Tailored Waveforms for Ion Energy Control in ALE applications

S Mohr(*)[1], HS Song[1]

[1] Quantemol Ltd, 320 City Rd, London EC1V 2NZ, United Kingdom

(*) s.mohr@quantemol.com

Background and Motivation

Ion Energy Control in ALE and ALD

Precise ion energy control is crucial in plasma processes like ALE and ALD, where energy must be high enough to sputter modified surfaces but low enough to protect the original material—requiring narrow, ideally monoenergetic ion energy distribution functions (IEDFs).

Charging Effects

DC voltage can yields monoenergetic IEDFs, but also accumulate charges on the wafer surfaces. These charges shields electric field into the plasma.

Waveform

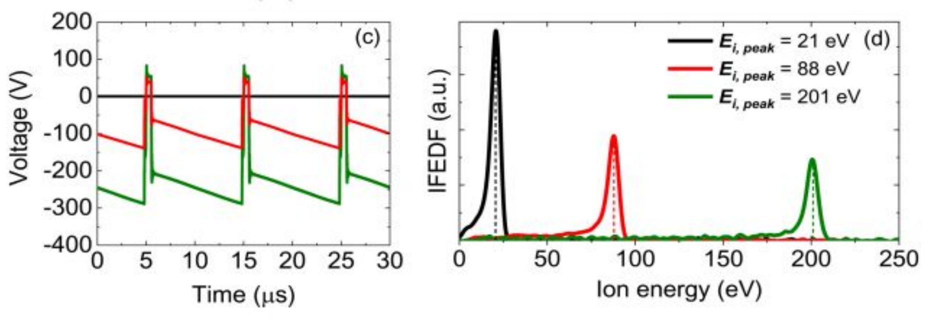
Sinusoidal waveforms prevent these charging effects, but typically produce bimodal IEDFs with two peaks. The position of these peaks also depends on the ion mass, so in multi-ion discharges, they produce two peaks per ion species. As a compromise, tailored waveforms have been proposed.

Tailored waveforms offer a compromise, enabling better energy control without surface charging.

Tailored Waveforms

Previous Work

Tailored waveforms have been proposed to realize both discharging of dielectric surfaces and (nearly) monoenergetic IEDFs. For example, Faraz et al. [1] have experimentally shown that the waveforms shown below produce nearly monoenergetic IEDFs while not charging up the wafer (and also not changing the ion flux). The waveform is close to a steplike waveform with a short positive phase (to attract electrons to the surface) and a long negative phase (to accelerate the ions). The major difference to an actual steplike waveform is the negative slope of the applied voltage in the negative phase; this is necessary to properly discharge the dielectric surfaces such as the processed wafer.

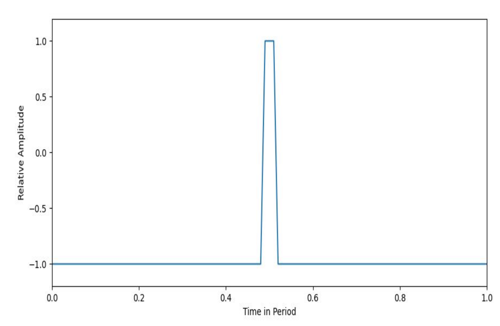


Applied tailored waveforms and measured IEDFs from [1].

Input Signal

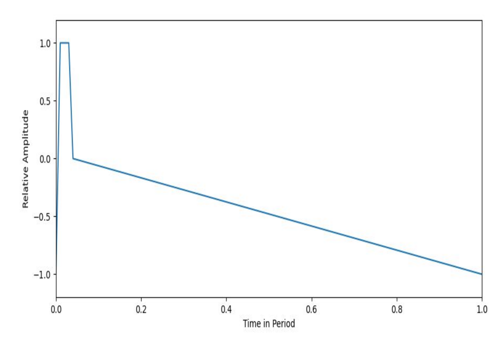
V_0 = 200V, Frequency = 0.1MHz

No Slope



The positioning of the steplike waveform within the time period exerts a minor influence on the mean ion energy; however, this effect is considered negligible.

