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Plasma sources for advanced semiconductor applications

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Special Collection: Plasma Sources for Advanced Semiconductor Applications

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I. INTRODUCTION

Semiconductors are the foundation of modern technology, used in our personal, industrial, and military-grade devices. Every aspect of U.S. society is closely tied to semiconductors, and our economy cannot progress at the current pace with existing chip manufacturing methods as chip features approach an atomistic scale.

While recent legislative efforts, such as the Chips and Science Act[1] and the European Chips Act,[2] have sought to address some of these challenges by providing funding for manufacturing plants, it is clear that we must continue to invest heavily in semiconductor research to develop the highly advanced chips necessary to maximize the potential of these plants. This underscores the promise of basic research science: It brings about advances that cannot be predicted based on existing methods, paving the way for transformative breakthroughs that propel society forward. By investing in cutting-edge plasma research, we can develop scientific foundations for future plasma reactors and processing systems, ensuring continued market competitiveness and economic prosperity. It is equally imperative that the results of such research be shared openly so that it can benefit from expert scrutiny, active discussion, and refinement. Publicly available research is also necessary to train a new workforce for the highly competitive new world of modern microelectronics.

A special issue on plasma sources for advanced semiconductors responds to this mission, given that plasma sources are essential tools for manufacturing semiconductors. Laser-produced plasma (LPP) powers state-of-the-art nanolithography by generating the required extreme ultraviolet (EUV) light. Reducing the size of features in modern semiconductors is a major theme for semiconductor manufacturing where feature sizes are approaching nanometers, often as a part of complex, three-dimensional (3D) structures. Predicting, modeling, and measuring the properties of plasma from advanced sources with high resolution is at the forefront of research for many advanced industrial applications.

This Joint Special Topic Collection in *Applied Physics Letters* and *Physics of Plasmas* covers all of these areas, welcoming submissions reporting recent research results and perspectives in the field of plasma sources and their many important applications to semiconductor and relevant computational technologies developed to model these plasma sources. This collection includes 24 articles published in *Applied Physics Letters*[3] and 13 articles in *Physics of Plasmas*.[4] The combined 37 papers cover topics related to Plasma Sources for Advanced Semiconductor Applications, including modeling and experimental studies related to the generation of EUV light (and beyond) via LPP. It also includes papers devoted to experimental and modeling studies of plasma sources for plasma processing, and plasma etching and deposition.

II. SUMMARY OF TOPICS COVERED

The submission to the special collections may be effectively categorized into two separate, but connected, research areas. In the following, an introduction to each research area will be presented followed by a summary of the contributions to the current special topic collection.

A. Research area A: Enabling future EUV sources to operate at ever higher power, reliability, and sustainability

In the semiconductor industries, current state-of-the-art nanolithography involves EUV light at just 13.5 nm wavelength. This short-wavelength light enables the imprinting of the smallest semiconductor features on chips given the well-known relation between limiting resolution (R), wavelength (λ), and the imaging numerical aperture (NA), as $R = \lambda/2NA$. Micrometer-sized droplets of molten tin are irradiated by high-energy CO_2-gas laser pulses at 10-μm wavelength some 50 000 times per second, generating plasma and with it the required EUV light. The plasma is produced in a two-step process. First, a low-energy pre-pulse generates a plasma, deforming the spherical tin droplet into a flat disk. Second, a high-energy main pulse creates a dense, rapidly expanding plasma containing the highly charged tin ions that emit EUV light. This EUV light is reflected out of the source vessel by a narrow-band multilayer collector mirror through a buffer gas environment. Producing the required in-band (13.5 nm $\pm$ 1%) EUV light has been a daunting and multi-faceted scientific and industrial challenge.

To enable EUV sources to operate at ever higher power, reliability, and sustainability, four objectives must be met, and the following key scientific questions must be answered:

1. Understand and control laser-tin interaction for the EUV source target formation

Key question: *What physical processes determine morphology and the state-of-matter of the tin "target" material, including its hydrodynamic deformation, fragmentation, and vaporization?*

EUV lithography is powered by EUV light that is currently produced by the interaction of high-energy CO_2-gas laser pulses with microdroplet tin targets to generate EUV light emitting, laser produced plasma. In the current collection of articles, Engels *et al.*[5] explored novel metrologies of tin target preparation schemes via high-resolution spectroscopic absorption imaging of atoms and nanoparticles, as produced from laser vaporization of very thin tin films prepared by a prior laser pre-pulse. Gonzalez and Sheil[6] study the role of the available tin target mass on the conversion efficiency (CE) of converting CO_2 laser light into useful in-band EUV photons in RALEF-2D radiation-hydrodynamics simulations.

2. Identify and extend the efficiency limits of converting laser light into useful EUV light

Key questions: *What sets the fundamental limit of converting laser light into useful EUV photons? How can this limit best be achieved? What is the actual origin of the emitted EUV light?*

Alternative "drive" laser systems are under active investigation, with the envisaged introduction of efficient, high-power solid-state laser systems operating near 2-μm wavelength. Experiments on the production of 13.5-nm light with particularly high conversion efficiency from 2-μm-laser-driven plasma are presented by Mostafa *et al.*[7] in a two-step scheme where the 2-μm laser light, generated from a home-built master-oscillator power amplifier, interacts with a 1-μm pre-pulse prepared thin film target. Independent simulations by Shi *et al.*[8] identify pathways for even higher efficiencies using further laser pre-pulses. A joint measurement of electron density, temperature, and emission spectrum of 1-μm (Nd:YAG) laser-produced tin plasma by Pan *et al.*[9] using collective Thomson scattering demonstrates the significance of such measurements for the validation validating atomic process models in radiation-hydrodynamics simulations, and the importance of considering self-absorption effects that are critical for future high-density, solid laser-driven EUV sources. The prominent contribution of multiple excited states in highly charged tin ions produced in the plasma to the overall EUV emission is further emphasized by calculations performed by Sasaki;[10] such contributions need to be taken into account in realistic atomic models.

