The transition from symmetric to asymmetric discharges in pulsed 13.56 MHz capacitively coupled plasmas

J. P. Booth, a) G. Cunge, and N. Sadeghi
Laboratoire de Spectrométrie Physique, a) Université Joseph Fourier, 38402 Saint Martin-d’Heres Cedex, Grenoble, France

R. W. Boswell
PRL, Australian National University, ACT. 200, Australia

(Received 27 December 1996; accepted for publication 2 April 1997)

The behavior of a rapidly pulsed radio-frequency capacitively coupled parallel plate reactor has been investigated using time-resolved voltage probe, microwave interferometer, and optical emission techniques. The reactor was operated with 50 mTorr of argon and 100 W rf power (measured at the generator) at 13.56 MHz supplied to the 100-mm-diam powered electrode, with pulse durations of 25 and 100 µs. For low repetition rates (50 Hz) the voltage envelope has a characteristic form which has been entitled the "Bird’s Head." There is no plasma present at the beginning of the pulse, so that an initial breakdown phase occurs. This phase lasts about 600 ns, after which time the plasma density is sufficiently high for the Debye length to enter the gap between the electrodes and for sheaths to form on the electrodes. In asymmetric parallel plate reactors the blocking capacitor in the matching circuit charges such that the powered electrode acquires a continuous negative voltage offset (the so-called dc bias). In this system the charging time of the capacitor is longer than the rise time of the rf voltage. Consequently, for the first few µs of the pulse the discharge is symmetric (no dc bias) and confined between the rf and the adjacent earthed electrode. As the bias voltage increases the discharge fills more of the reactor and becomes asymmetric. The rate at which the blocking capacitor charges (due to net electron current from the plasma to the powered electrode) is controlled by the Bohm-criterion limited flux of ions to the earthed walls of the reactor, as shown by particle-in-cell simulations in H. B. Smith, C. Charles, and R. W. Boswell, J. Appl. Phys. 82, 561 (1997). At high repetition rates (20 kHz) the plasma density is hardly modulated, there is no breakdown or symmetric phase, and only the electron temperature and dc bias are modulated. The conditions which lead to a symmetric discharge phase are defined. A simple analytical model is developed to describe the temporal evolution of the plasma density and electron temperature. The model is in good qualitative agreement with the observations, and predicts an average electron energy of 10 eV during the first few µs of the symmetric discharge.

© 1997 American Institute of Physics.

[SO021-8979(97)01514-4]

I. INTRODUCTION

Pulsing of low pressure rf and microwave discharges can be used to change the gas phase chemistry and to modify the energy of ions bombarding substrates placed on either the rf or the earthed electrodes. By varying the duty cycle, high average plasma densities can be obtained for lower average input powers. These effects can be used to improve industrial plasma processes. For example, etch selectivity (over Si) when etching SiO2 was greatly improved by pulsing the power supplied to an electron cyclotron resonance (ECR) source using fluorocarbon chemistry and very high selectivities (over SiO2) when etching silicon was obtained in a pulsed high density helicon source with SF6 gas. Improved films of amorphous Si have been grown when the plasma was pulsed at about 1 kHz. Apart from the possibilities for controlling the dissociation rate of molecular gases such as oxygen, ions accelerated by the high initial plasma potential can improve the quality of silica films deposited from SiH4/O2 gas mixtures. All surfaces of the reactor (not only the powered electrode) will be subjected to this ion bombardment and the gas phase chemistry can be significantly different from that obtained with continuous discharges. Two recent papers have shown that simple global modeling of pulsed inductive discharges is in surprisingly good agreement with the experimental measurements. In particular, when a plasma has been formed (after the initial breakdown phase, lasting about 1 µs), the assumption that all the incident rf power is absorbed by the plasma electrons, and is then lost predominantly by ions falling through the sheath carrying their ionization energy, is reasonably well justified by experimental measurements of the electron temperature, density, and ion energy. The present article investigates the applicability of this approach to a parallel plate capacitively coupled plasma, where large power dissipation also occurs in driving ions through the large sheath at the rf-powered electrode, so that estimating the power absorbed by the electrons is more complex.

