The application of the helicon source to plasma processing

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The results of a study of the mode transitions in the helicon source when used in the geometry required for plasma processing are presented. We find that the basic characteristics of high density ($>5 \times 10^{11} \text{ cm}^{-3}$ in the processing chamber at 500 W) and low plasma potential ($\sim 15 \text{ V}$) are observed in this configuration. The mode transitions can be interpreted in terms of the dispersion relation for the helicon wave. A study of the initial plasma breakdown has also been made and the results have aided in the understanding of the operation of the helicon source during pulsed plasma etching.

I. INTRODUCTION

In the past decade the use of plasma processing in the semiconductor industry has spread enormously. From the early barrel reactors, major advances have been made leading to the single-wafer reactive ion etching (RIE) machines available today. The shortcomings of this current generation of machines have spurred research into alternative technologies for plasma processing. In particular, a new generation of low-pressure reactors operating at around $10^{-3}$ Torr has been developed. Important among these are the microwave discharges operating at 2.45 GHz such as the electron cyclotron resonance (ECR) and distributed electron cyclotron resonance (DECR) systems, and the high-density rf system, the helicon source. The low-pressure regime in which these machines operate greatly reduces the problems that result from charge exchange interactions in the sheath while the inductive nature of the plasma production enables high plasma densities to be achieved without attendant high plasma potentials.

In the plasma research laboratory we have worked, for the past 10 years, on the application of rf helicon sources to the production of high-density plasmas for space plasma research and plasma processing. In this paper we present results of recent experiments that lead to a greater understanding of how these sources operate and confirm the advantages that this plasma source conveys when applied to plasma processing.

The body of the paper is divided into four sections. In Sec. II we described briefly the helicon source and the two pieces of apparatus on which the experiments were conducted. In Sec. III we present the results of a study of the stable operating modes of the source and how their dependence on the power and magnetic field can be related to the dispersion relation for the helicon wave. The results of an investigation of the time evolution of the plasma breakdown are presented in Sec. IV. These aid in the understanding of the etching behavior observed in pulsed plasmas. Finally we present results of measurements of the plasma density distributions in etching plasmas using SF$_6$ and CHF$_3$ gases.

II. THE HELICON SOURCE

The helicon source has been described in detail in a number of earlier publications and but we will review its fundamental characteristics briefly because a knowledge of them is required in order to understand the experimental results that follow. The plasma source operates by coupling externally generated electric and magnetic fields into a plasma confined by an axial magnetic field. The system can operate over a wide range of frequencies and excellent results have been obtained from 2 to 70 MHz. The coupling mechanism is believed to be as follows. An antenna consisting of two loops diametrically placed on the outside of the source tube produces a transverse rf magnetic field perpendicular to both the tube axis and a constant axial magnetic field $B_z$. This rf field excites the $m=1$ azimuthal mode of a helicon wave in the source tube. Energy is transferred from this wave to the plasma electrons, most probably via the mechanism of Landau damping.

If we consider the dispersion relation for an electromagnetic wave in a magnetized plasma with $\omega_p$ in the range $\omega_c < \omega_p < \omega_m$ and neglect electron inertia we arrive at the following approximate expression for the wavelength of the helicon wave:

$$\lambda \approx 5 \times 10^3 (B_z/\omega_f)^{1/2}$$

The dispersion relationship imposes a constraint on density, magnetic field, and wavelength for optimal coupling. The consequences of this constraint are observed in the results of our experiments and we will return to this point in Sec. III. It is interesting to note that for an excitation frequency of 13.56 MHz the plasma refractive index is $\sim 100$, giving a plasma wavelength of about 22 cm, a convenient size for a reactor geometry.

The helicon wave can exist only when there is an axial magnetic field in the source region, although the source can operate with no $B_z$, via electrostatic coupling (Sec. III). The $B_z$ plays three roles:

1. A very weak $B_z$ restricts the radial motion of the electrons and requires them to follow the field lines away from the region close to the exciting antenna. This is most effective at low neutral density where electrons are not scattered to the wall by collisions.

2. At higher $B_z$ the ions can also be confined. The balance between the loss rate of the ions and the ionization rate defines the plasma density. In order to confine the ions, which are accelerated radially by the ambipolar field, the $B_z$ must be high enough to produce an average cyclotron diameter which is less than the tube radius. For ions in the bulk of
the plasma the low ambipolar field implies that for a tube diameter of ~15 cm we require a $B_z$ of ~100 G. Under these conditions plasma is lost from the source region via axial flow from the ends of the tube and collisional transport across the tube radius.

3) Excitation of the helicon wave can occur only in the presence of $B_z$.

