

A decorative background graphic consisting of a network of nodes and edges. Nodes are represented by circles of varying sizes and colors (light blue, dark blue, orange). Edges are thin lines connecting the nodes, some solid and some dashed. The network is spread across the entire slide, with a higher density of nodes in the top-left and bottom-left corners.

Tailored Waveform Biasing: Impact on Advanced Semiconductor Processing

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10th October 2025

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Executive Summary

Precise ion energy control is critical for modern semiconductor manufacturing processes like Atomic Layer Etching (ALE) and Atomic Layer Deposition (ALD). Traditional methods using DC voltage or sinusoidal waveforms present significant drawbacks: DC voltage causes charge build-up on wafers, while sinusoidal waveforms result in complicated, multi-peaked ion energy distributions. This white paper introduces tailored waveforms as a superior solution, capable of preventing charge accumulation and creating a nearly monoenergetic ion energy distribution function. By employing a specific voltage slope within the waveform, this technology provides a predictable and flexible way to control ion energy. This approach is not just an academic concept but a foundational development for the next generation of semiconductor devices.



Introduction

The relentless drive towards smaller, more powerful, and more efficient electronic devices places immense pressure on semiconductor manufacturing processes. Core to these challenges are plasma-based processes like Atomic Layer Etching (ALE) and Atomic Layer Deposition (ALD), where the precise control of ion energy is critical. Ions must possess sufficient energy to effectively modify target surfaces, yet their energy must remain low enough to avoid damaging the underlying materials (i.e., metal, silicon, or polymer film). This delicate balance requires ion energy distribution functions (IEDFs) that are narrow and, ideally, monoenergetic.

However, existing ion energy control methods present significant limitations that impede the advancement of these crucial processes. Traditional approaches often force a compromise between preventing wafer charging and achieving a uniform ion energy distribution, hindering the ability to meet the stringent requirements of next-generation device fabrication. This white paper will explore these inherent limitations and introduce Quantemol's work on tailored waveform biasing, an approach designed to overcome these challenges and unlock new levels of precision and efficiency in plasma processing.



Background

Historically, controlling the energy of ions impacting a wafer surface has been fraught with challenges, leading to compromises in process efficiency and material quality. The two primary conventional methods, while offering some advantages, introduce critical drawbacks:

- **Direct Current (DC) Voltage:** DC voltage is known for its ability to yield monoenergetic IEDFs, which are highly desirable for precise processing. However, its significant drawback is the accumulation of charges on the wafer surfaces. These accumulated charges create a shielding effect, preventing the electric field from fully penetrating the plasma. This impedance results in limited ion acceleration, ultimately restricting control over ion energy and leading to inconsistent process outcomes.
- **Sinusoidal Waveforms:** In contrast to DC voltage, sinusoidal waveforms effectively prevent surface charging due to their alternating nature. However, they typically produce bimodal IEDFs, meaning ions arrive at the wafer with two distinct energy peaks. Furthermore, the position of these peaks is dependent on the ion mass, which complicates multi-ion discharges by producing multiple peaks per ion species. This lack of a uniform energy distribution makes precise, atomic-level control extremely difficult and limits the application of these waveforms in advanced ALE/ALD processes.

These inherent limitations of traditional methods highlight a critical gap in semiconductor manufacturing. The industry requires a solution that can achieve the precise, monoenergetic ion control necessary for advanced processes without the detrimental effects of surface charging or broad energy distributions.

The Solution (from previous work [1])

Tailored waveforms emerge as a sophisticated and effective solution designed to overcome the limitations of traditional ion energy control methods. These custom-engineered energy pulses offer a unique compromise, enabling both the effective discharge of dielectric surfaces and the generation of nearly monoenergetic ion energy distribution functions (IEDFs).

The efficacy of tailored waveforms lies in their specific structural design:

- **Short Positive Phase:** The waveform initiates with a brief positive phase. This phase is crucial for attracting electrons to the wafer surface, effectively preventing the accumulation of charges that can shield the electric field and hinder ion acceleration.
- **Long Negative Phase:** Following the positive phase, a prolonged negative phase is applied. This extended period is designed to accelerate ions towards the wafer, providing the necessary kinetic energy for etching or deposition processes.
- **Critical Negative Voltage Slope:** The most distinctive and crucial feature of the tailored waveform is the inclusion of a negative slope in the applied voltage during the negative phase. This specific slope is essential for properly discharging dielectric surfaces, such as processed wafers. By actively managing and releasing charging effects, the electric field can fully penetrate the plasma, directly accelerating ions and ensuring they achieve a uniform, monoenergetic distribution.

