Factors influencing ion energy distributions in pulsed inductively coupled argon plasmas

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Abstract
Pulsed plasmas are important for the fabrication of nanoscale features. Source biasing is generally associated with the control of the ion to radical flux ratio; how the ion energy distribution function varies over a pulse period is also important. In this paper, we experimentally investigate the effect of pulse transients (i.e. power on to power off phases) on ion energy distributions during different RF source power duty cycles (99%–20%) in a compact inductively coupled argon plasma with time average RF power of 150 W at a frequency of 13.56 MHz and pressure of 20 mT (2.67 Pa). The ion energy distributions were measured by retarding field energy analyzer. With the decrease of RF power duty cycle, the increase of ion energy and energy spread is observed and ion energy distribution changes from single peaked to bi-modal. The effect of RF power duty cycle on the ion energy transition is discussed. Fluid and test particle simulations are used to illustrate the origin of features in the measured ion energy distributions. Capacitive coupling from the RF induction coils is highlighted as the origin for important features in the ion energy distributions.

Keywords: ion energy distribution, pulsed plasma, pulse transient, fluid plasma simulation

With the shrink of semiconductor device dimensions, pulsed plasmas have emerged as promising candidates to address the formidable plasma etching challenges in sub 10 nm region [1, 2]. Compared to continuous wave (CW) plasmas, pulsed plasmas can improve etch uniformity [3–5], etch selectivity [6] and etch rate [5], minimize the surface damage [7, 8]. Pulsed plasmas can also improve unwanted micro-features in etching processes, such as notching, bowing, micro-trenching and aspect ratio dependent etching [1, 2, 9, 10].

Generally, pulsed plasmas refer to the modulation of a source power that sustains the plasma with the generation of ions and radicals and bias power that is used for ion acceleration needed for etching. Pulsed plasma schemes include source pulsing that sustains the plasma without power on the substrate electrode; source pulsing with CW power on the substrate electrode; bias pulsing, modulation of the power to the substrate electrode, with CW source power; and synchronous source and bias pulsing with or without a phase shift between the two. When the plasma is pulsed, the type of pulsing (source, bias and synchronous), the pulse frequency, and duty cycle (the ratio between the pulse on-time and the total pulse duration) provide additional knobs in controlling critical plasma parameters, such as ion and radical densities, ion energies, electron temperature, plasma potential [1, 2]. Specifically, plasma pulsing faster than the radical residence time and slower than the ion residence time allows for independent control of ion species and energy flux and neutral radical flux to the wafer,
which is key to eliminating several feature profile distortions at the nanometer scale.

The characteristics of pulsed plasmas have been investigated using a variety of computational models [11–17]. Studies show the electron temperature \( T_e \), plasma density and potential can vary significantly over a pulse cycle from active glow to afterglow period, as illustrated in figure 1 for a model case using Ar plasma with 20 \( \mu \)s of active glow and 100 \( \mu \)s of pulsing cycle. The chamber configuration will be described later in the paper (illustrated in figure 2(a)). This result assumes no capacitive coupling from the coil therefore the plasma potential profile shows no oscillatory behavior during the active glow. Figure 1 shows that \( T_e \) and the plasma potential rise abruptly after the RF is turned on, followed by a slight decay and an increase in the ion/electron density during the pulse-on time. In the afterglow period, \( T_e \) and the potential decay rapidly whereas the ion density does it more slowly. Lieberman et al [11, 12] investigated high density pulsed Ar and Cl\(_2\) plasmas using global models. They found similar trends to those shown in figure 1 for Ar plasma, with the electron density \( n_e \) increasing to steady values during the pulse-on time and also showing a higher time-average than that for CW plasma with the same time-average power. Economou et al demonstrated the transition of an electron-ion dominant plasma to an ion-ion plasma during the afterglow in pulsed Cl\(_2\) plasma [13, 14]. Subramonium and Kushner investigated the transient behavior of pulsed inductively coupled plasma (ICP) sustained in Ar with various pulse frequency, duty cycle, power and pressure [15]. They found the \( T_e \) at the leading edge of the power-on pulse increased with decreasing duty cycle as the same power was deposited into the initial smaller electrons remaining at the end of afterglow. Due to the concomitant high plasma potential, ions also attain high energies at the leading edge of the bias power pulse. Agarwal et al reported the way to decrease the energy of the ions at the leading edge of the bias power pulse is to reduce the bias power rise time compared to the inductive source power, or by bias power pulse with a phase lag from the inductive power [16]. The high ion energies can also be reduced by offsetting the bias pulse from the source with minimal impact on the etch depth rates [17].