The data presented in this paper were obtained on two experimental systems which utilize the helicon source. In a typical reactor the source is operated in the pressure range $10^{-4}$–$10^{-2}$ Torr and the plasma is allowed to diffuse from the source cylinder into a larger processing chamber. This diffusion is usually controlled either with extra solenoids or permanent magnets in a multipole configuration or a combination of both. The useful pressure range of the source is limited at the lower end by increasing electron temperature and plasma potential and at the upper end by the reduced collision length that prevents the plasma diffusing out of the source. Both systems used in these experiments comprise a dielectric source tube from which the plasma diffuses into a larger chamber. One reactor was designed specifically for plasma etching and has a source 15 cm in diameter, 22 cm long, attached to a 30-cm-diam chamber 30 cm in length. A schematic of this system is shown in Fig. 1. The other, slightly larger, system is used for studies of the physics of the source and plasma diffusion and has a 20-cm-diam source tube 50 cm long on an 80-cm-diam chamber, 50 cm in length.

In the etching reactor the ion density, plasma potential, and electron temperature were determined from analysis of Langmuir probe traces obtained from a single stainless-steel probe positioned in the etching chamber 3 cm below the exit of the source. A computer-based data-acquisition system was used to acquire and analyze the data. In addition, a high-voltage probe was used to monitor the voltage on the antenna so that the $Q$ of the antenna/tuning circuit could be calculated. In the larger system, a retarding field energy analyzer (RFEA) was used to obtain a more accurate determination of the plasma potential and the energy distributions of the ions and electrons.

III. RESONANT BEHAVIOR OF THE HELICON SOURCE

In earlier papers we have presented experimental evidence that supports our model of the wave excitation mechanism. Those data were obtained on "ideal" sources which had uniform $B_z$ and diameter over several wavelengths. The plasma processing machines have source lengths roughly equal to the helicon wavelength, but in spite of these recent experiments on these machines have confirmed that the desirable characteristics of the helicon source are also obtained in this processing configuration.

For plasma processing it is desirable to produce a high, uniform plasma density, e.g., for rapid etching of SiO$_2$, and profile control, but to have a low plasma potential so as to be able to control the energy of the ions incident on the semiconductor material. Here we present the results of a series of measurements of how these two important parameters vary as a function of the input power and magnetic field in the source.

At low power and low $B_z$, the plasma sources operate in a mode that resembles an electrostatic discharge. In Fig. 2 we show the voltage on the antenna as a function of power in this low-density mode. The antenna voltage scales approxi-

![Fig. 1. A diagram of the major components of the etching machine with 15-cm source tube. The solenoids around the processing chamber produced an additional axial magnetic field to confine the plasma. Experiments were also carried out with multipole confinement from permanent magnets around the processing chamber.](image1)

![Fig. 2. Overvoltage on the antenna as a function of the power in the low-density mode of operation of the source. The upper curve is from the 20-cm source and the lower curve is for the 15-cm source in argon at 1.5 mT.](image2)
mately as \sqrt{P}. Included in this figure are results from the 15-
cm source which show similar behavior.

This mode is of little interest for the application of the
source to etching since it produces a low density plasma with
a relatively high plasma potential. For some processing ap-
lications the mode can be used at high pressure and with no
B_y in order to operate the system in a downstream processing
mode.

As the power is increased further a major change occurs in
the plasma. The density increases abruptly—the first
jump—and the plasma potential and antenna voltage de-
crease. This change is clearly illustrated in Fig. 3 for an
argon pressure of 1.3 mT and B_y = 110 G in the plasma
etching machine. In this case the density increases tenfold
and the plasma potential decreases from 28 to 15 V.

In these experiments the plasma potential was assumed to
be at the maximum in the dI/dV curve for the probe.

Although the data in Fig. 3 were taken using a dc probe in
the presence of rf modulation, the important trend that they
show for V_y is still valid because the level of modulation is
small and the effect of the averaging of this rf component is
to lower the measured V_y when the rf modulation is large.
Therefore, the effect of any modulation would be to reduce
the change in V_y that is observed in the data.

The decrease in antenna voltage indicates that the dissipa-
tion in the antenna/tuning circuit has increased, hence the Q
of the circuit decreases. This is illustrated in Fig. 4, which
shows the Q factor of the tuning circuit just before and just
after the density jump for a range of magnetic fields.

There is no significant change in the electron temperature
which remains low at \sim 4 eV. We do not place too much
weight on electron temperatures derived from Langmuir
probe curves in magnetized plasmas but the magnitude of
the temperature is in agreement with a large number of mea-
surements made previously using Bernstein interferome-
try.\footnote{This post-jump plasma is much better suited to plasma
processing where ion bombardment plays an important role.
The density is high for modest input powers while the plas-
a potential is low and insensitive to the power. This is the
characteristic of this source that allows one to control the ion
current (proportional to the plasma density) independently
of the ion energy to the substrate immersed in the plasma.
In addition, the antenna voltage is low so that the risk of sputter
erosion of the source is reduced.

