

Effects of a chirped bias voltage on ion energy distributions in inductively coupled plasma reactors

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The metrics for controlling reactive fluxes to wafers for microelectronics processing are becoming more stringent as feature sizes continue to shrink. Recent strategies for controlling ion energy distributions to the wafer involve using several different frequencies and/or pulsed powers. Although effective, these strategies are often costly or present challenges in impedance matching. With the advent of matching schemes for wide band amplifiers, other strategies to customize ion energy distributions become available. In this paper, we discuss results from a computational investigation of biasing substrates using chirped frequencies in high density, electronegative inductively coupled plasmas. Depending on the frequency range and chirp duration, the resulting ion energy distributions exhibit components sampled from the entire frequency range. However, the chirping process also produces transient shifts in the self-generated dc bias due to the reapportionment of displacement and conduction with frequency to balance the current in the system. The dynamics of the dc bias can also be leveraged towards customizing ion energy distributions. *Publishing*. [http://dx.doi.org/10.1063/1.4993785]

I. INTRODUCTION

Inductively coupled plasma (ICP) reactors are extensively used in plasma materials processing for microelectronics fabrication.¹⁻³ The typical operating conditions use a radiofrequency (rf) biased substrate with the goal of separately controlling the flux of reactive ions and radicals to a wafer with the inductively coupled source and the energy of incident ions with the substrate bias. The magnitude of the fluxes determines the rate of processing, while controlling the incident ion energy distributions (IEDs) onto the wafer determines the etch selectivity required for control of the critical dimension (CD). Many strategies have been investigated to control IEDs, including adding a boundary electrode,⁴ using tailored voltage waveforms,^{5–8} multiple frequencies,^{9–12} and pulsing.^{13–17} When using multiple frequencies at multiple harmonics, the electrical asymmetry effect enables further customization of IEDs through, in part, control of the self-generated dc bias.¹⁸⁻²⁰ In plasma chambers, a dc bias forms due to the asymmetry in collection of current between the powered and grounded electrodes to balance the flow of current. The selfgenerated dc bias was recently shown to oscillate in a controllable manner using tailored voltage waveforms with slightly off-harmonic high frequencies in capacitively coupled plasmas, while retaining favorable properties such as constant ion flux to the substrate.²¹ Since the return currents in ICP reactors include both conduction current to the substrate and displacement current through the dielectric window beneath the antenna, dc bias formation is less straight forward than in capacitively coupled plasmas.^{22–24}

A "chirp" is where the frequency of a sinusoidal or repetitive waveform is linearly varied over time. (See Fig. 1.) For example, a purely linear chirp will vary the frequency between f_0 and f_1 , the initial and final frequencies, over a time τ to sweep across frequencies. For an initial phase φ_0 , a repetitive amplitude of the chirped signal is

$$a(t) = \sin\left[\phi_0 + 2\pi t \left(f_0 + \frac{(f_1 - f_0) \operatorname{mod}(t, \tau)}{\tau}\right)\right].$$
(1)

A chirped bias voltage provides an opportunity to customize IEDs by taking advantage of the variation in the energy width of the IEDs as a function of frequency, with an added level of control of the dwell time of the bias at any given

The width in energy of an IED striking the surface of an rf biased substrate can be controlled by the ratio of the rf period compared to the time required for the ion to cross the sheath.^{25,26} For low bias frequencies (long periods), ions transiting through the sheath in a small fraction of an rf period arrive with energies dependent on the phase and voltage of the bias when the ion enters the sheath. These conditions lead to dual peaked IEDs. For high bias frequencies (short periods), ions transiting through the sheath over many rf periods arrive at the substrate with a narrower distribution centered about the average sheath potential-the difference between the plasma potential and dc bias-resulting in a single peaked IED. However, for intermediate frequencies, both the number of rf cycles to transit through the sheath and phase dependence can affect ion energy distributions. This scaling in part motivates the use of multiple bias frequencies to customize the IEDs. To some degree, the IEDs will be super-positions of broad IEDs produced by low frequencies and narrow IEDs by high frequencies.