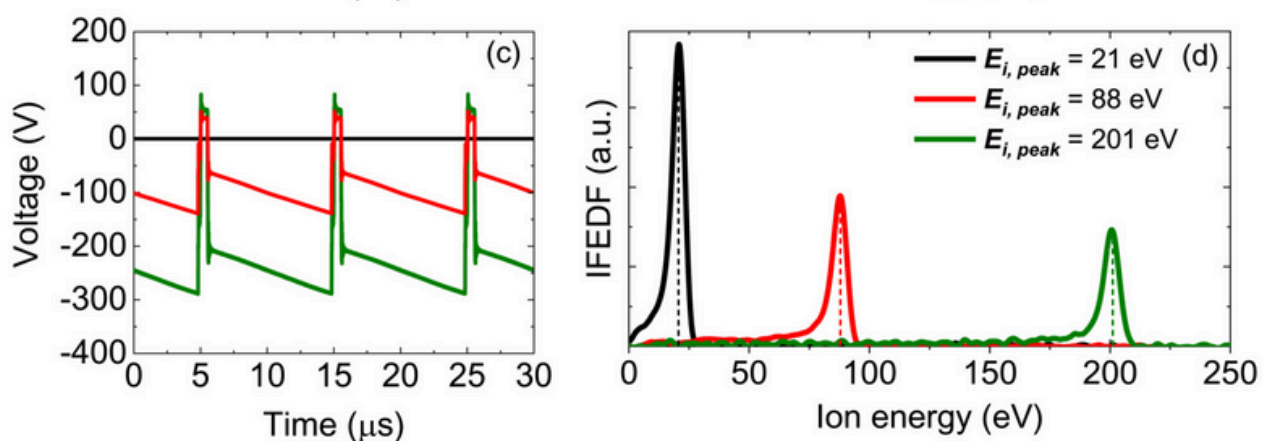


Figure 1. Applied Tailored Waveforms and measured IEDFs from [1].

Theory

Overview

Quantemol's research, led by scientists S. Mohr and H.S.Song, has provided compelling evidence supporting the efficacy of tailored waveforms for ion energy control in ALE applications. Their work builds upon previous experimental findings by Faraz et al. [1], which demonstrated that specific tailored waveforms could produce nearly monoenergetic IEDFs without charging the wafer.

Circuit Model of Tailored Waveform

Wendt and his colleagues used specifically designed radiofrequency (RF) voltage waveforms, applied through a blocking capacitor to an electrode, to manipulate a high-density plasma, which was generated using either an Inductively Coupled Plasma (ICP) or helicon source. A ramped voltage was used to compensate for the charge build up on a blocking capacitor, which was caused by a constant flow of positive ions to the electrode. The specific rate of this voltage ramp was chosen based on the ion current and the capacitance. This technique allowed the voltage across the sheath to remain at a constant negative level, interrupted only by brief positive excursions designed to attract electrons and prevent the build up of positive charge.

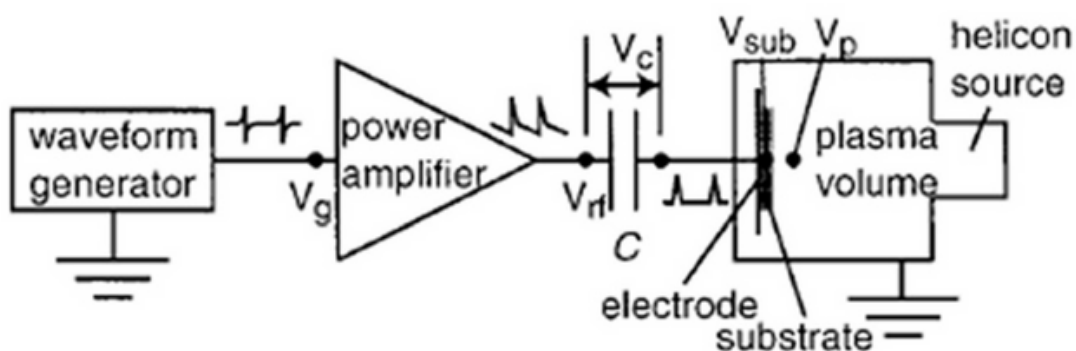


Figure 2. Circuit Diagram of ICP with a tailored waveform voltage source [2].