Absolute measurements of the plasma density produced

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.eps}
\caption{Antenna/tuning circuit Q just before (upper curve) and just after
the density jump (Fig. 3) as a function of the magnetic field in the etching
machine at 1.5 mT of argon. These data show that the Q is low and roughly
independent of the field.}
\end{figure}
by the 15-cm source were also made using a 36-GHz micro-
wave interferometer. The interferometer viewed the plasma in the processing chamber 15 cm from the exit of the source. The plasma in this region was confined using the chamber solenoids shown in Fig. 1. These data (Fig. 5) show that at higher powers further jumps occur. This is puzzling since for fixed $B$, the dispersion relation implies a fixed $n$ for optimum coupling assuming the wavelength remains constant.

We think that now the stable modes result from the geometry of the system. The antenna does not tightly impose the wavelength of the helicon wave in the plasma but can excite a range of wavelengths. The jumps observed in Fig. 5 are roughly consistent with the wavelength fitting into the source or the whole machine. We can see from the data in Fig. 5 that the overall trend for $n$ is to scale linearly with the input power. As the power is increased at a given resonance the plasma is again pushed away from its optimum wave-
length condition; $n$ scales more slowly with power and $V_p$ increases. Eventually, however, the power input to the plas-
ma is high enough for it to reach a new resonant configuration, there is a jump in $n$ and a decrease in $V_p$. At each jump the wavelength decreases. It is important to note that the plasma also resists moving away from a resonance point as the power is decreased. This leads to hysteresis around the transition power. Similar behavior has been observed in a large-volume space plasma machine.

The mode structure for a given configuration of antenna, source, and chamber is fixed so that once the structure has been mapped a stable operating condition suitable for plasma processing can be found easily. We can obtain reproducibly a high-density plasma with a low plasma potential.

The evolution of the plasma density as the axial $B$ field is increased for a constant input power has already been pre-
sented by Boswell. This data is reproduced in Fig. 6 for argon in a 10-cm source. These jumps are associated with changes in the wavelength bringing the dispersion back to that defined by the wavelength imposed by the antenna (dashed line).

We know that the dispersion relation imposes a constraint on $B$, $n$, and $f$ for a given wavelength. In this source we have a fixed frequency, the antenna imposes a wavelength, and we are changing $B$. However, as noted earlier, the wavelength is not strictly imposed.

To follow the dispersion relation with a varying $B$ field the density must change linearly but this implies a change in the energy deposition in the plasma since $V_p$ must also change. Since $n$ is not totally free to change, the plasma is pushed away from the ideal resonance. The change in $B$ changes the density profile which changes the wave energy deposition. Eventually the plasma finds a new stable mode again at the optimum wavelength. Since the input power is constant, the increased density at this new operating point on the dispersion curve must be a mode with lower $V_p$. It is obvious that this process cannot continue without limit at a fixed power where $n$ must decrease with further increase in $B$. This can be viewed as a return to the low-power mode where $n$ is low and $V_p$ is high. This effect is illustrated by the data plotted in Fig. 7.
IV. THE PLASMA BREAKDOWN

In addition to continuous plasmas we are also very interested in pulsed plasmas. Pulsing a process plasma can be used to change dissociation characteristics, control the ion/neutrual influx ratio, control selectivity, etc. The question that arises when using a pulsed plasma is, how does it breakdown?

A series of experiments have been conducted to investigate the plasma breakdown using a retarding field energy analyzer, which gives a good estimate of $V_p$ for low-density plasmas. The experiments were conducted in low-$B$, low-$n$, mode to avoid complications of mode changes. The data were collected at a power of 250 W in argon at 0.5 mTorr. The magnetic field was 35 G and the source diameter 20 cm.

At breakdown we have initially a high plasma potential associated with a high ion energy and low density. The density rises rapidly and the plasma potential decreases. This evolution is shown graphically in the time dependent ion characteristic of the energy analyzer (Fig. 8). Here the plasma electrons are excluded by a negative bias on a repeller grid and the ion energy distribution is determined by varying the bias on a discrimination grid.

If all the ions had the same energy then the current collected would decrease suddenly when the bias reaches that energy. The data shown in Fig. 8 were acquired over a large number of pulses with the discriminator bias changed from pulse to pulse. The behavior of the source is so reproducible that it is possible to build up the entire characteristic from these individual traces.

At the beginning of the pulse two trends are evident. The maximum energy of the ions is decreasing and the ion current at low discriminator bias increases, implying an increase in density. The maximum ion energy corresponds to the maximum potential in the source and is initially $> 100$ V. The potential drops rapidly as the ionization and loss rates from the plasma in the source are equalized.

The evolution of the electron current to the analyzer shows a structure similar to that of the ion current. It is shown for two fixed discriminator voltages in Fig. 9. The electron current rises rapidly at the beginning of the pulse and then reaches a roughly constant plateau. The current obtained at a higher discriminator bias shows that there is an initial high energy of spike electrons.