Alternatives to the current scheme of producing EUV light are also considered. Mazuz-Harpaz *et al.*[11] reported on the enhancement of EUV emission by double-sided laser illumination in a novel plasma-generation geometry. Laser-assisted discharge plasma is an alternative way to produce EUV light, and Sato *et al.*[12] investigated the influence of laser intensity on both EUV emission brightness and the ion debris speeds from such plasma. Reismann *et al.*[13] described the development of an EUV light source using a discharge-produced plasma using xenon plasma in a Z-pinch configuration employing an innovative switching system to overcome prior limitations. Such EUV light sources find application in the semiconductor industry for metrology, mask inspection, and resist development.

3. Understand and control the expansion of laser produced plasma and develop mitigation strategies against plasma damage to nearby light collection optics

Key questions: *What physics determines the plasma ion energy distribution and how can it be controlled? What impact does the plasma expansion have on its surroundings, and how can it be mitigated?*

Laser-produced tin plasmas are highly energetic, and in addition to the required EUV emission, these plasmas produce fast ($\sim$keV) ions that may negatively impact the lifetime of nearby light collection optics if not suitably mitigated. Totorica *et al.*[14] identified the key acceleration mechanisms of such energetic ion debris using particle-in-cell (PIC) modeling: the dominant acceleration mechanism is found to be a large-scale electric field supported mainly by the electron pressure gradient. Poirier *et al.*[15] experimentally studied the dependence of (highly anisotropic) ion charge-energy emission from tin-droplet LPP on the applied laser intensity, finding a match with power-law scaling derived from plasma radiation hydrodynamics theory, indirectly supporting the findings of Totorica *et al.*[14] pertaining to the importance of the electron pressure gradient. Existing ion debris mitigation solutions include the use of stopping gas, electric fields, and magnetic fields. A novel mitigation scheme using magnetic nulls was introduced by Israeli *et al.*,[16] which prevents a fraction of the ions from reaching nearby optics while avoiding issues of ion trapping. Effective cleaning of tin contamination on the EUV-light collecting mirrors using hydrogen radicals from hydrogen plasma improves throughput and cost performance in industrial applications. Hernandez *et al.*[17] experimentally demonstrated the efficient production of hydrogen radicals using vacuum ultraviolet light emitted from laser-produced high-Z plasma. Tanaka *et al.*[18] clarified the value of the plasma density and cleaning ability of EUV-produced hydrogen radicals through a laser-induced fluorescence technique.

4. Develop source concepts to produce beyond extreme ultraviolet (BEUV) light for producing superior semiconductor features

Key question: *How can laser produced plasma be used to produce light for next-generation nanolithography, and what are the limitations*?

Beyond the above-mentioned questions related to the current and alternative methods of producing EUV light at 13.5 nm, the industry is advancing toward even smaller semiconductor features. Historically, every major reduction in wavelength is followed by improvements in the numerical aperture until a new, shorter wavelength is introduced. It is thus justified to consider lithography powered by wavelengths shorter than 13.5 nm, beyond EUV (BEUV, or blue-X). Such BEUV wavelengths may be efficiently generated from laser produced plasma, and to enable powerful BEUV light sources, the same three key scientific questions would need to be answered for such systems.

Here, the works of Kume *et al.*[19] and Niinuma *et al.*[20] augment existing works on gadolinium plasma (producing light at 6.76 nm), detailing approaches for controlling, and achieving, high spectral purity of the radiative emission as well as the emission of energetic plasma ions. Even shorter wavelengths can be produced from laser produced plasmas and may also find application in water-window microscopy, as highlighted in the work of Mongey *et al.*[21] who produced small, micrometer-scale emission volumes in a 1.2- to 2.5-nm wavelength band, and compared the results to simulations.

B. Research area B: Advancing plasma sources to enable superior chip plasma processing

To advance plasma sources and enable superior chip processing, the scientific community needs to further advance fundamental low-temperature plasma research computationally and experimentally while providing solutions in a timely manner. Several priority research opportunities need to be addressed.

1. Enhance fundamental understanding of low-pressure plasma reactors for fast industrial cycle

Key question: *How can fundamental low-pressure plasma research advance computationally and experimentally while providing solutions in a timely manner?*

Many traditional plasma processing applications, such as plasma etching and deposition in capacitively-coupled plasmas, are performed at very low pressures (<5 mTorr) where kinetic phenomena are dominant. Fluid models developed for higher-pressure applications do not adequately capture the physics in these regimes. Kinetic models (particle-in-cell, Boltzmann equation solvers) are being developed but can be too computationally intensive for computer-aided design applications given the very fast commercial cycle. Fundamental research is needed to comprehensively understand the discharge physics in this low-pressure regime and to perform detailed experimental studies supplemented by rigorous theoretical models and advanced computational methodologies that can allow for fast modeling of these complex systems. Supercomputing hybrid central processing unit (CPU) and graphics processing unit (GPU) infrastructure for kinetic models (e.g., particle-in-cell codes) should be used to speed up simulations so they meet industry needs.