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FIG. 1. A linear chirp is shown in (a), where the frequency increases from 1 to 5 MHz, repeating every 5 μ s, and (b) the resulting rf voltage signal (arbitrary units).

frequency. If the range of frequencies or chirp periods is moderate, it may be possible to use a single amplifier and simple impedance matching circuitry, while achieving the advantages of using separate frequencies, power supplies, and matching networks. For example, commercial wideband amplifiers are available in the multi-kW range of powers for frequencies of <1 MHz to tens of MHz, which are within the range of chirped frequencies discussed here. In many systems using bias frequency to customize IEDs, multiple frequencies are simultaneously applied, which presents sufficient challenges to using a single matching network that multiple matching networks are typically used. With chirped frequency biases, only a single frequency is applied at any given time. Subject to the rate of chirping, matching is expected to be less challenging than simultaneously using multiple frequencies.

In this work, results from a computational investigation of controlling IEDs onto wafers using a chirped substrate bias in a high plasma density, electronegative ICP are discussed. In particular, the impact of the transient frequency during chirping on the self-generated dc bias and on the IEDs is quantified. Sweeping frequencies cause the blocking capacitor on which the dc bias resides to continually charge and discharge, shifting the ion energies striking the wafer from what would be obtained from the equivalent constant continuous wave (cw) frequency. A chirped frequency can be used to control the dc bias and to customize IEDs.

Descriptions of the computational models used in this work are discussed in Sec. II. In Sec. III, results from studies of basic chirped bias waveforms and how changes in operating conditions affect IEDs are discussed. In Sec. IV, the concept of customized chirping is then demonstrated to craft unique frequency waveforms. Concluding remarks are in Sec. V.

II. DESCRIPTION OF THE MODEL

The Hybrid Plasma Equipment Model (HPEM) was used to investigate the consequences of a chirped bias voltage in an ICP reactor. The HPEM is a two-dimensional fluid hydrodynamics computer model for low temperature plasmas, and the specific details can be found elsewhere.²⁷ HPEM executes by having separate modules which address different classes of physics. In this work, the Electromagnetics Module was used to determine the inductive electric fields for a specified input power. An electron Monte Carlo simulation within the Electron Energy Transport Module (EETM) was used to track electrons produced by secondary emission from surfaces. The Fluid-Kinetics Poisson Module (FKPM) was used to separately solve continuity, momentum, and energy equations for all heavy particle species and a drift-diffusion formulation for electrons. A semi-implicit form of Poisson's equation was used to solve for electrostatic fields. An electron energy conservation equation was used to obtain an effective electron temperature based on absorbed power electron convection, thermal conduction and electron collisional losses. Stationary solutions of Boltzmann's equation provided electron impact rate coefficients and transport coefficients as a function of effective electron temperature. The Plasma Chemistry Monte Carlo Module (PCMCM) was used to calculate ion energies incident onto a wafer by tracking ion pseudoparticles, influenced by electric fields and collisions, binning the resulting flux by energy and incident angle [Ion Energy and Angular Distributions (IEADs)].

The base case uses a chirped frequency of 2–20 MHz, repeated every 30 μ s. To work within the HPEM framework, the chirped waveform was approximated by using steps of the lowest frequency harmonics, shown in Fig. 2. The bulk plasma properties in high plasma densities systems, such as ICPs, are weak functions of the bias for moderate bias



FIG. 2. Typical voltage and frequency waveforms. (a) Chirped frequencies used in this work (blue) are shown compared to a true linear chirp (red), 2–20 MHz repeated every 30 μ s. This simplification can be checked by comparing the true voltage waveform (arbitrary units), shown in (b), to the simplified voltage waveform in (c). Note that only the first 10 μ s of the chirp is shown in order to visually resolve the change in frequency.

voltages. So to speed computational convergence, the model is first run with only the ICP power until a steady state is achieved. The chirped bias is then turned on, and a sufficient number of chirped periods are computed to achieve a pulseperiodic steady state.