Key Findings

- **Bulk Plasma Position and Ion Energy Gain:** A substantial voltage slope exerts a strong pull on the bulk plasma, drawing it closer to the electrode surface. This attraction is a function of both the chamber's height and the magnitude of the voltage slope. As a result, the reduced sheath width leads to different IEDFs.
- **Chamber Geometry for Mono-Energy:** To prevent a broad or noisy ion energy distribution, the chamber must be engineered with distinct regions: a large volume for the quasi-neutral bulk plasma and a separate, well-defined ion acceleration path (the sheath). This allows for a controlled, narrow energy distribution as they are accelerated solely within the sheath region.

These findings validate the theoretical underpinnings of tailored waveforms and provide a robust foundation for their practical application in advanced semiconductor manufacturing, offering a verifiable pathway to enhanced process control and material quality.



Application in Quantemol's Software

With a voltage slope of $14 \text{ V}/\mu\text{s}$, the bulk plasma is situated away from the wafer surface. Conversely, an increased voltage slope of $20 \text{ V}/\mu\text{s}$ results in the compression of the bulk plasma towards the wafer surface. This dynamic shift leads to a significant transformation in the ion energy distribution function (IEDF), changing from a mono-energetic peak to a broad, noisy distribution.

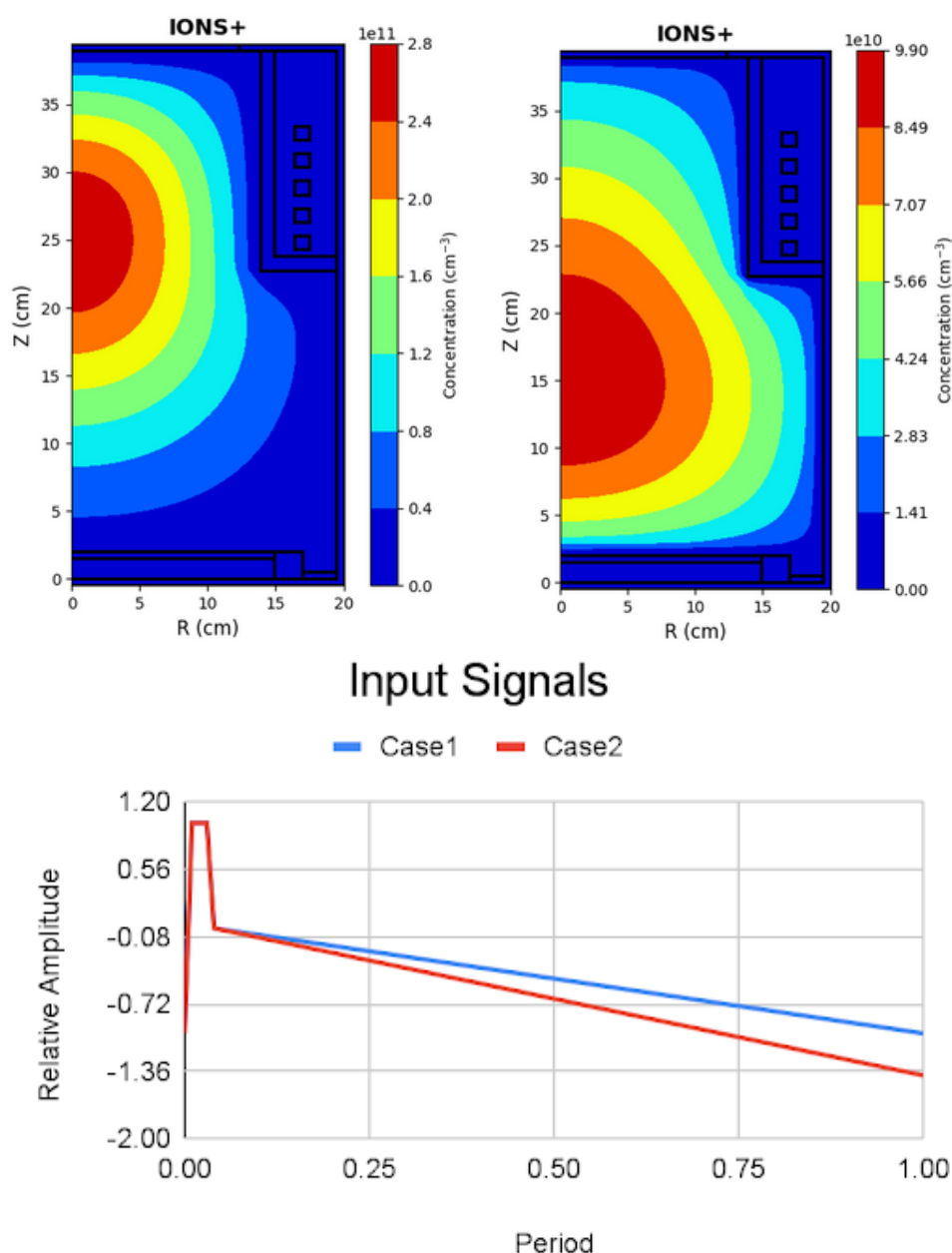


Figure 3. Ion density distribution at the 1.4 and 2 voltage slope.

Our findings demonstrate that a higher voltage ramp rate not only alters the spatial position of the bulk plasma but also fundamentally changes the ion bombardment characteristics.

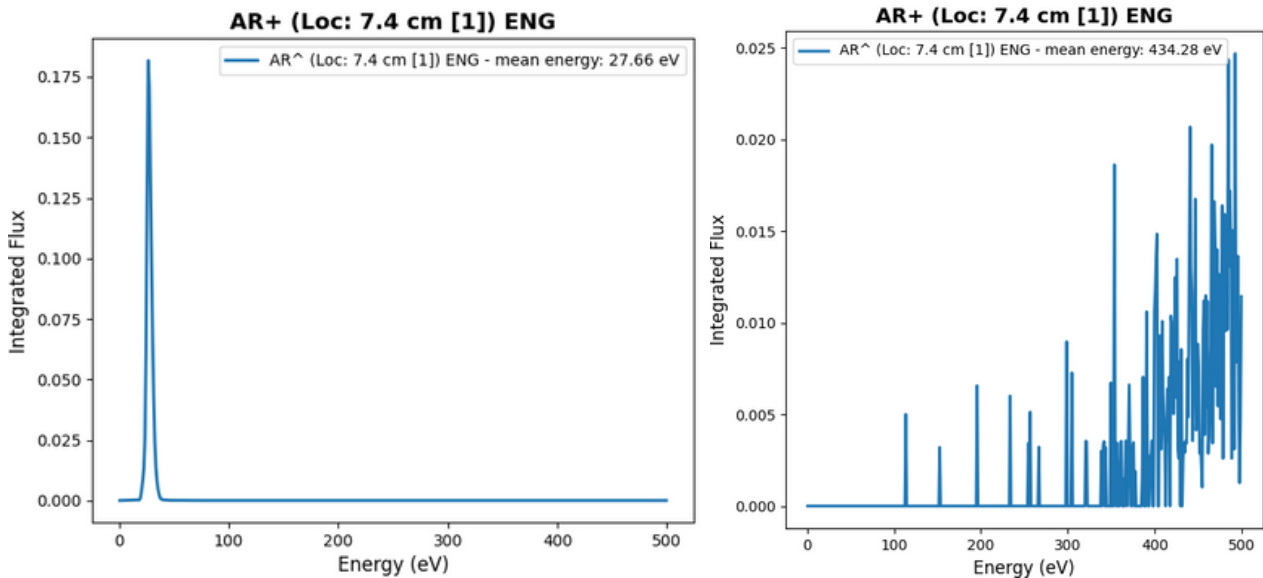


Figure 4. Ion energy distribution at the 14V/μs and 20V/μs voltage slope.

We investigated these phenomena using two distinct chamber geometries and two different voltage ramp rates. The first chamber, with a length of 40 cm and a radius of 20 cm, showed that the IEDFs remained insensitive to variations in the voltage slope (7 V/μs and 14 V/μs). Conversely, the second chamber, with a length of 60 cm and an identical radius of 20 cm, exhibited a pronounced dependence of the IEDFs on the voltage slope. The mean ion energy varied from 72.72 eV to 163.33 eV, directly correlating with the applied voltage ramp rate. This suggests that longer chambers are more susceptible to changes in the driving parameters, directly influencing the ion energy delivered to the substrate.