Large scale (PIC) modeling.–Achieving large-scale kinetic modeling is crucial for developing and optimizing modern plasma devices, as detailed in the paper by Sun *et al.*[22] In that work, the applicability of the direct implicit and explicit energy-conserving PIC methods to achieve much faster simulation times as compared with the standard momentum conserving method without loss of precision were studied. Powis and Kaganovich[23] report on the accuracy of the explicit energy-conserving PIC method for simulations of capacitively coupled plasma discharges where the Debye radius does not need to be resolved in the plasma center. Jubin *et al.*[24] studied the impact of numerical thermalization in several low-temperature plasma applications, including capacitively coupled plasma discharges, inductively coupled plasma discharges, beam plasmas, and hollow cathode discharges. They discuss possible strategies for mitigating numerical relaxation effects in two-dimensional (2D) PIC simulations.

*Capacitively coupled discharge sources.—*Voltage waveforms were investigated by Krüger *at al.*,[25] where the authors discuss the use of non-sinusoidal waveforms in low-pressure capacitively coupled plasmas intended for microelectronics fabrication to customize ion and electron energy and angular distributions to the wafer. The computational investigation was conducted by studying the relation between ion energy and direct current (DC) self-bias when varying the fundamental frequency f_0 for capacitively coupled plasmas sustained in Ar/CF_4/O_2 and how those trends translate to a high aspect ratio etching of trenches in SiO_2.

Tian *et al.*[26] combined experiments and PIC simulations to study the dual-frequency capacitively coupled plasma (CCP) and the effect of plasma uniformity on the ion angular and energy distribution function (IAEDF), especially near the outer edge of the electrodes, which is a crucial issue for the latest etching processes in 3D NAND and fin field effect transistor manufacturing.

The effect of driving frequency in the range of 13.56–73 MHz on electron energy distribution and electron heating modes in a 50 mTorr capacitively coupled argon plasma discharge was studied using 1D-3V particle-in-cell simulations by Simha *et al.*[27]

Wen *et al.*[28] explored the transition behavior of the formation of field reversal as a function of driving voltage amplitude and showed that the energy distribution function of electrons incident on the electrode exhibit peaks from around 3 to 10 eV, showing potentially beneficial effects in plasma material processing where relatively directional electrons are preferred.

The low-frequency dependence of the plasma density and IAEDF in a low-pressure (2 Pa), dual-frequency (DF) capacitively coupled argon plasma was studied by a combination of experiments and kinetic particle simulations by Zhou *et al.*[29] The observed enhanced ion flux and ion energy in DF discharges operated at low frequencies in the range of hundreds of kHz are beneficial for the high-aspect-ratio plasma etching extensively used in the semiconductor industry.

Breakdown.—Unintended gas breakdown in the narrow gaps of plasma processing chambers is one of the critical challenges in developing advanced plasma sources. Son *et al.*[30] presented a combined experimental and theoretical study of unintended discharges in the narrow gaps of plasma processing chambers and reported a significant drop of the gas breakdown voltage in the presence of a background plasma facing the gap. Hysteresis between gas breakdown and plasma discharge was modeled in Yamashita *et al.*[31]

Inductively coupled discharge sources.—The coupling effects between the RF bias and the inductive power in the RF-biased inductively coupled plasma with synchronous control were investigated by He *et al.*[32] by measuring electron energy distribution function using a compensated Langmuir probe. The effect of the bias power on the E and H mode transition was studied.

An example of complex hysteresis of plasma density in the spatial afterglow of inductively coupled plasmas (ICPs) was studied by Zhang *et al.*[33] A two-dimensional fluid/electron Monte Carlo hybrid model was employed to simulate nitrogen inductively coupled plasmas, and the spatial distributions of electron energy probability distributions (EEPFs) by Huang *et al.*[34] It is found that the EEPF exhibits a bi-Maxwellian distribution at 3 mTorr, but as pressure increases, the high energy tail declines due to the more frequent collisions. Moreover, a hole appears at around 3 eV in the EEPF due to the vibrational resonant excitations. Pulse modulation in inductively coupled plasmas (ICPs) has been often used to control the charging effect in etching trenches and the plasma uniformity. Lu *et al.*[35] utilized a two-dimensional fluid model to study the modulation of the radial uniformity in pulsed dual-antenna ICPs.

2. Develop diagnostics and modeling capabilities for moderate-pressure plasmas

Key question: *How should diagnostics and modeling capabilities be developed to address moderate-pressure plasma phenomena?*

Processing plasmas are regularly used in the moderate pressure range (1–30 Torr).[36] These plasmas exhibit phenomena that can be quite different from low-pressure (<200 mTorr) or atmosphere-pressure plasmas, which are much better studied. Striations, plasmoids, rotating structures, and spatial constrictions are commonly observed. However, there is a dearth of plasma diagnostics work in this moderate-pressure regime. The development of better plasma diagnostics techniques suitable for collisional plasma physics studies in the 1–30 Torr range is needed. Similarly, adequate 3D modeling tools that can capture this complexity are still lacking.

Srinivasan *et al.*[37] studied a radio frequency sputtering plasma reactor used for GaN deposition and applied nanosecond-two-photon absorption laser-induced fluorescence (TALIF) to determine the absolute density of N-atoms as a function of the pressure (tens of Pa range). These measurements, together with electron density measurements performed in the same pressure range using microwave interferometry, provide quantitative data on both electron and N-atom densities that can be used for fundamental understanding, process optimization, and modeling of magnetron discharge intended for nitride semiconductor deposition.

An example of using a laser-induced fluorescence diagnostic to study complex plasma phenomena is given by paper by Chopra *et al.*[38] They performed measurements of atom and ion velocity distribution functions in an e-beam $E \times B$ plasma at sub-mTorr argon pressures using a laser-induced fluorescence diagnostic and revealed the presence of a warm population of ions with temperatures of $\sim$1 eV that are sufficient to drive the ion flux by cross field diffusion in the direction opposite to the applied electric field, toward the plasma-bounded walls or substrate. Similar laser-induced fluorescence (LIF) measurements can be performed for moderate-pressure plasmas.