III. CHIRPED SUBSTRATE BIAS

The simulations in this study were performed for the ICP reactor schematically shown in Fig. 3(a). This reactor features a four-turn planar coil antenna that delivers purely inductive power. An $Ar/Cl_2 = 80/20$ gas mixture flows into



FIG. 3. Plasma parameters for the base case. (a) Schematic of the cylindrically symmetric ICP chamber used in the model. Computed (b) n_{e1} having a maximum density 3.7×10^{11} cm⁻³ and (c) T_e over the range of 2.6–3.2 eV. n_e and T_e are essentially constant over the chirped period.

the reactor through the inlet at 600 sccm. The reaction mechanism used is the same as that described by Tian and Kushner²⁸ with the exception that radiation transport was not included here. The basic circuit consists of the chirped bias power being applied to the metal substrate through an intervening blocking capacitor, a dielectric wafer functionally acting as a lossy capacitor on the substrate, the sheath above the wafer acting as a capacitor, the plasma acting as an impedance, and the sheath against the grounded metal wall and alumina window. Conduction current flowing out of the power supply returns to ground through the metal walls in contact with the plasma or as displacement current flowing through the quartz window which terminates on ground on the opposite side of the window. The dc bias forms on the blocking capacitor to balance the current flowing through the substrate and that returning to ground elsewhere. These flows of current are natural outcomes of the simulation by computing fluxes of charged particles and time variations of electric fields at surfaces, and are calculated by performing integrals of the conduction and displacement current densities entering the surface of metals. Although the majority of voltage that balances the currents resides on the blocking capacitor, the wafer and sheaths also hold some charge.

A. Base case

The ICP reactor was operated with 900 W of inductive power, with a chirped bias waveform having an amplitude of 150 V and a frequency excursion of 2 to 20 MHz repeated every 30 μ s. (The increasing frequency during the chirp is called the ascending chirp.) Computed plasma properties are shown in Figs. 3(b) and 3(c) after operating without a bias to approximate convergence and then applying 5 chirped bias cycles which was sufficient to achieve a pulse-periodic steady state. The electron density reaches a maximum of 3.7 $\times 10^{11}$ cm⁻³, slightly off-axis which reflects the maximum in the inductive power deposition beneath the coils. In this electronegative, molecular gas mixture, electron losses occur both in the volume by dissociative electron attachment to Cl₂ and dissociative recombination with Cl2⁺, as well as diffusion to the walls. The electron temperature, T_e , reaches a maximum of 3.2 eV beneath the coils, decreasing to 2.6 eV near the pump port. The plasma properties do not significantly vary over a chirped period since the majority of the power deposition from the bias is expended in ion acceleration. However, the amount of capacitive power does change with frequency during the constant voltage chirp. The minimum capacitive power occurs at the beginning of the chirp-200 W when the bias is 2 MHz. Near the end of the chirped period, the capacitive power is 300 W when the bias is 20 MHz.

The IEADs at various times (collected over a period of $0.5 \,\mu$ s) during the chirped period are shown in Fig. 4 for Ar⁺. At the beginning of the chirp with lower frequencies, ions are extracted with bimodal peaks in energy, with the high energy peak emphasized. At the beginning of the chirp (t = 0), ions having energies as large as 260 eV are extracted, characteristic of the low frequency (2 MHz).²⁶ During the chirp, the peak energy decreases while the minimum energy



FIG. 4. Ion Energy and Angular Distributions for Ar⁺ sampled over 0.5 μ s at times during the chirp period with the frequencies noted for each time. The IEADs exhibit a general decrease in peak ion energy and increase in minimum ion energy as the frequency increases over the chirp.

increases, reflecting the increasing frequency which shortens the rf cycle and so drives the IEADs towards being single peaked.

