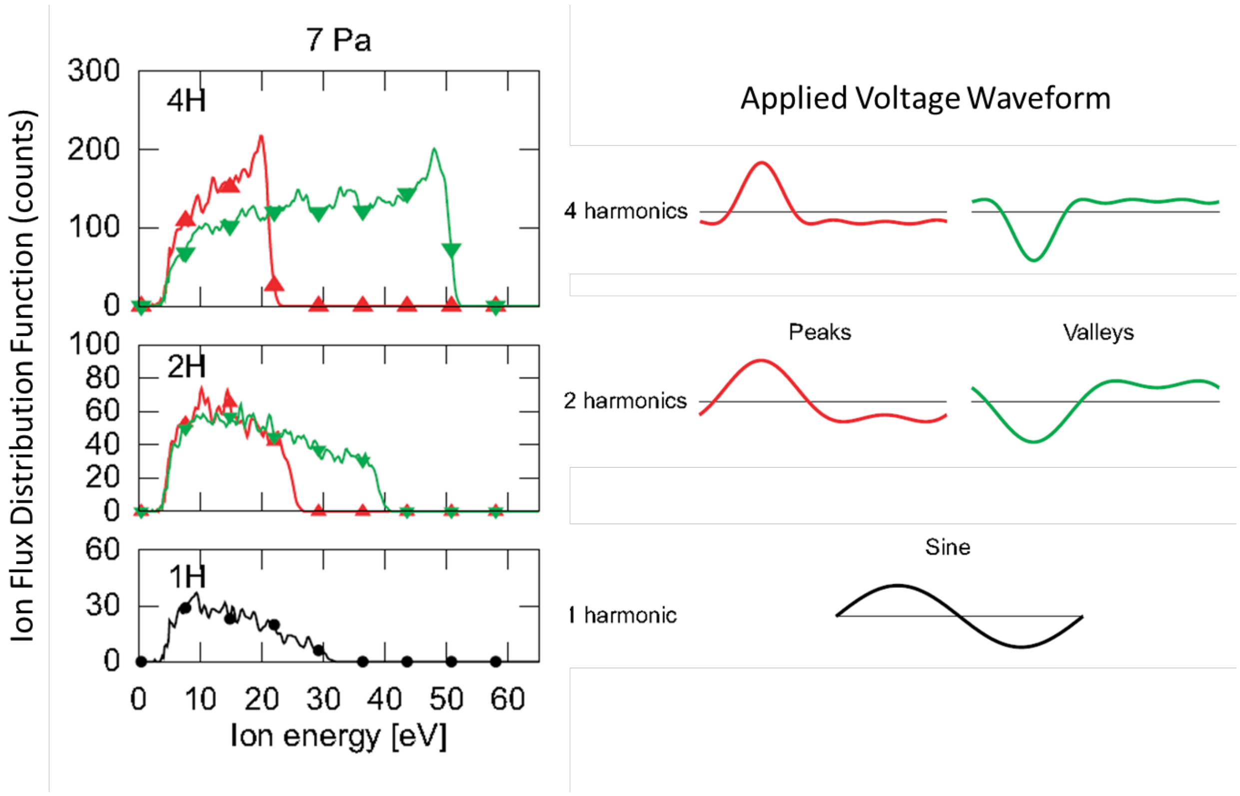

Figure 2 (from Ref. [8])

In addition to these extrema, one can construct waveforms providing the entire range of IBE's, but keeping the coupled power constant.

If one pictures the "Peaks" waveform as an alignment of all the maxima in a series of cosines (therefore a phase shift of 0 between harmonics), and the "Valleys" waveform as the alignment of all the minima (phase shift of pi), then by varying this phase shift from 0 to pi, one can construct all the intermediate waveforms. An experiment proof of the concept is shown in Figure 3, wherein by varying the phase, the power remains constant but the IBE varies over a large range.

This decoupling of the power and the IBE is a powerful tool, not just for optimization, but for understanding the underlying physical processes behind macroscopic observations in surface processing by plasmas.