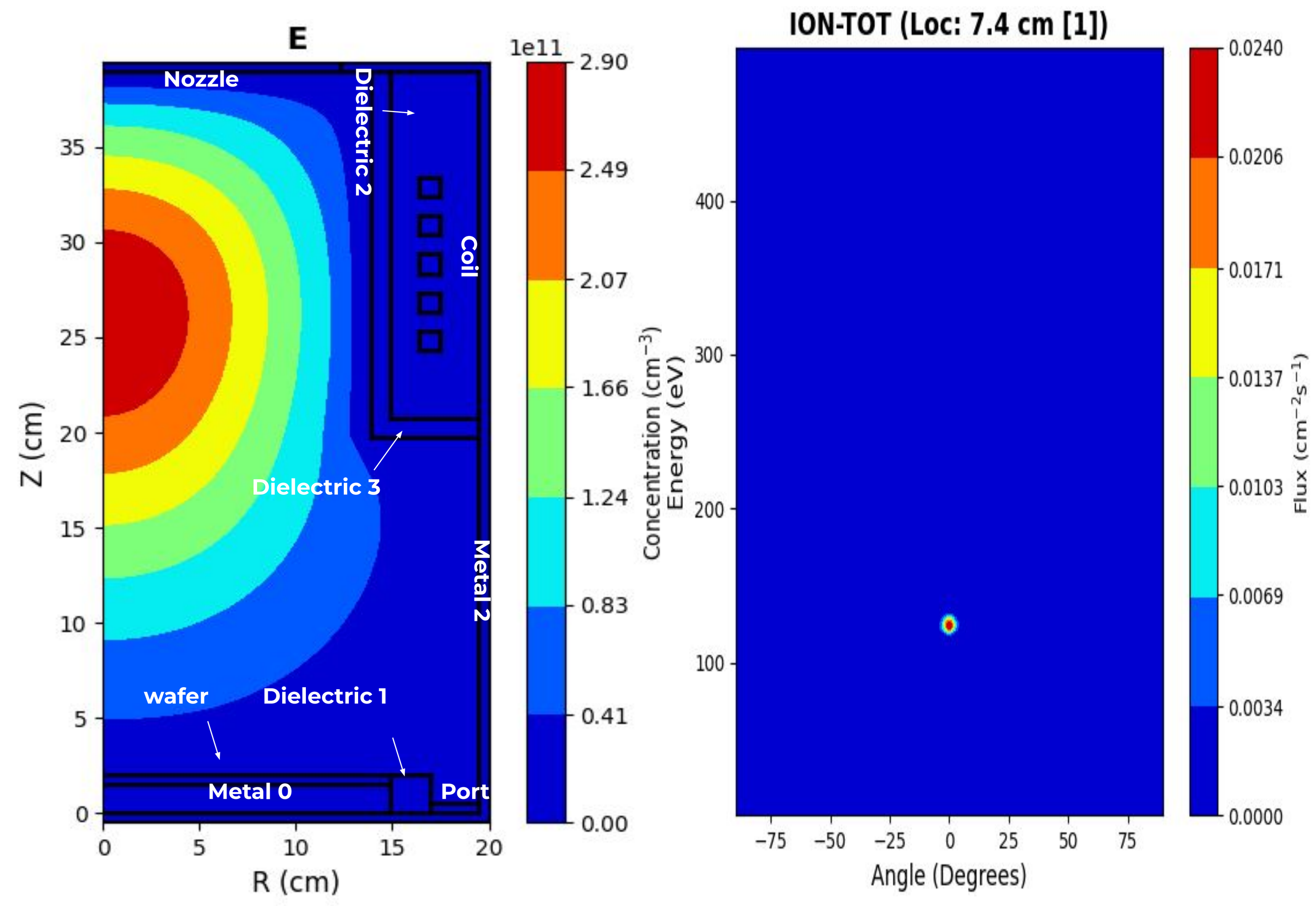
With Slope



The slope is calculated as the voltage variation from zero to its value at time 1, normalized by 1, with the time interval associated with the steplike waveform omitted from consideration.