II. EXPERIMENT

Experiments were carried out in a modified Nextral reactive ion etching (RIE) reactor with a 100-mm-diam rf electrode cooled by circulating thermostated fluid at 20 °C, separ...
rated by 33 mm from an 80-mm-diam counter electrode. The
two electrodes were situated in a 300-mm-diam 100-mm-
high grounded aluminium chamber fitted with three 80-mm-
diam fused silica windows. Pure argon was flowed at 30
scm via a mass flow controller through the reactor, which
was pumped by an oil diffusion pump via a throttle valve to
maintain a pressure of 50 mTorr inside the chamber. rf
power at 13.56 MHz was supplied via an
$\mathbf{L}$-type matching
network to the powered electrode. The electrical configura-
tion of the reactor is shown in Fig. 1, including the parasitic
capacitance between the powered electrode and ground,
$C_{\text{para}}$.

The plasma density was monitored by two different tech-
niques. The radial density distribution was estimated from
the ion saturation current to a cylindrical Langmuir probe,
which showed a broad maximum over the central 10 cm
(corresponding to the powered electrode) of the chamber. A
35 GHz microwave interferometer measured the electron
density integrated across the diameter of the chamber and an
effective length of 10 cm, determined from the probe data,
was used to obtain the absolute value of the electron density
with an uncertainty estimated to be less than 50%. A time
resolution of 1 $\mu$s was obtained by recording the sine and
cosine of the phase shift signals with a numerical oscillo-
scope.

The spatial and temporal dependence of the plasma in-
duced optical emission intensity was measured with an in-
tensified diode array optical multichannel analyzer (OMA)
placed behind the exit slit of a 60 cm focal length monochro-
mator. The center of plasma was imaged with a photographic
telescope onto the entrance slit of the monochromator with
the plasma axis parallel to the slit. The diode array of the
OMA was aligned parallel to the exit slit so the axial inten-
sity distribution was deduced from the signal on different
pixels. The signal from OMA was corrected for the relative
sensitivity of the different diodes, which varied by up to

III. RESULTS AND DISCUSSION

A. Low repetition rates

1. Overall behavior

The overall behavior of a 50 Hz repetition rate pulsed
plasma is shown in Fig. 2 for a 100 $\mu$s pulse, which is long
enough to allow the system to reach a steady state. The top
curve shows the maximum and minimum excursions of the rf
voltage on the driven electrode, $V_{\text{max}}$ and $V_{\text{min}}$, and their
average which is the bias voltage, $V_{\text{bias}}$. Under these condi-
tions the voltage envelope has a distinctive form which has
been named the “Bird’s Head”. This is characterized by a
period (lasting about 10 $\mu$s) during which $V_{\text{max}}$ has a large
positive value, before the dc bias becomes fully established.

The Ar (750 nm) optical emission intensity rises very

FIG. 1. The electrical configuration of the reactor, match box and generator.

FIG. 2. The measured maximum and minimum of the rf voltage and their
average (which is the bias voltage) for a 100 $\mu$s pulse at 50 Hz repetition
rate in a 100 W peak power 50 mTorr Ar plasma. Also shown are the
electron density (measured by the interferometer) and the Ar (750 nm) op-
tical emission intensity.
quickly, passing through a maximum at about 15 $\mu$s, where the electron density is about 1/10 of the steady state value. This can only be explained by a high electron temperature in this initial period, which is one of the most interesting phenomena occurring in pulsed plasmas. Although it is formally possible to measure directly the time dependence of the electron temperature using a Langmuir probe, sophisticated rf compensation techniques are needed in this type of plasma, and are difficult to implement in nonsteady-state situations.

The behavior of the plasma can be divided into various phases depending on the time, $t$, after the start of the application of rf power:

(i) rf voltage rise ($t=0$–2.9 $\mu$s),
(ii) Breakdown ($t=2.9$–3.5 $\mu$s),
(iii) Bias establishment ($t=3.5$–20 $\mu$s), and
(iv) Approach to steady state (20–100 $\mu$s).