IEDs averaged over the chirped cycle are shown in Fig. 5 for Ar^+ , Cl^+ , and Cl_2^+ . To give context to these results, IEDs are also shown in Fig. 5 when holding the bias at a constant frequency for the same conditions (2, 10, and 20 MHz with 150 V amplitude). The trends in the IEDs for increasing ion mass at higher frequencies show decreasing energy between the peaks due to their longer transit time through the sheaths. At 2 MHz, the IEDs are nearly identical for all ions, which suggests that the ion transit time through the sheath is shorter than the rf period for all masses, and so, the IEDs are dominantly dependent on the time which the ion enters the sheath. The IEDs for Ar^+ will be discussed in detail and used to compare trends to other conditions.



FIG. 5. Time averaged IEDs for the base chirped case for (a) Ar^+ , (b) Cl^+ , and (c) Cl_2^+ . The chirped results (black) are compared to IEDs produced with constant frequency: 2 MHz (red), 10 MHz (blue), and 20 MHz (green).

For the constant frequency cases, the IED for 10 MHz extends to the highest energy. This is caused by a combination of a decrease (more negative) dc bias, -60 V, combined with the more extended IED that is produced at lower frequencies. (See Fig. 6.) Although one might expect a more extended IED at 2 MHz, the dc bias is only -24 V at this



FIG. 6. Transient dc bias on the blocking capacitor for the chirped case (black), compared to constant frequency cases: 2 MHz (red), 10 MHz (blue), and 20 MHz (green). The dc bias is dynamic when using a chirp.

frequency. The steady state dc bias results from balancing the rf cycle averaged current through the powered electrode with that returning to ground. A negative bias indicates that in the absence of the bias, more current would be collected on the grounded side of the circuit. In parallel plate capacitive systems, these differences in currents are typically a result of the powered and grounded metal surfaces having different areas. If the area of the grounded electrode is greater than that of the powered electrode, the blocking capacitor should naturally charge to a negative voltage.

In this system, the accounting of currents is complicated by much of the return current to ground passing as displacement current through the dielectric window. With the ICP power, plasma density, and bias voltage all constant, the thickness of the sheath and electric field in the sheath at the surface of the dielectric remain approximately constant during the chirp. The displacement current, $\varepsilon_0(dE/dt)$, then scales directly proportional to frequency. For example, changing the bias frequency from 2 to 20 MHz during the chirp increases the displacement current through the window by about an order of magnitude, thereby making the system appear more asymmetric and producing a more negative dc bias. The displacement current is more sensitive to frequency than the combination of conduction and displacement current that returns to ground at the walls of the chamber. The energy between the peaks in the IEDs decreases with increasing frequency due to ion transit times through the sheath that can span multiple rf periods. For the 10 MHz case, the dc bias decreases at a faster rate than the peaks come together, leading to higher energy ions.

The IEDs for the chirped case have characteristics of the low and high frequency cw bias cases. The IEADs resulting from the ascending chirp sampled over 0.5 μ s when the bias is at 2, 10, and 20 MHz are compared to IEADs for Ar^+ produced with constant frequency biases in Fig. 7. Over the chirped period, the IEAD transitions from having low and high energy peaks (as the 2 MHz case) to peaks closer together in energy (characteristic of 20 MHz). However, the chirped IEAD has a higher energy tail compared to any of the cw cases. This high energy tail results from the transient nature of the "dc" bias when chirping, as shown in Fig. 6. The dc bias changes in times given by the effective RC time constant in response to the change in currents over an rf cycle to the powered and grounded surfaces. For this geometry, higher frequencies produce a more negative dc bias. At the end of the chirped period with 20 MHz excitation, the negative bias is becoming even more negative. The frequency changes to 2 MHz at the beginning of the next chirped period, a frequency which for continuous excitation would produce a more positive bias. However, the more negative dc bias produced by the high frequency persists into the part of the chirp that has low frequency as the RC time constant for these conditions is approximately $25 \,\mu s$. The end result is that the 2 MHz portion of the chirp that naturally produces an IED that extends to higher energy has an abnormally more negative dc bias compared to the cw case. This abnormally more negative dc bias enables the IED to extend to even higher energy. With the chirp now at low frequency, the dc bias begins to become more positive.