Simulation Setup

Reactor Layout, Electron Density and Ion Surface Profiles



Chemistry Set

- $Ar^+ + Ar \rightarrow Ar + Ar^+$
- $e^- + Ar \rightarrow Ar^* + e^-$
- $e^- + Ar \rightarrow Ar^+ + 2e^-$
- $e^- + Ar^* \rightarrow Ar + e^-$
- $e^- + Ar^* \rightarrow Ar^+ + 2e^-$

Process Conditions

Pressure : 10 mTorr
ICP power: 300 W
Gas flow : 50 sccm

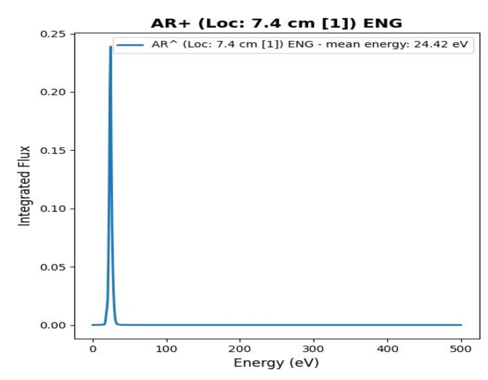
Material Table

Material	Dielectric Constant	Conductivity
Dielectric 1	3.8	1e-18
Dielectric 2	1	1e-10
Dielectric 3	3.6	1e-8
Wafer	3.9(SiO2), 11.7(Si)	1e-4 - 1e1

- Hybrid Plasma Equipment Model (HPEM) [2] was used for simulations.
- A wafer was added to the bare metal electrode.
- An idealized reactor was used for proof of concept.
- Inductive coupling generated plasma, with a tailored waveform applied.
- Argon gas was used with chemistry data from QuantemolDB (QDB) [3].