The ion energy distributions over a pulse period are important to understand as they directly influence feature profile, damage and selectivity. In this paper, we investigate the origin of important features of ion energy distributions during pulsing. Ion energy distributions (IEDs) were measured for a range different duty cycles using source pulsing with a coaxial coil inductively coupled plasma source with and without a Faraday cage to isolate capacitive coupling. The effect of duty cycle on the IEDF is discussed using simulation results for context.

A schematic of the plasma source, a modified version from reference [18], is illustrated in figure 2(a). The inductively coupled plasma (ICP) is ignited in a 1.4 in. inner diameter, 7.63 in. long quartz tube, surrounded by a 4 in. outside diameter co-axial stainless steel (SS) cylindrical enclosure. Teflon tubing around the outer wall of the quartz tube provides water cooling. The ICP coil (3-turn, \( \frac{1}{4} \) in. copper tubing) is Galden-cooled. Argon is introduced from the top of the ICP and is regulated by a mass flow controller. A slotted 316 stainless steel (SS) cylindrical sleeve serves as boundary electrode to control ion energy distribution. It is electrically floating in this study. Ordinarily, a bias would be applied to this electrode to modify the plasma potential. In this paper, no bias is applied since we focus on source pulsing. Slits on the electrode minimize the inductive coupling of RF power from coil to cylindrical sleeve. The reactor is pumped by a turbomolecular pump backed by a roughing pump. The base pressure was \( 2 \times 10^{-7} \) Torr (2.67 \( \times 10^{-5} \) Pa). Reactor operating pressure is measured by a capacitance manometer at the top flange. A pressure rise (a couple of mT) was observed after plasma ignition, due to gas dissociation and gas heating. The vacuum system, downstream ultrahigh vacuum (UHV) stainless steel chamber houses the sensor for ion beam characterizations. With a typical pressure of 20 mT (2.67 Pa) in the plasma source, the downstream chamber pressure is about \( 5 \times 10^{-5} \) Torr (6.65 \( \times 10^{-3} \) Pa).

A radio frequency (RF) amplifier driven by a function generator was employed to supply power to the coil at a frequency of 13.56 MHz, through an impedance-matching network. The matching network consists of two variable capacitors, \( C \), and
The extracted ions show energy distributions at ∼100 eV. It is observed there are two ion energy distributions around 50 eV with FWHM of 3 eV. The energy distribution of extracted ions becomes much broader compared to that with 60% RF duty cycle. The FWHM is approximated to be more than 150 eV. Upon decreasing the RF duty cycle to 40%, the energy distribution of extracted ions has peak around 82 eV, which is higher than that with 99% RF duty cycle. In addition, the ion energy spread increases, as the RF duty cycle decreases to 80%, the energy distribution of extracted ions is broader with FWHM of 25 eV. When the RF duty cycle decreases to 60%, the extracted ions have a higher energy peak of 137 eV. For the shortest FR duty cycle (20%), the entire energy distribution of extracted ions becomes much broader compared to that with 60% RF duty cycle. The FWHM is approximately 100 eV. It is observed there are two ion energy distribution peaks; one is at ∼90 eV and the other at ∼137 eV. For the shortest FR duty cycle (20%), the entire ion energy distribution become even broader with FWHM is more than 150 eV. The extracted ions show energy distributions at ∼84 eV and ∼170 eV.

Figure 2. (a) Schematic of the rf inductively coupled plasma source. The plasma is ignited by Galden-cooled RF coil in a water cooled quartz tube. A slotted 316 SS cylindrical sleeve serves as a boundary electrode to control ion energy distributions. The ions are extracted by a grounded grid plate located at the bottom of plasma source. Gas is introduced from the top of source. (b) The plasma is modulated by RF source pulsing at 10 kHz with various RF duty cycles from 20% to 99%

$C_p$, in series and in parallel to the RF power supply, respectively. In-line bird-meters before matching network measured forward and reflected, and the reflected power is almost zero for continuous wave mode.