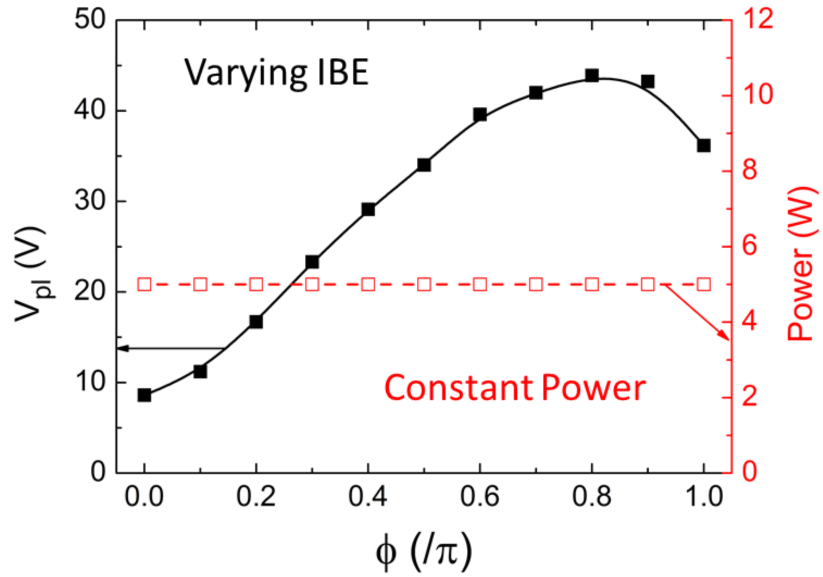

Figure 3

Sawtooth Waveforms

Referring to the section above, it can be shown that the waveform for a phase shift of pi/2 begins to approximate a "Sawtooth" waveform. The idealized version of such a waveform is shown in Figure 4, and this type of Tailored Voltage Waveform has unique properties when used to ignite a plasma.

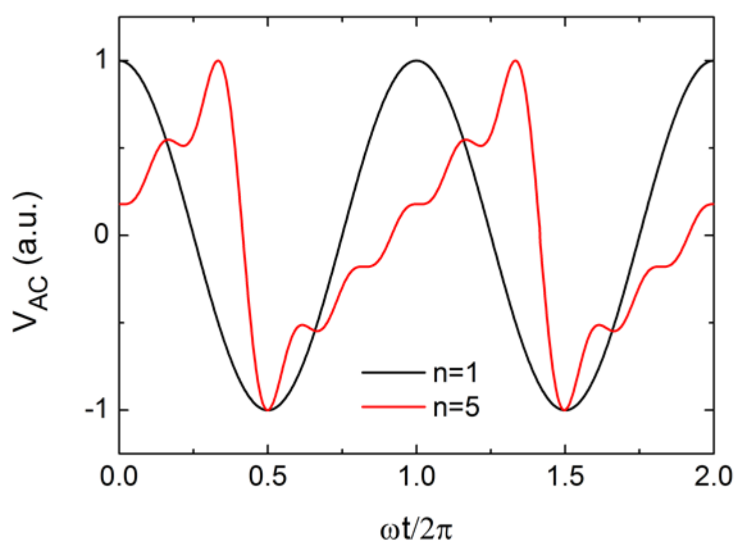

Figure 4 (adapted from Ref. [2])

Figure 5 below shows the Particle in Cell (PIC) simulation of a plasma excited by a Sawtooth waveform. One can see that the electron excitation process (ionization rate) in this case occurs almost exclusively on one side of the plasma.

The experimental confirmation of this phenomenon has been done collaboration with the plasma group of York University. Fast CCD images of the plasma were acquired, and the emission confirms that Sawtooth waveforms give outstanding control over the localization of excitation processes [1].