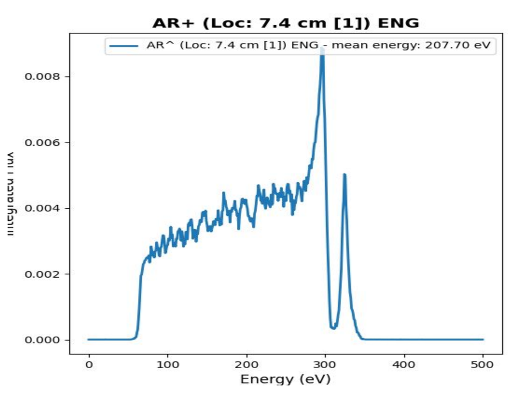
Simulation Results

conductivity < 10^{-7}



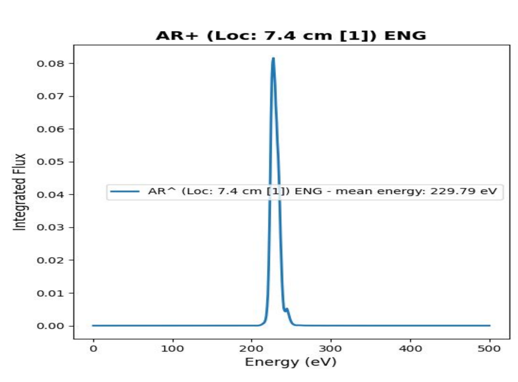
Mono energy distribution

10^{-7} < conductivity < 10^{-4}

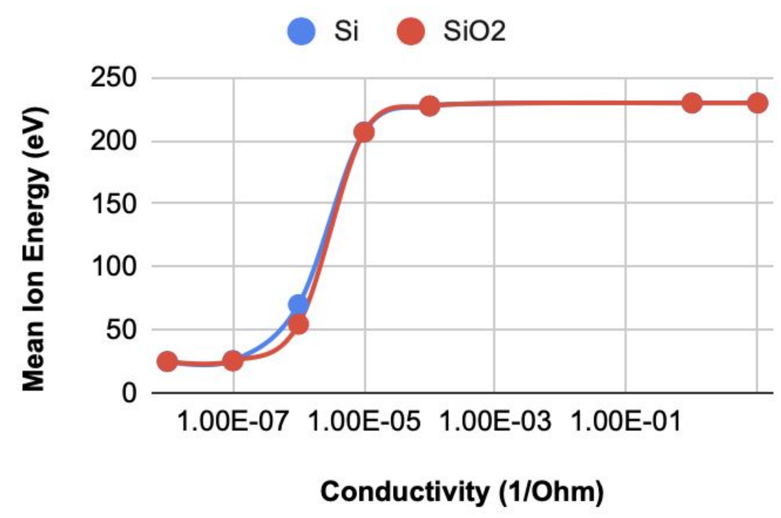


Broaden energy distribution

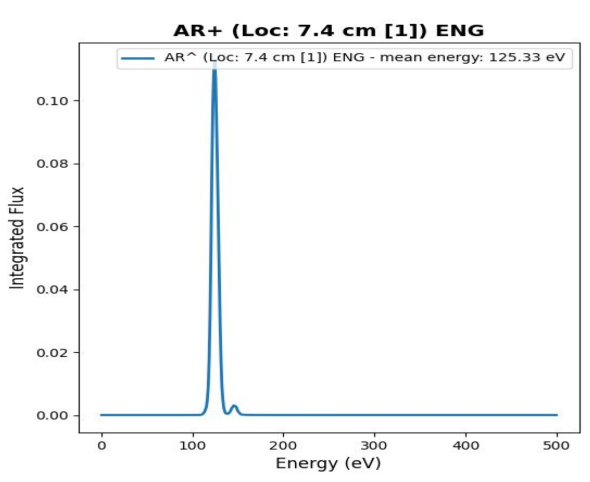
10^{-4} < conductivity

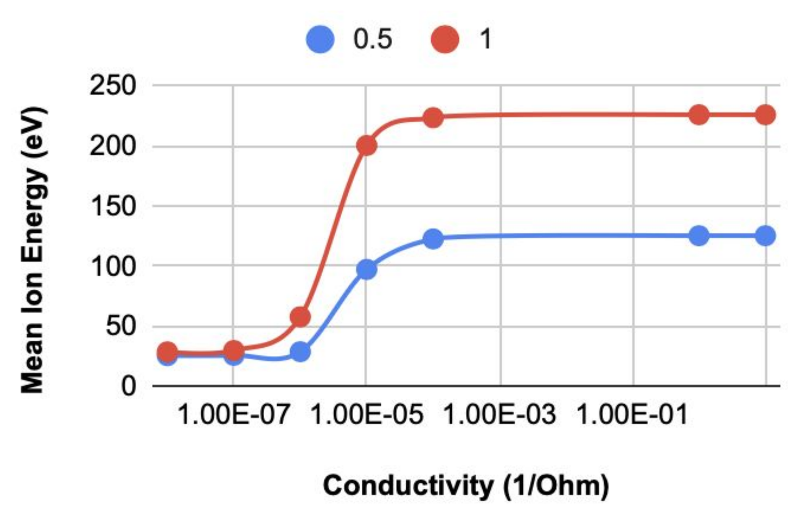


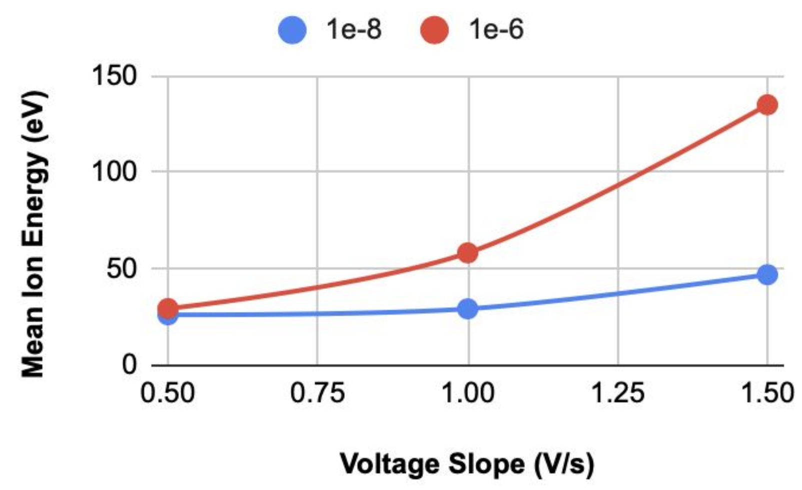
Saturated energy distribution



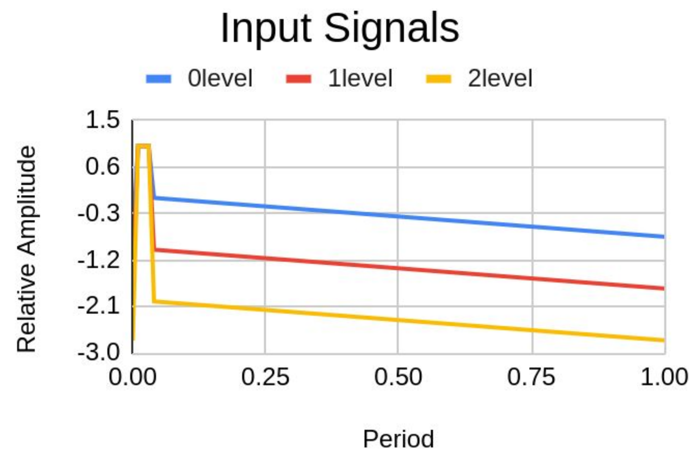
- Accumulated surface charges on the wafer impede current flow at low conductivity.
- This charge accumulation shields the electric field, resulting in limited ion acceleration and low-energy peaks.
- Increased conductivity induces current flow, partially discharging the surface and enhancing ion energies.
- At sufficient conductivity, surface charges dissipate, permitting full electric field penetration and ion energy saturation.
- Ion energy demonstrates a dependency on wafer conductivity, reaching a saturation point.





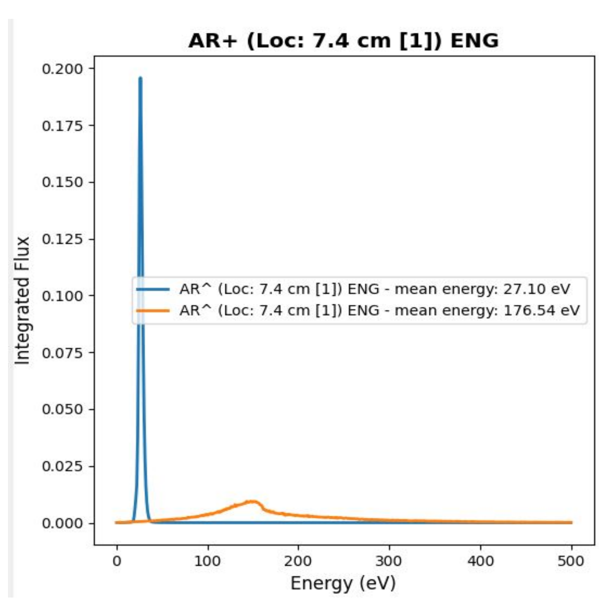