Brooks and Paliwoda[39] studied a plasma impedance probe (PIP) with efforts to streamline and simplify its design. A PIP is a radio frequency probe that is traditionally used to measure plasma properties (e.g., density) in low-density environments such as the Earth's ionosphere but can be used in laboratory settings if optimized for signal-to-noise ratio (SNR).

As the semiconductor manufacturing process becomes more complicated, measurement of the actual ion energies at the bottom surface of high aspect ratio (HAR) structures being etch become increasingly important. Lee *et al.*[40] developed a measurement method using a capillary plate with a high-aspect-ratio that was proposed to measure ion energy distribution during etching.

3. Develop capability to generate fundamental data for semiconductor industry relevant plasma simulation

Key question: *How should the dearth of fundamental data for species interactions, transport and surface processes in semiconductor industry relevant plasma simulation be addressed?*

Modeling and simulation play a major role in the development of plasma sources and processes that rely on plasma science and fundamental data. For plasma processing equipment design, the fidelity of plasma models critically depends on the fundamental data regarding species interactions (e.g., cross sections for electron–neutral collisions, ion-neutral collisions, and multibody collisions), transport (e.g., ion mobility), and surface processes (e.g., secondary electron emission). Plasma models have greatly benefited from past research, both experimental and theoretical, on atomic and molecular physics pertinent to plasmas.[41] However, there is little research being conducted on fundamental collision processes in plasmas, the development of improved measurement techniques, and advancement in relevant computational methods. Fundamental data are especially lacking for more complex molecules that have been used recently in industry-relevant development. Quantum chemistry-based computational models for examining the rates of atomic and molecular chemical interactions in plasmas need to be more widely used to produce such data with sufficient accuracy and validated by precise experimental measurements. The cross sections calculated by quantum-mechanical scattering-theory codes need to be also validated using past and specially measured experimental data. Similarly, secondary electrons emitted from the substrate's surface due to the bombardment of ions, electrons, photons, and fast neutrals (see, for example, Derzsi *et al.*[42]) as well as reactions on the surfaces, can strongly affect plasma behavior in low-temperature plasmas. These processes depend on the material and condition of surfaces. Experimental data and theoretical models for the secondary electron emission and surface reactions are needed to improve the accuracy of plasma models for the plasma processing system.

Kropotkin *et al.*[43] developed a set of electronic and chemical reactions for a plasma discharge in octafluoropropane (C_3F_8), which is used in etching and cleaning processes. The resulting complete set of reactions was tested against published experimental data on the concentration of electrons, negative ions, and electronegativity in a capacitive plasma discharge at different gas pressures and discharge input powers.

4. Improve fundamental understanding of complex plasma phenomena for novel plasma source design

Key question: *How can computational modeling and diagnostics capabilities be improved for novel plasma source design for advanced microelectronics?*

In order to process novel materials and devices for advanced microelectronics, novel plasma sources should be developed and investigated. This might include exploiting electron beams, magnetized plasma, microwave power, or laser produced plasmas, among others. Plasma-generated photons should be further exploited, both for plasma processing and lithography, building on plasma-based EUV lithography and other laser plasma developments. A fundamental understanding of plasma phenomena (e.g., electron beam plasma interactions, resonance microwave power absorption, anomalous transport in magnetic field, and striations) using computational modeling and diagnostics is needed for novel plasma source design.

Flat-cutoff sensors.—Various plasma diagnostic sensors embedded into a chamber wall and on-wafer sensors need to be developed for plasma measurements. Such devices have to measure the plasma density on the wafer surface in real time when processing plasma with bias power, such as in the semiconductor etching process. Yeom *et al.*[44] measured the transmission spectrum of the flat-cutoff sensor when the bias was applied, and plasma-density profiles near the wafer were analyzed using an electrode-embedded flat-cutoff sensor via electromagnetic simulations and experiments under applied bias power.

Effects of magnetic field on discharges.—Magnetized discharges have been a cornerstone of many applications for more than half a century, including thin-film deposition and electric propulsion, garnering extensive study of their fundamental discharge mechanisms to their industrial applications. Zheng *et al.*[45] performed a theoretical study of breathing oscillations and the electron energization mechanism in magnetized discharges. Rotating structures are commonly observed in magnetized CCP.[46,47] The thorough study of conditions where and how external magnetic field affects CCP discharge was performed by Ganta *et al.*[47] Experimental investigations of a cylindrical capacitively coupled geometrically asymmetric plasma discharge with an axisymmetric magnetic field were performed by Dahiya *et al.*[48,49] Zhao *et al.*[50] studied the effect of improving plasma uniformity in the inductively coupled plasma by the application of an external magnetic field. The effect of collisions on the motion of magnetized ions in sheath and presheath plasma regions was investigated by Lee *et al.*[51] The experiment was conducted in hydrogen and deuterium plasmas for varying magnetic field angle to the target surface and measurements of ion incident angle of a hydrogen ion at a graphite surface were performed. Yang *et al.*[52] developed scaling laws of magnetized capacitive radio frequency plasmas.