FIG. 7. Time resolved IEADs for Ar^+ sampled over 0.5 μ s for the base case having an ascending chirp (column 1) and a descending chirp (column 2), compared to the IEAD produced with a constant frequency (column 3). The IEADs are shown at the same frequencies, (a) 2 MHz, (b) 10 MHz, and (c) 20 MHz. Note that these IEADs then correspond to different times during the chirp cycle for the ascending and descending chirps (noted in each frame).

The remainder of the IEAD generally has less structure than the IEADs obtained with single frequencies, though this is not a universal trend. For example, the IEAD with chirping for Cl_2^+ retains some semblance of two-peaks, indicating

that the IEADs for the heavier ion are less sensitive to changes in frequency due to their longer sheath crossing time.

The base case uses an ascending chirped frequency from 2 to 20 MHz (150 V). The dc bias is sensitive to the rate of change of the applied frequency and the change in frequency from high to low at the end of the chirp. A descending chirp—chirping from 20 to 2 MHz, as shown in Fig. 8(a) should then produce a different sequencing of the dc bias. Reversing the bias frequency from ascending to descending modifies the IEDs for Ar⁺, particularly at high energies, as shown in Fig. 8(b). The descending chirp produces an IED having a lower maximum energy. With the ascending chirp, the dc bias is most negative when the highest frequency (20 MHz) changes to the lowest frequency (2 MHz). The lowest frequency naturally produces the broadest bimodal distribution function (2 MHz). The combination of large dc bias and bimodal IED produces a larger maximum in ion energy.

The descending chirp has the opposite trend in dc bias. The dc bias is most positive at the end of the chirped period at the lowest frequency (2 MHz), as shown in Fig. 8(c), at which time the chirp switches to the highest frequency (20 MHz) which naturally produces the narrowest IED with a single peak. The dc bias immediately becomes more negative in response to the higher frequency. However, the more



FIG. 8. Comparisons of ascending and descending chirps for base case conditions. (a) Frequencies for ascending and descending chirps. (b) Time averaged IEDs for Ar^+ and (c) dc bias. The differences in IEDs result from contrasting transients in the dc bias.

positive dc bias persists beyond the switch in frequency, decreasing the ion energies when the 20 MHz is applied. These trends for IEADs are shown in Fig. 7. The IEAD at 20 MHz for the descending chirp [Fig. 7(c)] has a maximum energy that is \approx 40 eV smaller than that for 20 MHz for the ascending chirp. This difference is equal to the increase in dc bias for the descending chirp. The shift in the average energy of the IEADs for ascending and descending chirps in Fig. 7 for the same frequency is largely a result of the opposite trending dynamics of the dc bias.

B. Source power

The effect of varying the ICP source power was investigated for the base case ascending chirped waveform for Ar⁺ over the range of 600–1200 W. The resulting IEDs are shown in Fig. 9 for constant bias frequencies of 2 MHz and 20 MHz and the ascending chirped waveform. The maximum electron density increases from 1.6×10^{11} cm⁻³ for 600 W to 5.9×10^{11} cm⁻³ for 1200 W with the same general spatial



FIG. 9. IEDs for Ar^+ as a function of ICP source power (600–1200 W) for different bias waveforms: (a) 2 MHz, (b) 20 MHz, and (c) ascending chirp (2–20 MHz) with $V_{rf} = 150$ V.

trends. The electron temperature was largely unaffected by these changes in inductive power, which partly results from the high flow rate that minimizes the amount of dissociation of Cl_2 by replenishing the feedstock. The dominant change with increasing power is the thinning of the sheath, which then broadens the energy range of the IEDs, particularly at the higher constant frequency. The broadening of the IEDs with thinning of the sheath is tempered by a decrease in dc bias with increasing power, shown in Fig. 10.