The plasma is modulated by RF source pulsing as illustrated in figure 2(b). Base case conditions for pulsed-plasma experiments were 150 W time-averaged forward power, 10 kHz power modulation frequency, 20%–99% RF duty cycle, and 20 mT (2.67 Pa) pressure. The ions are extracted by a grounded grid plate located at the bottom of plasma source. The aluminum extraction grid plate is 0.4 in. diameter, 380 μm thick, with 380 μm diameter holes and 60% opening area. After exiting the plasma, ions drift 2 cm before reaching the retarding field energy analyzer (Simion 2500 by Impedans). The energy distribution of the extracted ions is measured by RFEA. The energy resolution of the RFEA is about $\Delta E/E = 1\%–2\%$. Since the downstream pressure is $\sim 5 \times 10^{-5}$ Torr (6.65 $\times 10^{-3}$ Pa), there is no collision of the extracted ions with background gas. The RFEA composes of three grids and a current collector. The top grid is an electron repellor, and the middle grid is swept from 0 to 250 V referenced to ground potential at 1 eV intervals. The bottom grid is biased 10 V negatively than collector to suppress any secondary electron emitted from current collector.

In this work we also performed computational simulations using VizGlow™ software [19]. VizGlow™ simulation results provided estimates fluxes of reactive species to the substrate in the experiment. VizGlow™ allows the modeling of non-equilibrium plasma discharges. It uses boundary conditions for Gauss’ law and an external circuit in order to solve the Poisson’s equation. Also, VizGlow™ solves Maxwell’s equations to model electromagnetic waves in the frequency domain, i.e. it allows the inclusion of ICP pulses. The simulations performed in this work were similar to Raja et al [20], except that the model system used was one dimensional, as in Iwao et al [21], and the driving frequency was 13.56 MHz. Ion energy distributions were computed using VizGrain, a test particle Monte Carlo collision simulation companion to VizGlow™. The ions were launched using volumetric sources generated by the fluid plasma simulation and transported to plasma boundaries mediated by collisions and the forces of the electric fields in the plasma. Collisions with background species included symmetric charge exchange.

Figure 3 shows the RF coil voltage for duty cycles ranging from 20% to 99%. The RF ramping up and down times were about 1 μs according to waveform measured by oscilloscope. To maintain a constant time average power of 150 W (measured by birdmeter), the shorter duty cycles, the higher voltage applied to the coil. Nominally, the power should increase inversely with duty cycle. The coil voltage amplitudes measured using a high voltage probe attached to one end of the coil were 1.5 kV, 1.2 kV, 1.0 kV and 0.9 kV for 20%, 40%, 60%, 80% and 99% duty cycles, respectively.

The first set of experiments was performed without a Faraday shield between the coils and quartz tube. The Faraday shield is made of cylindrical copper strips coaxially surrounding the quartz tube. The width is 6 mm and length is equal to the length of quartz tube. The distance between each copper strip is about 6 mm. Figure 4(a) shows the measured IED in various RF duty cycles from 20% to 99% without Faraday shield. With 99% RF duty cycle, the extracted ions have energies around 50 eV with FWHM of ∼25 eV. When the RF duty cycle decreases to 80%, the energy distribution of extracted ions has peak around 82 eV, which is higher than that with 99% RF duty cycle. In addition, the ion energy spread increases, as shown in FWHM by ∼40 eV. Upon decreasing the RF duty cycle to 60%, the extracted ions have a higher energy peak around 104 eV and larger energy spread about ∼50 eV. When the RF duty cycle decreases to 40%, the entire energy distribution of extracted ions becomes much broader compared to that with 60% RF duty cycle. The FWHM is approximately 100 eV. It is observed there are two ion energy distribution peaks; one is at ∼90 eV and the other at ∼137 eV. For the shortest FR duty cycle (20%), the entire ion energy distribution become even broader with FWHM is more than 150 eV. The extracted ions show energy distributions at ∼84 eV and ∼170 eV.
The plasma potential (~50 eV, the ion peak energy) with 99% RF duty cycle, which is approximately a CW plasma, is higher than that of conventional ICP plasma [22]. The high plasma potential is attributed to the small volume of our plasma source. For the same applied RF power, the smaller volume of the plasma source results in higher power density, leading to higher $T_e$. Therefore, the plasma potential, which scales with $T_e$, increases.