Electron beam (e-beam) generated plasmas with applied crossed electric and magnetic ($E \times B$) fields can be used for low-damage processing of 2D materials, such as graphene and single-crystal diamond due to the low energy of ions incident to the substrate surface.[53] As discussed above, the authors of Ref. 38 performed measurements of atom and ion velocity distribution functions in an e-beam $E \times B$ plasma at sub-mTorr argon pressures using a laser-induced fluorescence diagnostic and revealed the presence of a warm population of ions with temperatures of ~ 1 eV that are sufficient to drive the ion flux by cross field diffusion in the direction opposite to the applied electric field, toward the plasma-bounded walls or substrate. Cao *et al.*[54] performed numerical studies of beam–plasma interaction. The excitation of obliquely growing waves is observed, which is found to have a significant impact on the transport of beam electrons, thereby leading to the non-uniformities of plasma density and electron temperature. Specifically, the obliquely growing waves increase the local plasma density while reducing the electron temperature. Experimental study of the optical properties of plasma generated by electron beams in nitrogen and argon was investigated by Yan *et al.*[55]

5. Enable integration of physics-based machine learning model to plasma processing tools

Key question: *How can a predictive plasma model using physics-based machine learning be developed to integrate into plasma processing tools?*

High-fidelity plasma simulation models necessitate spatiotemporal resolution, coupled multiphysics, etc., leading to a higher computational cost. This precludes the integration of such models in plasma processing tools where the models are required to be simulated very rapidly, several times. To overcome these challenges, a deep, learning-based, non-linear model order reduction method needs to be developed to generate surrogate models for low-temperature plasmas. The surrogate model needs to predict spatiotemporal plasma phenomena in a timescale suitable for use in plasma process development. The use of physics-based machine learning models for plasma processing tools is rapidly exploding.[56,57]

An example of developing a practical reference index to model the data-driven plasma control logic and collaboration with artificial intelligence for plasma processes is proposed by Park *et al.*[58] for use in the mass production of the OLED display panels: optimization of the mass production etching process recipe and understanding of the capacitive coupling in the inductive discharge.

6. Improve understanding of energy transport from plasma

Key question: *How can an understanding of overall energy balance, especially energy transport from plasma, be improved?*

There has been considerable research on how low-pressure plasmas absorb power from external electric fields (e.g., Refs. 59 and 60). Mechanisms, such as stochastic and Ohmic heating, are reasonably well studied. However, limited attention has been paid to how energy leaves the technological plasmas. While the energy output processes for electrons and ions are somewhat understood, many other energy exit channels have not been adequately investigated. Given that considerable energy comes out through chemical species and photons, these two channels seem particularly ripe for investigation. There are also virtually no studies on energy balance in technologically relevant plasmas. It is important to understand the relative importance of the different energy-output mechanisms in different plasma sources (e.g., inductively and capacitively coupled plasmas, magnetized plasmas) in different operating regimes. This is especially important as processing increasingly involves very high RF power conditions, which put high thermal stress on systems interfacing with the plasma. In a recent paper by Villafana *et al.*,[61] hollow cathode-produced plasma was studied. Electrons are emitted from the cathode surface and are accelerated by the sheath electric field and form a beam of electrons. The energetic electrons from the cathode can produce ionization before thermalizing in Coulomb collisions. In this case, the system has to be described using kinetic simulations. In the opposite case—when the energetic electrons from the cathode thermalize in Coulomb collisions faster than they produce ionization—fluid models can be used. A criterion for two different cases was derived.

Global models of inductively coupled discharge sources. The HBr/Cl_2 mixed gas discharge is often used in semiconductor etching processes, and there have been a few reports of high etching selectivity for silicon oxide mask structure in the HBr/Cl_2 mixed gas discharges. However, experimental and theoretical studies on plasma parameters caused by mixing HBr gas and Cl_2 were extremely rare. Chung *et al.*[62] proposed a model that extends the previous global model of the HBr/Cl_2 plasma, and it was compared with experimentally measured plasma parameters in HBr/Cl_2 mixture gas inductively coupled plasmas.

7. Improve understanding of surface chemistry for etching and deposition in plasma processing

Etching.—Atomic layer etching (ALE) with extremely low ion energies and a complete absence of ions has emerged as a promising technique for the precise and controlled removal of materials in nanoscale devices. ALE processes have gained significant attention due to their ability to achieve high material selectivity, etch uniformity, and atomic-scale resolution. Fischer and Lill[63] provide a perspective of the important role of plasma in ALE including thermal ALE for nanometer-scale device manufacturing. A tally-up of known plasma-based ALE processes is listed, and novel thermal ALE processes are described that are based on the so-called ligand addition mechanism. The benefits and challenges of different plasma sources in ALE are discussed, and an outlook for future development is provided. Important productivity issues, such as particle avoidance and process stability, are also discussed.

In contrast to low ion energy ALE, high aspect ratio etching of SiO_2 and SiN for advanced 3D memory devices is characterized by escalating ion energies. A larger normal ion energy component narrows ion angular distributions (IAD) and provides a brute force method to overcome surface charging. Avoidance of surface charging would address the root cause but solutions for tailoring the sidewall composition to meet profile requirements while also conducting current remain elusive. A significant increase (three and six orders of magnitude) in the surface electric conductivity of SiO_2 films was observed when exposed to down-flow plasmas containing hydrogen fluoride (HF) at cryogenic temperature ($-60\,^{\circ}$C) in Hsiao *et al.*[64] This phenomenon was attributed to the absorption of HF and/or its compounds and the presence of H_2O, which is likely originating from the etching by-product of SiO_2 and/or within the reactor. *These results strongly suggest that the cryogenic plasma etching with HF-contained gases can be used to alleviate the charge build-up issues.*

A method was proposed in Jüngling *et al.*[65] to achieve 3D directionality during etching and deposition by using masks in front of the substrate surface in a plasma etch reactor in combination with local magnetic fields to steer the incident ions in the plasma sheath region toward the surface to reach 3D directionality during etching and deposition.