The IEDs for chirping the bias frequency with different ICP powers are shown in Fig. 9(c). With chirping the frequency, the relative flux of ions with lower energies increases and at high energy decreases with increasing power. These trends largely result from the change in dc bias with source power, shown in Fig. 10. As with the fixed frequency, increasing source power produces an increase in dc bias (to less negative values) and more so at higher frequencies. These trends in dc bias have been experimentally²⁹ and analytically³⁰ investigated and are attributed to increased capacitance of the ion sheath above the wafer. A more negative dc bias for the 600 W case results in ions generally being extracted with higher energy. Since the magnitude of the flux to the wafer scales with ICP power, the low flux at 600 W produces a less transient dc bias. The small change in dc bias for 2 MHz at the higher powers (900 W and 1200 W) likely results from the contribution from displacement current being small while the change in electron current density with power is also small. The Cl⁻ density for both powers is small. As a result, the effective asymmetry of the reactor does not change.

C. Blocking capacitor size

With continuous excitation for a fixed frequency in the steady state, the dc bias is not a function of the size of the blocking capacitor. The initial transient to the steady state bias does depend on the size of the blocking capacitor due to the larger RC time constant. However, the final dc bias should not depend on the size of the blocking capacitor. With the repeating, chirped frequency bias, the system is driven by what is a functionally dynamic pulsed bias—the system is never in a true steady state. If these transients have times that are commensurate with the RC charging time of



FIG. 10. dc bias on the blocking capacitor as a function of source power (600-1200 W) for 2 MHz, 20 MHz, and an ascending chirped substrate bias (2-20 MHz).

the blocking capacitor, the resulting dc bias will also have modulation. These trends are shown in Fig. 11 where IEDs and dc bias are shown for values of the blocking capacitor of 10 nF to 1 μ F. The bulk plasma properties were essentially unchanged from the base case shown in Fig. 3. The energies at which the peaks occur in the IEDs are consistent for all blocking capacitor values. The main difference between the IEDs is the slope at high energies—a steep slope for the responsive 10 nF blocking capacitor case and a shallower slope for the 1 μ F blocking capacitor.

The differences in IEDs are caused by differences in the transient dc bias. The 10 nF blocking capacitor has a rapid enough response that its transient dc voltage nearly spans the range of the dc biases produced by the cw 2 and 20 MHz voltages. The dc bias at a given frequency is close to that for the cw bias. For the large blocking capacitor (1 μ F), the response is long enough that the dc bias is relatively constant over a chirped period, an average of the currents collected between 2 and 20 MHz. The excursion in dc bias is least negative at high frequency at the end of the chirp for the $1 \,\mu\text{F}$ capacitor and most negative for low frequency at the beginning of the chirp. These trends account for the IED being more highly populated at high energy with the $1 \,\mu\text{F}$ capacitor. On the other hand, the dc bias for the 10 nF blocking capacitor quickly responds upon starting the low frequency part of the chirp. The bias quickly increases towards more positive values while the frequency is low, thereby reducing the ion flux at high energy.



FIG. 11. Plasma properties for the ascending chirp (150 V, 2–20 MHz, repeated $30 \,\mu$ s) as a function of blocking capacitor sizes: 10 nF (blue), 250 nF (base case, black), and 1 μ F (red). (a) IEDs for Ar⁺ and (b) dc bias. The dc bias oscillates between the values set by the cw extreme frequencies without reaching a steady-state value. The dc bias for the smaller capacitor approaches these extreme values.