2. rf voltage rise ($t=0$–2.9 $\mu$s)

In all experiments the match box was adjusted to give optimal matching for a continuous plasma. In the absence of plasma (i.e., with no gas in the reactor), the $LC$ circuit of the match-box and plasma chamber was resonant at a frequency slightly higher ($\approx 14.0$ MHz) than the operating frequency of 13.56 MHz, with a quality factor of about 5 on resonance. When the rf pulse from the generator was applied to the empty reactor, the voltage rise (1/e risetime of $\approx 2$ $\mu$s, fully established in 5 $\mu$s) was determined by the risetime of the rf generator. The maximum voltage reached (with 100 W nominally applied) was 400 V peak-to-peak (p-p), as the system was off-resonance without plasma present.

With 50 mTorr of argon present in the reactor, the rf voltage initially rises in the same way until breakdown occurs (at 2.9 $\mu$s), at which time the voltage drops momentarily due to the resistive load of the plasma. However, the voltage subsequently continues to increase, reaching a steady state value of 1200 V p-p. In effect, the presence of the plasma increases the capacitance of the chamber (due to the presence of sheaths), bringing the resonance frequency down to 13.56 MHz, so that the optimal overvoltage is achieved.

3. Breakdown and transition to a plasma ($t=2.9$–3.5 $\mu$s)

The period between pulses (20 ms) is long enough to allow the plasma density in the afterglow to decrease nearly to zero, but not to so low a value that the plasma would not re-ignite consistently. If the rf power is ‘‘off’’ for longer times ($\approx 100$ ms), all the electrons and ions will leave the chamber, and the plasma breakdown commences at a random interval after the rf pulse is applied: the plasma breakdown requires a random event (such as a cosmic ray or field emission effect) to produce the first electrons.

The electron kinetics during this period have been simulated with a particle-in-cell model, described elsewhere. During this initial period the fields in the inter-electrode gap are basically those characteristic of a capacitor. The electrons will attain an average energy (several 10’s of eV) determined...
by the applied voltage, the distance between the electrodes, and the pressure. As the mean free path for ionization at 50 mTorr (2 cm) is comparable to the inter-electrode distance (3.3 cm), a rapid avalanche breakdown occurs between the rf and grounded electrodes, and the electron density grows exponentially. When the Debye length, defined by

$$\lambda_D = \sqrt{\frac{e_n T_e}{en_e}},$$

(where $T_e$ is the electron temperature in eV and $n_e$ is the electron density) becomes smaller than the inter-electrode distance the effect of ions and electrons on the electric field becomes significant, and collective effects must be considered: a plasma has been established. This transition is seen in Fig. 4 by a clearly defined break in the rate of increase of the Ar emission intensity at about 600 ns after breakdown ($t = 3.5 \mu s$). Assuming an average electron energy of 20 eV, a plasma density of $10^7$ cm$^{-3}$ gives a Debye length of 1 cm, allowing a plasma to form between the electrodes with two sheaths.

4. Bias establishment ($t=3.5–20 \mu s$)

At this point the discharge becomes a symmetric plasma with a high average electron energy and low density. As there is as yet no dc bias, the rf voltage is equally divided between the two (identical) sheaths, and the average plasma potential is high, and strongly modulated at the rf frequency. The plasma is confined to the diameter of the powered electrode, which can be seen visually by operating with very short rf pulses ($<4 \mu s$). This situation occurs because the rf risetime ($\tau_{RF}=5 \mu s$) is shorter than the bias establishment time ($\tau_{bias}=15 \mu s$ under these conditions). The overall shape of the rf voltage on the powered electrode resembles a birds head with the beak defined by the breakdown “glitch.” As the bias voltage increases, the positive excursion of the powered electrode voltage will decrease until the steady state value is reached, defined by the impedance division between the sheath on the powered electrode and the sheaths on the earthed electrode and the walls. During this period the plasma density is still far below, and the electron temperature is considerably above the steady state values.