Dusty plasma.—Dusty plasmas were extensively used for spontaneous growth of nanoparticles from reactive gases, primarily growing hydrocarbon and silicate particles. In Ramkorun *et al.*,[66] the authors have grown titanium dioxide, a wide bandgap semiconductor, as dusty plasma nanoparticles. The successful synthesis of these particles opens avenues for rapid and controlled growth of titanium dioxide via dusty plasma.

III. CONCLUSIONS

Ongoing investment in plasma processing research that will lay the scientific groundwork for future plasma reactors and processing technologies is critical for maintaining market competitiveness and promoting economic growth. This research must be open access, allowing for expert review, discussion, and improvement. Making such research publicly available is also essential for educating the next generation so they are prepared for the rapidly evolving landscape of microelectronics.

This special topic collection has provided a small snapshot of current research in the field of industrial applications of plasma sources as well as a glimpse of future research areas in this fast-moving, impactful field.

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REFERENCES

[1]CONGRESS.GOV, see https://www.congress.gov/bill/117th-congress/house-bill/4346 for "H.R.4346 - CHIPS and science act 117th congress (2021–2022)" (2021).
[2]European Commission, see https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en for "European chips act" (2023).
[3]"Plasma sources for advanced semiconductor applications," Appl. Phys. Lett., see https://pubs.aip.org/apl/collection/992/Plasma-Sources-for-Advanced-Semiconductor.
[4]"Plasma sources for advanced semiconductor applications," Phys. Plasmas, see https://pubs.aip.org/pop/collection/992/Plasma-Sources-for-Advanced-Semiconductor.
[5]D. J. Engels *et al.*, "High-resolution spectroscopic imaging of atoms and nanoparticles in thin film vaporization," Appl. Phys. Lett. **123**, 254102 (2023).
[6]J. Gonzalez and J. Sheil, "On the role of target mass in extreme ultraviolet light generation from CO_2-driven tin plasmas for nanolithography," Phys. Plasmas **31**, 050701 (2024).
[7]Y. Mostafa *et al.*, "Production of 13.5 nm light with 5% conversion efficiency from 2 μm laser-driven tin microdroplet plasma," Appl. Phys. Lett. **123**, 234101 (2023).
[8]Z. Y. Shi *et al.*, "Enhanced extreme ultraviolet conversion efficiency of a 2 μm laser-driven preformed tin-droplet target using short picosecond pre-pulses," Phys. Plasmas **30**, 043107 (2023).