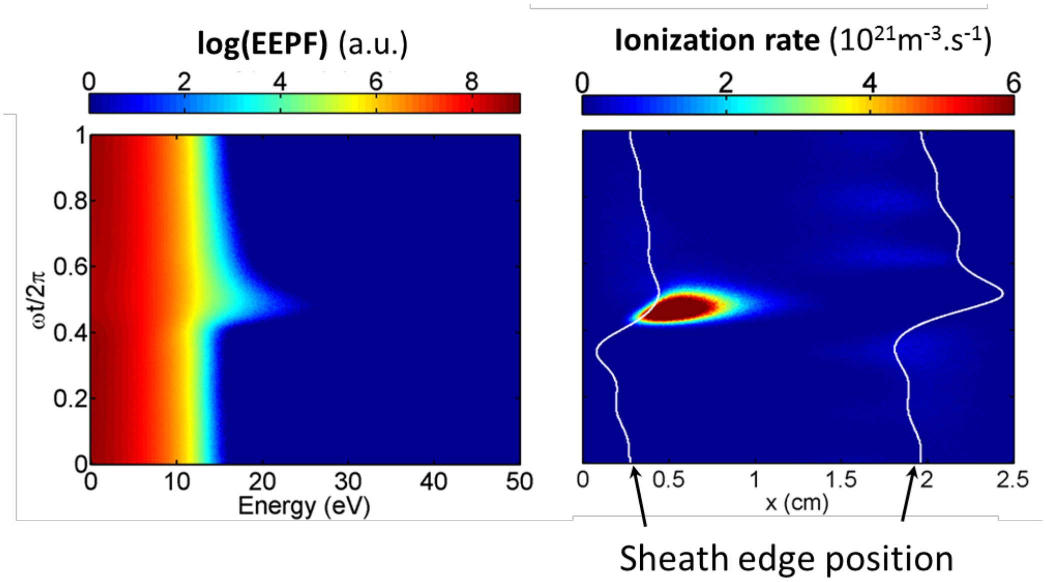

Figure 5 (adapted from Refs. [2] and [5])

Application to thin-film deposition and processing

The control over the maximum ion bombardment energy that Tailored Voltage Waveforms provide gives one a unique opportunity to study the role of ions in plasma processing. An example is provided below. In Figure 6, time-resolved ellipsometry spectra are shown, as acquired during the growth of silicon on a bare crystalline silicon surface under two different IBE conditions. In the case of low energy, a dense, smooth, epitaxial film is grown. However, by changing only the IBE, the growth transitions into a rougher, microcrystalline one. We have made the link between these phenomena and the underlying physical processes to provide an explanation for this sensitivity.

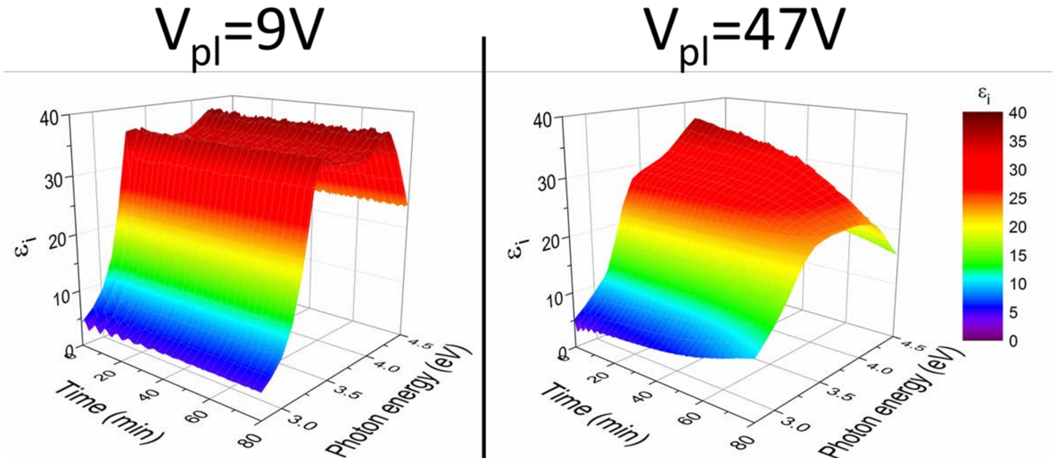

Figure 6 (from Ref.[3])

Further data from this study is depicted in Figure 7, wherein the proposal that the presence of ions above a certain energy threshold (around 30eV) discourages epitaxial growth and encourages re-nucleation (and therefore smaller less dense microcrystalline grains. This is observed through the breakdown of epitaxial growth above a certain maximum IBE.