- Mean ion energy demonstrates a non-linear relationship with electric field slope when wafer charging occurs.
- Proportionality between mean ion energy and electric field slope is observed under conditions of fully penetrating conductivity.
- Full electric field penetration results in energy broadening of ions.
- Optimal control necessitates operating within low conductivity and refining voltage slope.

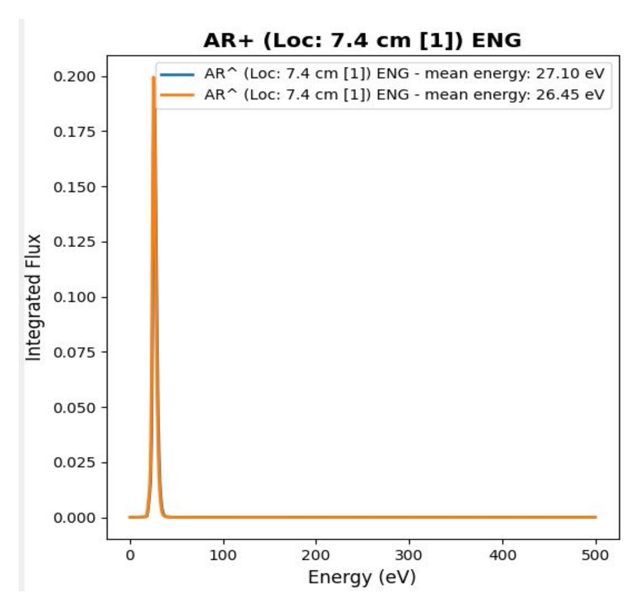


- To control ion energy conserving mono-energy distribution, 3 waveforms are applied.
- Voltages at the negative phase starting are 0V, -200V, -400V

0V vs -200V



0V vs -400V



Conclusions and Outlook

- Increasing wafer conductivity artificially, charging effects are removed and ion flux has mono-energy.
- The voltage slope in a tailored waveform negative phase discharges dielectric materials by releasing charging effects.
- Applying a DC voltage within the waveform may enable control of ion energy impacting the surface.

References

1. Faraz et al, J. Appl. Phys. **128**, 213301 (2020)
2. M. Kushner, J. Phys. D **42**, 194013 (2009)
3. www.quantemoldb.com