[9]Y. Pan *et al.*, "Joint measurement of electron density, temperature, and emission spectrum of Nd:YAG laser-produced tin plasma," Appl. Phys. Lett. **123**, 204103 (2023).
[10]A. Sasaki, "Effect of multiply excited states to the EUV emission from yttrium-like tin," Appl. Phys. Lett. **124**, 064104 (2024).
[11]Y. Mazuz-Harpaz *et al.*, "Enhancement of Sn plasma EUV emission by double-sided laser illumination," Appl. Phys. Lett. **123**, 204104 (2023).
[12]F. Sato, A. Nagano, and Y. Teramoto, "Influence of a laser intensity on EUV brightness and ion speed from a laser-assisted discharge-produced plasma," Appl. Phys. Lett. **124**, 034101 (2024).
[13]D. B. Reisman, D. J. Arcaro, and F. Niell, "Inductively coupled plasma light source driven by an all solid-state pulsed power system," Appl. Phys. Lett. **123**, 182105 (2023).
[14]S. R. Totorica *et al.*, "Acceleration mechanisms of energetic ion debris in laser-driven tin plasma EUV sources," Appl. Phys. Lett. **124**, 074101 (2024).
[15]L. Poirier, A. Lassise, R. Hoekstra, J. Sheil, and O. O. Versolato, "Dependence of ion charge-energy emission from Nd:YAG-laser-produced plasma on laser intensity in the 0.4–40 $\times$ 10^{10} W/cm^2 range," Phys. Plasmas **30**, 083505 (2023).
[16]B. Y. Israeli, C. B. Smiet, M. Simeni Simeni, and A. Diallo, "EUV debris mitigation using magnetic nulls," Appl. Phys. Lett. **123**, 043507 (2023).
[17]J. E. Hernandez *et al.*, "Efficient photo-dissociation-induced production of hydrogen radicals using vacuum ultraviolet light from a laser-produced plasma," Appl. Phys. Lett. **124**, 012101 (2024).
[18]N. Tanaka *et al.*, "Absolute density measurement of hydrogen radicals in XUV induced plasma for tin contamination cleaning via laser-induced fluorescence," Appl. Phys. Lett. **124**, 152113 (2024).
[19]M. Kume *et al.*, "Spectral control of beyond extreme ultraviolet emission from a dual-laser-produced plasma," Appl. Phys. Lett. **124**, 052107 (2024).
[20]T. Niinuma *et al.*, "Angular distribution separation of the extreme ultraviolet emission and suprathermal ions with energy reduction," Appl. Phys. Lett. **124**, 054104 (2024).
[21]K. Mongey *et al.*, "Characterization of experimental and simulated micrometer-scale soft x-ray-emitting laser plasmas: Toward predictive radiance calculations," Appl Phys Lett. **124**, 102104 (2024).
[22]H. Sun *et al.*, "Direct implicit and explicit energy-conserving particle-in-cell methods for modeling of capacitively coupled plasma devices," Phys. Plasmas **30**, 103509 (2023).
[23]A. T. Powis and I. D. Kaganovich, "Accuracy of the explicit energy-conserving particle-in-cell method for under-resolved simulations of capacitively coupled plasma discharges," Phys. Plasmas **31**, 023901 (2024).
[24]S. Jubin, A. T. Powis, W. Villafana, D. Sydorenko, S. Rauf, A. V. Khrabrov, S. Sarwar, and I. D. Kaganovich, "Numerical thermalization in 2D PIC simulations: Practical estimates for low-temperature plasma simulations," Phys. Plasmas **31**, 023902 (2024).
[25]F. Krüger, H. Lee, S. K. Nam, and M. J. Kushner, "Voltage waveform tailoring for high aspect ratio plasma etching of SiO_2 using $Ar/CF_4/O_2$ mixtures: Consequences of low fundamental frequency biases," Phys. Plasmas **31**, 033508 (2024).
[26]P. Tian, J. Kenney, S. Rauf, I. Korolov, and J. Schulze, "Uniformity of low-pressure capacitively coupled plasmas: Experiments and two-dimensional particle-in-cell simulations," Phys. Plasmas **31**, 043507 (2024).
[27]S. Simha, S. Sharma, A. Khrabrov, I. Kaganovich, J. Poggie, and S. Macheret, "Kinetic simulation of a 50 mTorr capacitively coupled argon discharge over a range of frequencies and comparison to experiments," Phys. Plasmas **30**, 083509 (2023).
[28]D.-Q. Wen, J. Krek, J. T. Gudmundsson, E. Kawamura, M. A. Lieberman, P. Zhang, and J. P. Verboncoeur, "Field reversal in low pressure, unmagnetized radio frequency capacitively coupled argon plasma discharges," Appl. Phys. Lett. **123**, 264102 (2023).
[29]Y. Zhou, K. Zhao, F.-F. Ma, Y.-X. Liu, F. Gao, J. Schulze, and Y.-N. Wang, "Low-frequency dependence of plasma characteristics in dual-frequency capacitively coupled plasma sources," Appl. Phys. Lett. **124**, 064102 (2024).
[30]S. H. Son, G. Go, W. Villafana, I. D. Kaganovich, A. Khrabrov, H.-C. Lee, K.-J. Chung, G.-S. Chae, S. Shim, D. Na, and J. Y. Kim, "Unintended gas breakdowns in narrow gaps of advanced plasma sources for semiconductor fabrication industry," Appl. Phys. Lett. **123**, 232108 (2023).
[31]Y. Yamashita, K. Hara, and S. Sriraman, "Hysteresis between gas breakdown and plasma discharge," Phys. Plasmas **31**, 073510 (2024).
[32]Y. He, M. Lu, X. Liu, J. Huang, J. Zhang, X. Ma, L. Huang, L. Xu, and Y. Xin, "On the coupling effect in the RF-biased inductively coupled plasma with the synchronous control," Phys. Plasmas **31**, 023503 (2024).
[33]Y. Zhang, W. Yang, F. Gao, and Y.-N. Wang, "Jump and hysteresis of plasma density in the spatial afterglow of inductively coupled plasmas," Phys. Plasmas **31**, 073506 (2024).
[34]J.-W. Huang, F.-J. Zhou, X.-Y. Lv, Y.-R. Zhang, F. Gao, and Y.-N. Wang, "Investigation of spatial distribution of EEPFs and neutral species in nitrogen inductively coupled plasmas by 2D hybrid simulation," Phys. Plasmas **30**, 093502 (2023).
[35]C. Lu, J.-W. Huang, Y.-R. Zhang, F. Gao, and Y.-N. Wang, "Modulation of the plasma radial uniformity in pulsed dual-antenna inductively coupled plasmas," Phys. Plasmas **30**, 063506 (2023).
[36]MKS website, see https://www.mks.com/n/thin-film-deposition-overview#:~:text=The%20thin%20films%20that%20are,a%20deposit%20on%20a%20substrate for "Thin film deposition," (2024).
[37]L. Srinivasan, L. Invernizzi, S. Prasanna, K. Gazeli, N. Fagnon, P. Roca i Cabarrocas, G. Lombardi, and K. Ouaras, "Nitrogen atoms absolute density measurement using two-photon absorption laser induced fluorescence in reactive magnetron discharge for gallium nitride deposition," Appl. Phys. Lett. **124**, 104101 (2024).
[38]N. S. Chopra, I. Romadanov, and Y. Raitses, "Production of warm ions in electron beam generated E $\times$ B plasma," Appl. Phys. Lett. **124**, 064101 (2024).
[39]J. W. Brooks and M. C. Paliwoda, "Uncertainty analysis of the plasma impedance probe," Phys. Plasmas **31**, 053514 (2024).
[40]H.-W. Lee, J.-H. Kim, and C.-W. Chung, "Ion energy distribution measurement device using a capillary plate with high-aspect ratio," Phys. Plasmas **30**, 123504 (2023).
[41]L. G. Christophorou and J. K. Olthoff, *Fundamental Electron Interactions with Plasma Processing Gases* (Springer, 2004).
[42]A. Derzsi, I. Korolov, E. Schüngel, Z. Donkó, and J. Schulze, "Effects of fast atoms and energy-dependent secondary electron emission yields in PIC/MCC simulations of capacitively coupled plasmas," Plasma Sources Sci. Technol. **24**, 034002 (2015).
[43]A. N. Kropotkin and D. G. Voloshin, "Construction and validation of C_3F_8 electron impact and heavy particle reaction scheme for modeling plasma discharges," Phys. Plasmas **31**, 033504 (2024).
[44]H.-J. Yeom, G.-S. Chae, M. Y. Yoon, W. Kim, J.-H. Lee, J.-H. Park, C.-W. Park, J.-H. Kim, and H.-C. Lee, "Effect of radiofrequency bias power on transmission spectrum of flat-cutoff sensor in inductively coupled plasma," Phys. Plasmas **31**, 093501 (2024).
[45]B. Zheng, Y. Fu, K. Wang, H. Wang, L. Chen, T. Schuelke, and Q. H. Fan, "Scale-invariant breathing oscillations and transition of the electron energization mechanism in magnetized discharges," Appl. Phys. Lett. **124**, 194101 (2024).
[46]L. Xu, H. Sun, D. Eremin, S. Ganta, I. Kaganovich, K. Bera, S. Rauf, and X. Wu, "Rotating spokes, potential hump and modulated ionization in radio frequency magnetron discharges," Plasma Sources Sci. Technol. **32**, 105012 (2023).
[47]S. Ganta, K. Bera, S. Rauf, I. Kaganovich, A. Khrabrov, A. T. Powis, D. Sydorenko, and L. Xu, "Investigating instabilities in magnetized low-pressure capacitively coupled RF plasma using particle-in-cell (PIC) simulations," Phys. Plasmas **31**, 102107 (2024).
[48]S. Dahiya, N. Sharma, S. Geete, S. Sharma, N. Sirse, and S. Karkari, "Experimental investigation of an electronegative cylindrical capacitively coupled geometrically asymmetric plasma discharge with an axisymmetric magnetic field," Phys. Plasmas **31**, 083512 (2024).
[49]S. Dahiya, P. Singh, Y. Patil, S. Sharma, N. Sirse, and S. K. Karkari, "Discharge characteristics of a low-pressure geometrically asymmetric cylindrical capacitively coupled plasma with an axisymmetric magnetic field," Phys. Plasmas **30**, 093505 (2023).
[50]Y. Zhao, X. Zhou, J. Zhang, S. Song, and Y. Zhao, "Improving plasma uniformity in the inductively coupled plasma by external magnetic field," Phys. Plasmas **31**, 083507 (2024).
[51]M.-G. Lee, N.-K. Kim, J. Song, K.-B. Roh, S.-R. Huh, and G.-H. Kim, "Investigation of collision effects on ion dynamics in the presheath and sheath of weakly collisional and magnetized hydrogen plasmas," Phys. Plasmas **31**, 063506 (2024).