This example shows the power of the Tailored Voltage Waveform technique in exploring physical phenomena. Many more activities are underway using this technique, with more results to be published soon.

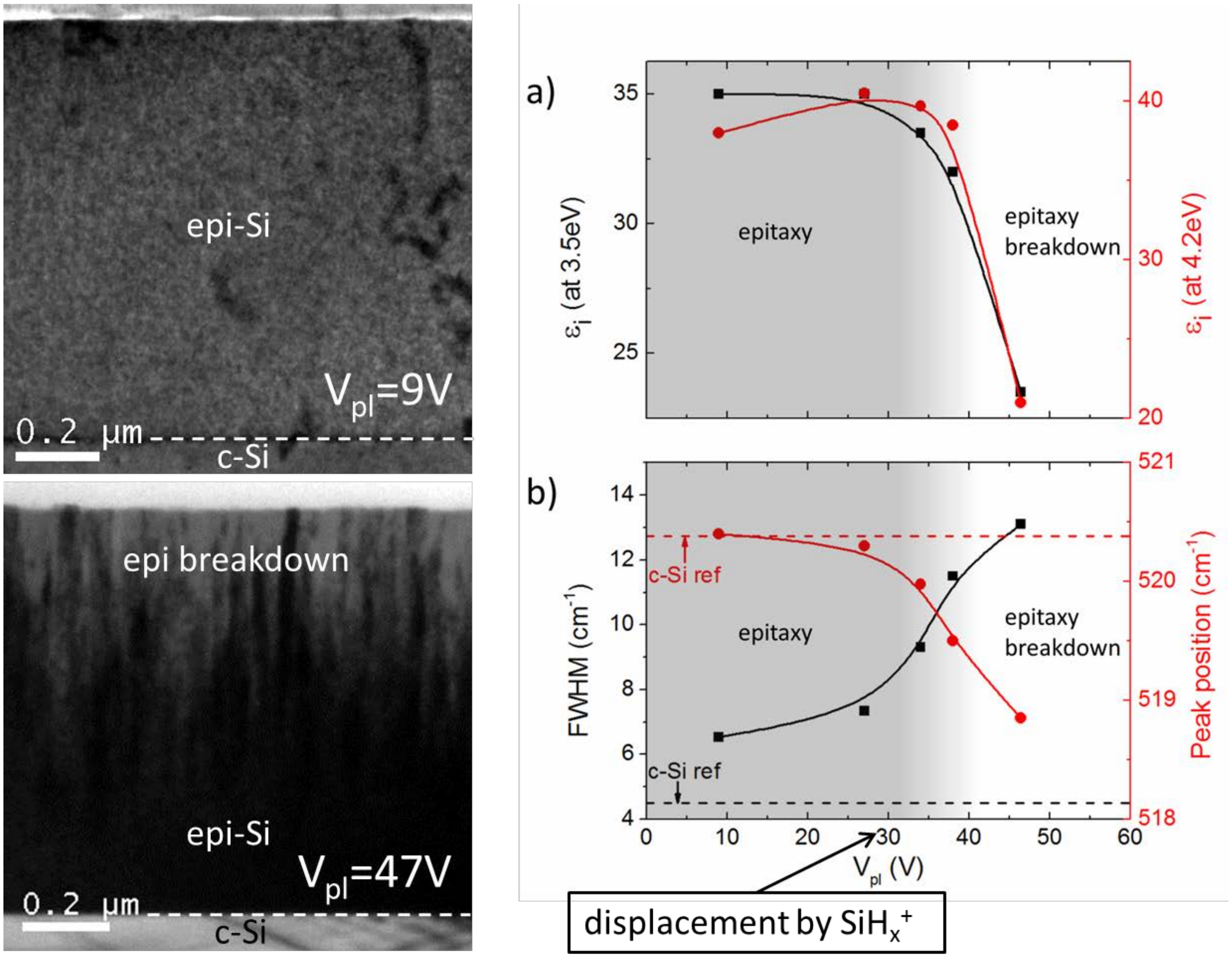

Figure 7 (from Ref. [3])

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