Comparison of the energy distribution of extracted ions at different RF duty cycles shows that with decreasing the RF duty cycle from 99% to 60%, the energy spread of extracted ions becomes larger and the ion energy distribution shifts to higher energy. Recall that in our experiments, the average RF power during a pulsing period (100 μs) is fixed at 150 W. In pulsed plasma, the $T_e$ at the leading edge of the RF power-on period has a sharp rise and overshoot before reaching a steady value. The electron temperature decays rapidly in the afterglow period [11, 12]. The magnitude of the $T_e$ overshoot becomes more apparent with decreasing duty cycle for the same average RF power in one pulsing period [15]. The reason for this is the small electron density relative to steady-state to which the azimuthal electric fields driven from the RF coils must couple at the beginning of a pulse. The plasma potential scales with $T_e$ and should possess the same temporal excursion as the electron temperature when the power is turned on. As shorter pulses have higher powers the sharp rise of $T_e$, and thereby, plasma potential, at the initial RF power-on period is higher. At shorter RF duty cycles, the higher average plasma potential could be responsible for the higher energy of extracted ions, while the more fluctuation of plasma potential would increase the ion energy spread and broaden the ion energy distribution.

More insight into the nature of the ion energy distributions is revealed with further decreasing the RF duty cycle to 40% and 20%. Two ion energy peaks are seen in the IED. In inductively couple Ar plasma, one relatively narrow ion energy distribution peak was typically observed [23]. The two ion energy peaks in figure 4(a) suggests part of RF power is capacitively coupled into plasma. This is not surprising as there is no Faraday shield between the quartz tube and RF coil (figure 2(a)). In capacitively coupled Ar plasma, the main feature of the IED is the bi-modal, saddle shaped structure [23]. At low driving voltages bi-modality need not appear most likelydue to the proximity of the two peaks being narrower than can be resolved. Ultimately, for capacitive coupling, higher driving voltages results in a greater separation between low and high energy peaks [24]. The capacitively coupling from the coils generates a RF sheath at the grounded grid plate. The critical parameter that controls ion modulation in RF sheaths is $\omega \tau_i$, where $\omega$ is the frequency of the applied field, and $\tau_i$ is the ion transit time through the sheath [25, 26]. When $\omega \tau_i \ll 1$, ions traverse the sheath in a short time compared to the field oscillations. In the absence of collisions, the ion energy will reflect the variation of the sheath voltage with time; thus ion energy distributions are double peaked with the maximum and minimum energies corresponding to ions crossing the sheath during the maximum and minimum sheath potential, respectively. The ion transit time is related to the ion plasma frequency ($\omega_{pi}$) based on the plasma density at the sheath edge ($n_{i0}$) [25, 26]. $\tau_i = 1/\omega_{pi}$, where $\omega_{pi} = (e^2 n_{i0}/\epsilon_0 m_i)^{1/2}$. $n_{i0}$

![Figure 3. The pulse RF power voltage waveforms measured at 1.5 kV, 1.2 kV, 1.0 kV and 0.9 kV for 20%, 40%, 60%, 80% and 99% RF duty cycles of over one pulse period (100 μs), respectively, as well as the waveform in 5 RF cycles during RF power on period for the case at 20% RF duty cycle. All waveforms are for a time average power of 150 W at 20 mT (2.67 Pa).](image-url)
depends on the ion flux through the sheath ($\Gamma_i$) and the Bohn velocity ($V_B$), where $V_B \sim (T_e/m_i)^{1/2}$. Using measured flux values and estimates of $T_e$, $\omega \tau_i$ during the plasma on time is about 0.4 for the cases of 40% and 20% RF duty cycles. Without collision due to low downstream chamber pressure ($5 \times 10^{-5}$ Torr/6.65 $\times 10^{-3}$ Pa), ions energy will experience the RF sheath voltage with time, therefore the energy of extracted ions is modulated and the ion energy distribution shows two peaks.

To separate the influence of the $T_e$, excursion at the beginning of the source from the influence of capacitive coupling experiments were then conducted with Faraday shields which should eliminate all but the fringing electric fields that can be sensed through the slots of the shield. Figure 4(b) shows the measured IED in various RF duty cycles from 20% to 99% with a Faraday shield between the quartz tube and RF coil. It is clearly seen there is only one energy peak in the IEDF when RF duty cycle is 40% and 20%. A shoulder exists on the IEDF at 20% duty cycle. This illustrates the Faraday shield effectively reduces the capacitively coupling of RF power into plasma. As a result one ion energy peak is observed. At the same time, the plasma potential drops and the ion energy peak is about 25–29 eV. The corresponding $T_e$ is 5–6 eV, which is comparable to that in conventional ICP plasma [22]. Without the Faraday shield, the coils driving voltages are sensed directly by the plasma resulting is lower power directly coupled to electrons, lower peak and time averaged electron densities and a higher plasma potential when compared to the same power applied with a Faraday shield. The large bi-modal features without Faraday shields and the shoulder at the 20% duty cycle/Faraday shielded condition are possibly due to capacitive coupling.