[52]D. Yang, H. Wang, B. Zheng, X. Zou, X. Wang, and Y. Fu, "Scale-invariant resonance characteristics in magnetized capacitive radio frequency plasmas," Phys. Plasmas **30**, 063510 (2023).

[53]F. Zhao, Y. Raitses, X. Yang, A. Tan, and C. G. Tully, "High hydrogen coverage on graphene via low temperature plasma with applied magnetic field," Carbon **177**, 244–251 (2021).

[54]Q. Cao, J. Chen, H. Sun, G. Sun, S. Liu, C. Tan, and Z. Wang, "Characterization of transversely confined electron beam-generated plasma using two-dimensional particle-in-cell simulations," Phys. Plasmas **30**, 103501 (2023).

[55]S. Q. Yan, Y. Chen, Y. Ma, J. K. Gao, and X. D. Zhu, "Optical properties of N_2/Ar plasma generated by electron beams with silicon nitride transmission window at high pressures," Phys. Plasmas **30**, 073504 (2023).

[56]M. Kambara *et al.*, "Science-based, data-driven developments in plasma processing for material synthesis and device-integration technologies," Jpn. J. Appl. Phys. **62**, SA0803 (2023).

[57]J. Trieschmann, L. Vialetto, and T. Gergs, "Review: Machine learning for advancing low-temperature plasma modeling and simulation," J. Micro/Nanopatterning, Mater., and Metrol. **22**(4), 041504 (2023).

[58]S. Park, Y. Park, J. Seong, H. Lee, N. Bae, K-b Roh, R. Seo, B. Song, and G.-H. Kim, "Plasma heating characterization of the large area inductively coupled plasma etchers with the plasma information for managing the mass production," Phys. Plasmas **31**, 073512 (2024).

[59]M. M. Turner, "Collisionless electron heating in an inductively coupled discharge," Phys. Rev. Lett. **71**, 1844 (1993).

[60]I. D. Kaganovich, "Effects of collisions and particle trapping on collisionless heating," Phys. Rev. Lett. **82**, 327 (1999).

[61]W. Villafana, A. T. Powis, S. Sharma, I. D. Kaganovich, and A. V. Khrabrov, "Establishing criteria for the transition from kinetic to fluid modeling in hollow cathode analysis," Phys. Plasmas **31**, 093504 (2024).

[62]S.-Y. Chung, Y. G. Yook, W.-S. Chang, H. Choi, Y. H. Im, and D.-C. Kwon, "Spatially averaged global model of HBr/Cl2 inductively coupled plasma discharges," Phys. Plasmas **31**, 053502 (2024).

[63]A. Fischer and T. Lill, "Plasma application in atomic layer etching," Phys. Plasmas **30**, 080601 (2023).

[64]S.-N. Hsiao, M. Sekine, K. Ishikawa, Y. Iijima, Y. Ohya, and M. Hori, "An approach to reduce surface charging with cryogenic plasma etching using hydrogen-fluoride contained gases," Appl. Phys. Lett. **123**, 212106 (2023).

[65]E. Jüngling, S. Wilczek, T. Mussenbrock, M. Böke, and A. von Keudell, "Plasma sheath tailoring by a magnetic field for three-dimensional plasma etching," Appl. Phys. Lett. **124**, 074101 (2024).

[66]B. Ramkorun, S. Jain, A. Taba, M. Mahjouri-Samani, M. E. Miller, S. C. Thakur, E. Thomas, and R. B. Comes, "Introducing dusty plasma particle growth of nanospherical titanium dioxide," Appl. Phys. Lett. **124**, 144102 (2024).