In Fig. 5 the spatial distribution of the 750.4 line measured with the OMA for a pulse frequency of 50 Hz and an “on time” of 25 $\mu s$, is shown. Note that the times given are relative to the start of the breakdown (i.e., $t = 2.9 \mu s$). At the very beginning (the lower two curves, less than 1.5 $\mu s$ after breakdown) the distribution of the light emission shows a broad maximum at the center of the plasma, with two identical width sheaths. At about 2 $\mu s$ after breakdown, biasing starts and the maximum of the light emission shifts towards the powered electrode. The light emission in the steady state is similar to the last (2.8–3.3 $\mu s$) curve. In this case the majority of the power deposition occurs at the edge of the powered electrode sheath, where the most bright emission occurs. The results demonstrate that a transition occurs from a symmetric to an asymmetric discharge, and that this transition is associated with the start of dc biasing. On short time scales (less than 1 $\mu s$ after breakdown) it should be possible to create a discharge with a very high electron temperature which exists for a period too short for the ions (with high inertia) to be accelerated to the maximum energy given by the plasma potential. Under these circumstances, the injected rf power is absorbed only by the electrons and is dissipated mainly by inelastic electron neutral collisions (and not in accelerating the ions to the walls).

Although the risetime of the rf voltage is mostly defined by the electrical system and can be measured simply, the process by which the blocking capacitor charges (which defines the bias voltage) is not evident. At first glance, it would seem that the blocking capacitor would charge very quickly as the electrons in the plasma are highly mobile and will flow rapidly to the powered electrode in the positive part of the cycle. The bias would then be established as soon as enough electrons are created to charge the blocking capacitor. This number is given by

$$n_{bias} = \frac{C_{bias} V_{RF}}{e},$$

where $C_{bias}$ is an effective value, including $C_{tune}$ and any parasitic capacitance, $C_{para}$ between the powered electrode and ground, which can be comparable to the value of the capacitor in the match box. In this case we measured (using an LCR meter) $C_{bias}=400$ pF, of which about half was parasitic capacitance. With a maximum applied voltage amplitude of $V_{RF}=600$ V, $n_{bias}=1.5 \times 10^{12}$ electrons. However, the flow of electrons out of the plasma causes the plasma potential to rise rapidly, which then reduces the charging rate: electroneutrality of the plasma must be conserved. To understand the mechanisms that control the flow of electrons to the powered electrode we must look in greater detail at the behavior of the plasma potential. In a symmetric plasma (i.e., one in contact with equal areas of grounded and rf powered surfaces), both sheaths are identical and no dc biasing occurs. The amplitude, $V_p$, of the rf modulation of the plasma potential is one half of the applied rf amplitude, $V_{RF}$ and the time-averaged plasma potential, $V_p$, is equal to $(V_{RF}/2) + \Delta V$, where $\Delta V$ is a few times $T_e$. Thus each electrode in

---

FIG. 5. The time and space resolved Ar optical emission intensity for the same conditions as Fig. 3. The times given are relative to the start of breakdown i.e., after $t=2.9 \mu s$ in Figs. 1, 2, and 3.
voltage across the grounded sheath (displacement current is the same for the two sheaths, the rf capacitance of the grounded electrode sheath will increase as grounded area exceeds the powered electrode area. The plasma has started to expand, so that the effective current is therefore limited by the Bohm-criterion limited ion flux to ground, given by

\[ I = 0.6 A_g n_e v_{\text{Bohm}}^e, \]

where \( v_{\text{Bohm}} \) is the Bohm velocity,

\[ v_{\text{Bohm}} = \sqrt{\frac{e T_e}{m_i}}, \]

and \( A_g \) is the area of the grounded surface in contact with the plasma. As dc biasing is an inherently non-one-dimensional effect, there are radial and axial variations in the plasma density, and the “Bird’s head” phenomenon is accompanied by plasma expansion, it would seem difficult to define \( A_g \). However, as biasing starts as soon as asymmetry appears, and as the central (dense) plasma region will dominate the ion current, we can make the approximation \( A_g = A_p = 100 \text{ cm}^2 \), the area of the powered electrode. At \( t = 10 \mu\text{s} \), \( n_e = 5 \times 10^9 \text{ cm}^{-3} \), giving a charging current of 13 mA (assuming \( T_e = 3 \text{ eV} \)). The actual charging current can be determined from

\[ I = C_{\text{bias}} \frac{dV_{\text{bias}}}{dt}. \]