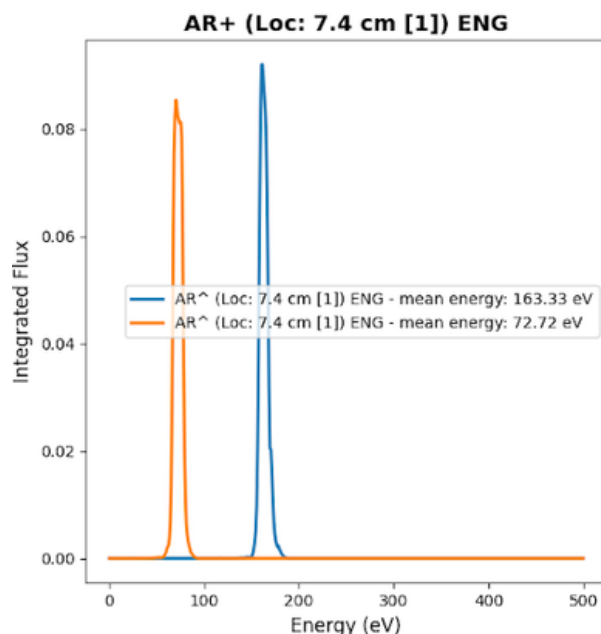


Figure 5. 40cm chamber and 60cm chamber with the voltage slopes, 7 V/μs and 14 V/μs each.

Conclusion

Achieving atomic-level precision in semiconductors has historically been impeded by the limitations of traditional ion energy control methods. DC voltage, while offering monoenergetic ions, creates problematic wafer charging, while sinusoidal waveforms, though preventing charging, yield undesirable bimodal ion energy distributions.

Tailored waveforms represent a significant leap forward, providing a sophisticated solution that addresses both challenges simultaneously. By strategically incorporating a short positive phase, a longer negative phase, and, critically, a negative voltage slope, these waveforms effectively discharge dielectric surfaces and ensure a nearly monoenergetic ion flux



Company

Quantemol specialises in developing advanced computational tools for plasma simulation, building on decades of expertise in fundamental plasma physics. This expertise uniquely positions the company to address the challenges of modern semiconductor manufacturing. Our integrated software suite - including **Quantemol-EC** for electron-molecule scattering, **Quantemol-VT** for industrial tool simulation, and the **Quantemol-DB** (database) - provides the foundational data and modelling capability required for innovation. This enables us to model, predict, and optimise advanced techniques, such as tailored waveform biasing, which is crucial for precise control over ion energy and flux in next-generation processes, including atomic layer etching.

Using Quantemol's software, you can:

- **Unleash First-Principles Precision:** Our flagship software, Quantemol-VT, delivers simulated results rooted in fundamental physics. By leveraging conservative fluid equations for continuity, momentum, and energy balance, we provide a reliable, accurate window into plasma behaviour. While this article focuses on argon, our extensive Quantemol-DB gas reaction database opens the door to countless gas configurations, allowing you to explore new chemistries with confidence.
- **Validate Your Idea:** Academic papers offer brilliant ideas, but translating them into industrial-scale products is a different challenge. Quantemol-VT bridges this gap, providing powerful functions to validate your concepts before you ever build a prototype. In this white paper, we've validated the ground breaking tailored waveform, giving you critical insights into chamber parameters to ensure your ideas work in the real world.
- **Gain Practical, Actionable Insights:** Theoretical models often falter because they rely on broad assumptions that don't hold up in real-world scenarios. Quantemol-VT cuts through the noise, providing practical insights that directly apply to your designs. Our software's ability to model axisymmetry gets you closer to real-world conditions, while integrated modules like the Boltzmann solver and Monte Carlo kinetics boost the accuracy of transport coefficients, giving you a unique understanding of your system. This isn't just theory, it's a digital blueprint for success.

References

To learn how tailored waveform solutions can optimise your specific ALE/ALD applications and deliver superior performance, please contact Quantemol at info@quantemol.com for a detailed consultation. You can also request a free product trial through our [website](#).

References:

1. Faraz et al. J. Appl. Phys. 128, 213301 (2020).
2. Wang and Wendt, J. Appl. Phys. 88, 644 (2000).

Author Contributions:

Sebastian Mohr and Hyungseon Song performed the core research, conceptualised the experimental/simulation design, executed the analysis, and reviewed the final manuscript.

Annie Laver drafted and finalised the original manuscript and edited the content for clarity. Hyungseon Song provided substantial input to the drafting of the Theory, Key Findings, Application in Quantemol's Software, and Conclusion sections.



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