Plasma simulations permit the addition of capacitive coupling from so its contribution to the IEDF can be separated from the initial $T_e$ excursion. Figure 4(c) shows the IED obtained from simulations for RF duty cycles of 99%, 80%, 40% and 20% respectively. These voltages are substantially lower than the driving voltages as potential drops between the coil and plasma through the quartz and cooling tubes that wrap the quartz. Not only the energy spread increases with the decrease of the RF duty cycle but also the position of the ion energy peaks at $\sim$50 eV and $\sim$70 eV for the RF 99% and 80% duty cycles agree quite well with our ICP measurements. We were not able to reproduce the larger shift observed for the RF 60% duty cycle, which shows the ion energy peak beyond 100 eV, nearly

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**Figure 4.** Measured ion energy distributions for different RF duty cycles under pulsed plasma conditions with time average power of 150 W and pressure of 20 mT (2.67 Pa) without a Faraday shield (a) and with a Faraday shield (b). The corresponding simulated ion energy distributions without a Faraday shield (c) and with a Faraday shield (d).
and 20% RF duty cycles is increased capacitive coupling. The calculated plasma potentials (and electron temperatures) ought to be very similar. In the experiment, the absence of the Faraday shield results in some capacitive coupling which lowers the plasma potential, i.e. there is an overshoot in the potential and then, an increased ion energy spread. The peak potential computed at the plasma midplane during the power on phase are 92, 242, 293 and 322 V for RF duty cycles of 80%, 60%, 40% and 20%, respectively. These potentials are primarily due to the inclusion of capacitive coupling from the coils in the simulations. The difference between peak potential values and the voltage amplitudes are between 40 and 20 V which should be approximately the same as the plasma potential ‘peak’ in the IED (50 V) for 99% duty cycle in the measured data figure 4(a) and 100% duty cycle (cw) in the simulated data figure 4(c).

Finally, figure 4(d) shows the IED obtained from VizGlow simulations for various RF duty cycles including a Faraday shield between the quartz tube and the RF coil by accounted for by a coil voltage directly applied to the plasma. RF voltage amplitudes of 0, 25 and 50 V were applied to the replicate reduced capacitive coupling expected with the presence of a Faraday shield. Just as in the experimentally measured IEDF displayed in figure 4(b), for the three RF duty cycles shown (99%, 40% and 20%), only one ion energy peak predominates, at slightly higher energies of 40–50 eV. The peaks in figure 4(b) are all between 20 and 30 eV. In the simulations 100% of the power from the coil is coupled to the plasma inductively. Therefore at 100% duty cycle, the simulated plasma potentials (and electron temperatures) ought to be very similar. In the experiment, the absence of the Faraday shield results in some capacitive coupling which lowers the power inductively coupled to the plasma, the plasma density probably increasing $T_e$ and the plasma potential. The 20% RF duty cycle shows a broader IED feature, but the shoulder arising from the initial plasma charging is very similar to the one observed in our experiments suggesting its origin is increased capacitive coupling. The calculated $T_e$ for the 40% and 20% RF duty cycles is $\sim 5.2$ eV, also in excellent agreement with our experimental data.

In summary, we characterized in detail how the IED in a compact ICP Ar plasma varies when the RF power to the driving coil is varied with and without a Faraday shield. The averaged RF power in one pulsing period is fixed, as consequence, the smaller RF duty cycle, the higher RF power applied. IED measurements show ion energy distribution has a single peak in 99% RF duty cycle operation (effectively equal to cw operation) with and without the Faraday shield. For the same power, the peak plasma potential is about half that when the Faraday shield is omitted from the experiment. Since $T_e$ should drop with increasing coupled power, the decrease in potential can be attributed to decreased capacitive coupling when the shield is used. Bi-modal features are especially evident when RF coil powers are larger (and coil voltages are larger) at lower duty cycles. One could also attribute these features to $T_e$ excursions when the pulses turn on. However, the magnitude of $\langle T_e \rangle$ and the potential overshoot without the consideration of capacitive coupling are much lower than any measured peak ion energy. We conclude therefore that capacitive coupling from induction coils can dominate the low ion energy behavior in source only pulsing experiments. This is critical when bias is applied to a wafer seeking low bias voltages at moderate powers given the presence of a high density plasma. The sheath potential drop and ion energy may be entirely attributable to other sources of capacitive coupling (e.g. the induction coil) in an ICP system.

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