IV. CUSTOM FREQUENCY WAVEFORMS

Chirping is typically performed with a linear ramp between minimum and maximum frequencies. However, a more general form of chirping is a waveform of frequencies, which might be used to achieve a desired shape of the IEAD. For example, the chirped-waveform shown in Fig. 12(a) was used to demonstrate the possible utility of this method. The waveform consists of chirping between two frequencies while holding the upper and lower frequencies for a specific time. In this case, the 2 MHz and 20 MHz are held constant for 11 μ s with a linear chirp between them lasting 4 μ s, for a period of 30 µs. The IEADs collected at different times during the chirp are shown in Fig. 12(b). The IEDs averaged over the chirp and dc bias during the chirp are shown in Fig. 13. The IEADs at points 1 and 4 are at the same frequencies as are the IEADs at points 2 and 3. However, the predicted ion energies shift by $\approx 40 \,\text{eV}$ when going from the leading to the trailing edge of the chirp for 2 MHz and shift by $\approx 20 \text{ eV}$ for 20 MHz between the beginning and end of its portion of the waveform. These shifts result from the dynamics of the dc bias, which is most negative at the end of the high-frequency plateau in the chirp.

If not for the response of the dc bias, the chirp averaged IEDs should dominantly be a function of the integral of the ion flux arriving at the wafer for each frequency component. Custom frequency waveforms were investigated by varying the time for which the high-and-low frequencies are held



FIG. 12. A custom chirp waveform for customizing IEADs. (a) Frequency of custom chirped waveform and (b) IEADs for Ar^+ sampled over 0.5 μ s at times during this repeated period. Ion energies shift in energy even when the same frequency is applied (points 1 and 4 for 2 MHz; and points 2 and 3 for 20 MHz) due to the dynamics of the dc bias.



FIG. 13. Plasma properties for the custom chirp waveform. (a) Time averaged IEDs for Ar^+ for the 30 μ s custom frequency waveform compared to IEDs for constant frequencies (2 MHz and 20 MHz). (b) Transient bias on the blocking capacitor, producing shifts in the IEDs for the same frequencies.

constant, producing cycle times of 10 to 50 μ s. These waveforms and the resulting IEDs are shown in Fig. 14. The IEDs are most sensitive to the longer dwell time at the low frequency, with longer dwell time at the low frequency corresponding to larger low-energy peaks in the IEDs. The lack of corresponding large high energy peaks stems from the dynamics of the dc bias, shown in Fig. 14(c). For the 10 μ s cycle time, the dc bias oscillates very little over the chirp period, while the longer cycle times enable the dc bias to nearly reach the steady-state limits of the cw cases. It could prove beneficial to customizing IEDs to control the range over which the dc bias oscillates. Operating with different cycle times enables control over the proportion of the IEDs in the high and low energy peaks, while keeping the energy of the peaks essentially unchanged. This could be valuable for other gases with more complicated etching mechanisms, such as C_4F_8 ,³¹ which benefit from a controllable distribution of ions having both low and high energies.

V. CONCLUDING REMARKS

A computational investigation has been used to assess the ability to control IEADs using chirped substrate biases. Chirped substrate biases produce customizable IEADs incident on the substrate due to both the integral of IEADs produced by different frequency components and due to there being a dynamic self-generated dc bias. Using different bias frequencies can change the effective asymmetry of the system, producing shifts in the dc bias that forms to balance the current. By sweeping the applied frequency, the potential



FIG. 14. Selection of custom frequency waveforms. (a) Custom frequency waveforms varying the time spent holding the extreme frequencies by the length of the chip period. (b) IEDs for Ar^+ for different chip periods of 10 μ s to 50 μ s (varying times holding the extreme frequencies). (c) The transient dc bias for chip periods 10 μ s to 50 μ s. Holding the extreme frequencies for less time results in a less transient dc bias.

drop across sheaths differs compared to the expected value for constant frequency due to transients in the dc bias on time scales of the RC time constant.

One potential use for a chirped bi/as frequency would be when a mix of high and low energy components in the IEADs is desired. Operating with a single frequency leaves little flexibility in this regard since the dc bias and ion energy distribution are, to some degree, predetermined for a given set of plasma operating conditions. For a constant 2 MHz frequency with the operating conditions in this work, the majority of ions are extracted at low energies. Using a chirped frequency could be one method to tune the low energy peak in the IED while having a minimal impact on the plasma. Chirped frequencies have many of the advantages of using multiple fixed frequencies for biasing the substrate with perhaps the additional feature of dynamic dc biases.

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