This gives, for the maximum charging rate (observed at \( t = 10 \mu\text{s} \), see Fig. 3) a current of 12 mA, or 0.12 mA cm\(^{-2} \), in excellent agreement with the simple calculation. As the dc bias is established, \( V_{\text{p}} \) will drop, until electrons can again escape to ground. The net currents will thus decrease towards zero as the steady state bias condition is approached at \( t = 20 \mu\text{s} \). The exact modelling of this fall-off region is beyond the scope of this article, and is discussed in detail elsewhere. \(^1^2\)

5. Approach to equilibrium (20–100 \( \mu\text{s} \))

The subsequent evolution of the plasma is characterized by a steady increase of the density to a stable state at \( \sim 100 \mu\text{s} \), where the ionization rate balances the loss rate. The intensity of the 750.4 nm line, which initially increases much more rapidly than the density, goes through a maximum at about 15 \( \mu\text{s} \) and then decreases slightly, as the steady state is approached.

B. High repetition rates

The situation is considerably different when the period between pulses is short enough that the afterglow plasma density has not had time to decrease significantly between pulses, but long enough for the dc bias to disappear and for the electron temperature to cool significantly. This is the case for Fig. 6, where the power off time was 25 \( \mu\text{s} \). The optical emission intensity shows no breakdown, but instead risen progressively as the electron temperature increases towards the steady state value. The maximum excursion of the powered electrode voltage, \( V_{\text{max}} \), does not pass through a maximum, but also increases steadily towards the steady state value of a few 10’s of volts. Each pulse starts with an initial plasma density sufficiently high that a plasma sheath is immediately formed on the powered electrode, thereby shielding the plasma from large rf fields and preventing rapid electron heating. The electrons are only heated progressively by mechanisms such as collisions with the moving sheath, internal plasma fields due to electron inertia, secondary electron emission from the powered electrode, and ohmic heating.

---

FIG. 6. The powered electrode voltage, electron density, and argon emission intensity for a 20 kHz pulsed discharge (25 \( \mu\text{s} \) on/off) in 50 mTorr Ar, 100 W peak power.

C. Conditions for the existence of a symmetric plasma

The bird’s head will be formed if the rf voltage risetime is fast compared to the bias establishment time

$$\tau_{RF} < \tau_{bias}.$$  \hspace{1cm} (6)

The bias establishment time can be estimated from Eqs. (2) and (3) (assuming constant $n_e$ and $T_e$) to give

$$\tau_{bias} = \frac{C_{bias}V_{RF}}{0.6A_g n_e V_{Bohm}^6}.$$  \hspace{1cm} (7)

This allows us to estimate the initial plasma density above which the “bird’s head” will not appear. As the afterglow plasma fills much more of the reactor, the effective value of $A_g$ is much bigger than above: the surface area of the whole reactor is about 2000 cm$^2$. In our case $\tau_{RF} = 5$ $\mu$s, so the Bird’s head will not appear unless the plasma density present at the beginning of the pulse is less than $\sim 10^9$ cm$^{-3}$ (assuming $T_e = 3$ eV; although the electron temperature in the afterglow is very low, as soon as the rf power is applied it will quickly approach the steady state value). This corresponds to plasma off times longer than a few 100 $\mu$s. In Fig. 6 the density at the start of the pulse is $\sim 10^{10}$ cm$^{-3}$, and no Bird’s head is observed. In fact, when there is a plasma already present, the rf voltage risetime becomes somewhat slower, as this introduces resistance into the resonant circuit; from Fig. 6, we observe $\tau_{RF} \approx 8$ $\mu$s.

D. Global model for the electron density and temperature ($t = 3.5$–$100$ $\mu$s)

Several studies$^8,9$ have used simple global modeling of the electron temperature and density variations for pulsed inductive discharges. These models assume a Maxwellian electron energy distribution, ignore spatial variations in $T_e$ and $n_e$ and solve the differential equations concerning the power and particle balance for the electrons. In an inductive plasma the applied power is only absorbed by the electrons, and reasonable agreement with the experimental observations has been obtained by assuming constant power absorption throughout the approach to equilibrium. We have applied the same approach to a pulsed capacitive rf discharge, but with the following modifications:

1. The bulk electrons absorb power due to stochastic heating, which depends on $T_e$ and on the applied rf voltage.
2. In addition to ionization by the bulk (Maxwellian) electrons, there is ionization by a beam of secondary electrons emitted from the powered electrode. Evidence for the presence of these high energy electrons has been obtained from gridded electron energy analyzer measurements.$^{13,14}$ In order to keep the model simple, these electrons are assumed not to contribute any power to heating the bulk electrons.
3. Large rf power is dissipated in accelerating ions across the sheaths, which have much bigger voltage drops when rf voltages are applied; due to their larger inertia (compared to electrons), they are only affected by the time-averaged electric fields, defined by the dc bias of the sheath. However, this phenomenon can be treated separately from the electron power balance, as the power transfer between the two species is negligible.

For the sake of simplicity, the model assumes constant plasma volume and sheath area although, as we have seen above, this is not strictly accurate for the early stages of an asymmetric capacitive discharge.

1. Electron power balance

The electron power balance is given by

$$P_{el} = P_{sheath} + P_{ionization} + P_{excitation} + e n_e V \frac{dT_e}{dt},$$  \hspace{1cm} (8)

where $V$ is the plasma volume and

$$P_{sheath} = 2 \pi e \Phi_{Bohm} (\Delta V + 2 T_e)$$  \hspace{1cm} (9)

is the power expended by energetic electrons escaping across the two sheaths of area $A_s$ and striking the walls with an average kinetic energy of $2T_e$. The electron flux is equal to the Bohm criterion limited ion flux to conserve electroneutrality, given by

$$\Phi_{Bohm} = 0.6 n_e V_{Bohm}.$$  \hspace{1cm} (10)

The parameter $e \Delta V$ is the average energy expended by the electrons in crossing the sheath. For a dc sheath this is simply equal to the plasma potential, $V_p$, given by

$$V_p = \frac{T_e}{2} \ln \left( \frac{m_i}{2 \pi n_e m_e} \right),$$  \hspace{1cm} (11)

where $m_i$ and $m_e$ are the masses of the ions and electrons, respectively. For Ar, this can be simplified to $V_p \approx 4.7T_e$. For an rf sheath the situation is more complicated; in fact, $\Delta V$ for an rf sheath is somewhat less than for a dc sheath, as electrons only escape at the instant when the potential difference between the plasma and the electrode is at the minimum.$^{15}$ However, for the sake of simplicity, we have used the dc sheath formula. During bias charging, electrons only escape across one sheath, but the flux is correspondingly higher by a factor of 2, so this formula is still appropriate. The power dissipated in ionizing $e$-Ar collisions was approximated by

$$P_{ionization} = V n_e n_{Ar} e E k_{ion} \sqrt{T_e} \exp(-E_i/T_e).$$  \hspace{1cm} (12)

The value of $k_{ion}$ was obtained from the best fit to the data for the variation of ionization rate with electron temperature given in Ref. 16. The power dissipated in $e$-Ar collisions leading to Ar excitation was approximated by

$$P_{excitation} = V n_e n_{Ar} e E k_{ex} \exp(-E_{ex}/T_e).$$  \hspace{1cm} (13)

Again, the value of $k_{ex}$ was obtained by fitting to the data of Ref. 16. Note that the term $\sqrt{T_e}$ was omitted here, simply because this functional form gave a better fit to the excitation rate over the $T_e$ range of interest. The principal mechanism leading to power absorption by electrons in capacitively coupled discharges is the so-called “stochastic heating” effect at the rf sheath edge. Simple treatments for the collision-free$^{17}$ and collisional$^{18}$ cases indicate that the power absorbed is independent of the plasma density, is linear in
the applied rf voltage, and depends only weakly \((\sqrt{T_e})\) on the electron temperature. We have thus used the functional form

\[ P_{el} = A k_{stoc} \sqrt{T_e} V_{RF}. \]  

(14)

Lieberman and Lichtenberg\(^{16}\) give an expression for \(k_{stoc}\) which, for a frequency of 13.56 MHz and in the collisional sheath limit, gives \(k_{stoc} = 0.095 \text{ W m}^{-2} \text{ eV}^{-1/2}\). However, the experimentally observed steady state plasma densities could only be reproduced by using a value larger by a factor of 5. A reasonable fit to the experimentally observed time behavior of the rf voltage was given by

\[ V_{RF}(t) = V_{RF}[1 - 0.75 \exp(-t/\tau_{RF})], \]  

(15)

where \(t\) is the time after breakdown.

2. Electron particle balance

The electron particle balance is described by

\[ V_d n_e/\text{dt} = V I_{\text{bulk}} \mp A I_{\text{beam}} - 2 A \Phi_{\text{Bohm}}, \]

(16)

where

\[ I_{\text{bulk}} = n_e n_{Ar} k_{\text{ion}} \sqrt{T_e} \exp(-E_i/T_e), \]  

(17)

and

\[ I_{\text{beam}} = \gamma Y \Phi_{\text{Bohm}}, \]  

(18)

where \(Y\) is the number of ionizations each secondary electron makes before reaching the reactor wall, and \(\gamma\) is the ion-induced secondary electron emission coefficient. The relatively large value of \(\gamma (=0.2)\) used is nevertheless comparable to recent measurements\(^{19}\) performed on oxidized aluminum surfaces. The effective value may also be increased due to photon-induced electron emission, as there is intense UV photon emission by the plasma (accounting for most of \(P_{\text{excitation}}\), which amounts to several watts). The value of \(Y\) must take into account the effect of \(e\)-Ar elastic collisions, which greatly increase the effective path length of the electrons through the gas. As the mean free path \((= \frac{1}{\sqrt{n_{Ar} \sigma_{el}}} \approx 3 \text{ mm})\) is small compared to the reactor dimensions, we can treat this as a one-dimensional diffusion problem. A flux of secondary electrons leaves the powered electrode, and diffuses towards the counter-electrode where they are lost. The average time, \(t_e\), the electrons take to cross the reactor is

\[ t_e = \frac{L^2}{2D_e} = \frac{3L^2 n_{Ar} \sigma_{el}}{2v_e}, \]  

(19)

where \(D_e\) and \(v_e\) are the effective diffusion coefficient and the velocity of the electron, respectively, and \(L\) is the electrode spacing. The effective distance traveled through the gas, \(L_{\text{eff}}\), is simply \(t_e v_e\), the electron yield \(Y\) is then \(L_{\text{eff}} \sigma_{el} n_{Ar} \), giving

\[ Y = \frac{2n_{Ar} \sigma_{el} \sigma_{ion} L^2}{\gamma^2 n_{Ar} \sigma_{el}}, \]  

(20)

which is independent of the electron energy (assuming that the cross sections are constant). Taking values of \(\sigma_{ion} = 4 \times 10^{-20} \text{ m}^2\) and \(\sigma_{el} = 7 \times 10^{-20} \text{ m}^2\) this gives \(Y = 8\). This simple treatment does not take into account the energy dependencies of the secondary electron emission coefficient, or of the yield, \(Y\). However, during the period where the secondary electron mechanism is important, the applied voltage changes from 300 to 600 eV, the electrons on average reach the other side having lost only \(8E_i = 130 \text{ eV}\), and the cross sections for ionization do not vary greatly over the range 150–600 eV. The model also assumes that the electrons created by beam ionization have zero kinetic energy, which is not strictly accurate.\(^{20}\)

3. Model results

The two differential equations were integrated numerically, taking initial conditions of \(n_e = 1 \times 10^5 \text{ cm}^{-3}\) and \(T_e = 10 \text{ eV}\) at \(t = 3 \mu\text{s}\), corresponding to the end of the breakdown and the start of the plasma phase. The parameters used in the model are given in Table I. The values of \(k_{stoc}\) and the product \(\gamma Y\) were adjusted to give good agreement with the experimentally observed steady state electron density and the density increase rate. The argon emission intensity variation was calculated from

\[ I_{Ar} n_e \exp(-E_i/T_e), \]  

(21)

Excitation by the secondary electron beam can be ignored as the cross section for the observed level drops rapidly after 50 eV. The results are shown in Fig. 7. The temporal variation of the argon emission intensity is in excellent agreement with the observations. In the first 10 \(\mu\text{s}\), while the electron temperature is high, the bulk (Maxwellian) electrons are responsible for the majority of the ionization. The high electron temperature leads to high argon excitation rates, even though the electron density is low. The electron density subsequently drops towards a steady state value of around 2 eV. This rather low value is a consequence of the dominance of ionization by the secondary electron beam: a high bulk electron temperature is not needed to ensure adequate ionization. This is in agreement with electron energy distribution measurements under similar conditions,\(^{13}\) which show two-temperature distributions with a rather cold bulk electron temperature.

4. Ion power balance

The nonlinearity of the powered electrode sheath rectifies the rf voltage, so that the blocking capacitor charges, approaching a steady state potential \(V_{\text{bias}}\) close to the value of the applied rf voltage amplitude, \(V_{RF}\), and a large sheath is formed around the powered electrode. Electrical power is
now also absorbed directly by ions as they are accelerated across this sheath, and this in fact dominates the total power absorption. This power is entirely dissipated in heating the electrode, and does not heat the electrons (except in accelerating secondary electrons). The ions do not respond to the time varying electric field, and arrive at the powered electrode with an energy of $e(\bar{V}_p + V_{bias})$, where $\bar{V}_p$ is the time-averaged value of the plasma potential. In the limit of a highly asymmetric reactor, the plasma potential is little modulated throughout the rf cycle, and $\bar{V}_p \approx 5T_e$ as before. The power absorbed by the ions in the powered electrode sheath (and dissipated in heating the powered electrode) is then given by

$$P_{ion} = 0.6A_p \nu_e eV_{Bohm}V_{bias},$$  

where $A_p$ is the area of the powered electrode. The power dissipated by the electrons is only a small fraction of the total power. Electrons flow to the grounded reactor walls as before, but also to the powered electrode, as the net current to this surface is also zero under steady state conditions. However, they only do so in short pulses when the electrode voltage is near it’s maximum. Now let us consider the steady state. Putting in approximate values for our system ($A_p = 100 \text{ cm}^2$, $n_e = 4 \times 10^{10} \text{ cm}^{-3}$, $T_e = 3 \text{ eV}$, $\nu_e = 15.5 \text{ eV}$, $V_{bias} \approx V_{RF} = 600 \text{ V}$), we obtain a value of $P_{ion} \approx 50 \text{ W}$. The value of $P_{ion}$ is about 8 W (although it is difficult to estimate the effective area of the grounded electrode, due to the inhomogeneous plasma distribution). This low value of the power compared to the input power measured on the front panel of the generator was puzzling, and so a simple test was conducted to see where the extra power was being dissipated. A continuous plasma was created with 100 W shown on the generator to produce 1200 V$_{pp}$ on the powered electrode. The gas flow was then turned off and the match box and generator power adjusted to produce, once again, 1200 V$_{pp}$ on the powered electrode, but this time for such a low gas pressure that no plasma was created. The measured power was about 2/3 of that measured with the plasma and we hence deduced that only about 1/3 of the input power was dissipated in creating the plasma, the rest being dissipated in heating the match box. Consequently only about 33 W was being absorbed by the plasma, in quite good agreement with the calculated value.

### IV. CONCLUSIONS

Experiments using pulsed rf power at 13.56 MHz were conducted in a capacitively coupled plasma reactor typical of single wafer systems used in industry. Results of the rf voltage on the powered electrode, the electron density, and the time and space resolved optical emission are presented for the breakdown phase lasting some 100’s of ns and for the transition to and eventual equilibrium of the plasma phase. A simple analytical model is developed for the electron temperature and is in qualitative agreement with the experiment. The model indicates the existence of high “temperature” electrons for the first few μs of the pulse, which are required to explain the experimental results. These high “temperature” electrons appear to be created during the breakdown phase of the discharge, before the Debye length has entered the inter-electrode gap and during the time when large electric fields can exist between the electrodes. Before the bias is established, the plasma is a symmetric discharge, and only becomes asymmetric on a time scale determined by the charging of the blocking or “tune” capacitor in the matching network. Surprisingly, this is limited by the diffusion of ions to the earthed surfaces of the reactor, and not by the diffusion of electrons to the powered electrode.