What is happening at this early stage of the breakdown? At first we apply rf with no plasma and no antenna loading and consequently have a high $Q$ and high antenna voltages. In the source there is an axial magnetic field which restricts the electrons to axial motion but there is also an axial component of the electric field which is set up between the antenna and the end cap of the source. This field can produce fast electrons and the rapid charge buildup also suggests that secondary electron production could also be important, perhaps leading to a multipactor-type effect in the early stages of the breakdown. The high-energy electrons lead to rapid ionization of the neutral gas in the source region, and some of them escape from the source and are observed at the end of the diffusion region as the sharp spike in the current early in the breakdown.

The loss of these energetic electrons produces a rapid increase in the plasma potential which reduces further loss of electrons and increases the ionization rate. The plasma potential cannot start to decrease until ions begin to escape from the source since ionization produces no change in the charge balance. The time scale for an ion to be lost radially is of the order of 10 $\mu$s.

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Fig. 8. Time-dependent ion characteristic from the retarding field energy analyzer for the plasma breakdown. This demonstrates the rapid decay of the high initial plasma potential.

Fig. 9. Electron characteristic for two different electron energies during the plasma breakdown. (a) Bias of 0 V, (b) bias of $\ldots 20$ V. The early spike of high-energy electrons is clear in the current distribution for high discriminator bias.

Using the RFEA we have made measurements of the electron energy distribution both for the steady-state plasma and when the spike is observed. These data are plotted in Fig. 10. In the steady state we observe a distribution that is consistent with a Maxwellian of roughly 9 eV. The rounding off evident at low energy results from a grid effect.  

The distribution during the occurrence of the spike is much noisier but we can see that 5% of the electrons have energies in excess of 500 eV and there are electrons with energies in excess of 1500 eV, which is about the peak rf voltage on the antenna.

As the plasma potential falls from its initial high value the average electron energy begins to fall since the fast electrons in the tail of the distribution are no longer confined. In addition, the antenna voltage decreases as the loading—resulting from the increased density—begins to increase. This reduces the fields in the source so that electrons are not accelerated to such high energies.

As noted earlier these data were obtained from pulses which were well separated. If the delay between pulses is reduced to be comparable to the decay time of the plasma then the initial spike is greatly reduced. It is therefore possible to choose an average electron energy and modify the dissociation by choosing the repetition rate of the pulsing.

For plasma etching there are two time scales involved, that of the ions and that of the active chemical species. By adjusting the duty cycle of the pulses it is possible to change the ratio of ion bombardment to the rate of arrival of the etching species on the substrate. This facilitates control over the etch profile, when etching silicon, for example.

V. APPLICATION TO ETCHING

To use this source in plasma processing a uniform high-density plasma must be produced over a large area. The simplest method for producing a uniform plasma, with the helicon source, over the diameters currently required by the semiconductor industry (<200 mm) is to surround the processing chamber with permanent magnets in a multipole configuration. This produces a very uniform plasma density as can be seen from the data in Fig. 11 for SF$_6$ and Fig. 12 for CHF$_3$.

There are two drawbacks with this technique. The first is that higher input powers to the source must be used to achieve high plasma density. The second is that the maxi-

**Fig. 11.** Saturation ion current density as a function of the radius in an SF$_6$ plasma confined using a multipole cage in the chamber. Pressure is 0.5 mT with input powers of 500 W (lower curve) and 1000 W.

**Fig. 12.** Saturation ion current density distribution in a CHF$_3$ plasma with multipole confinement. Pressure is 0.5 mT with input powers of 500 W (lower curve) and 1000 W.
maximum pressure at which good uniformity is achieved is low
(<5 x 10^{-3} \text{Torr}) because the plasma must diffuse a long
way from the source exit before it is affected by the cusp field
from the multipole.

One problem that can occur in systems such as these, in
which there is a decrease in density from the source to
the substrate in a rapidly decreasing (expanding) magnetic field
is that the self-consistent Boltzmann potential that is set up
can accelerate ions onto the substrate. As noted earlier, the
source in our processing reactors is typically 15 cm in diame-
ter and is coupled to a processing chamber < 30 cm in diam-
eter. The reduction in density that occurs as the plasma ex-
spands into the processing chamber is <4. From the
Boltzmann relation
\[ n = n_i \exp(eV/kT), \]
we would therefore expect a potential gradient of roughly
1.4kT, and since kT is 3-4 eV in these systems we expect an
accelerating potential of less that 5 V. In addition, the end
cap at the top of the source is an earthed conductor that
provides a ground reference for the plasma. This greatly re-
duces the sensitivity of the plasma potential to the bias on
the substrate at the bottom of the processing chamber.

When etching materials such as SiO\textsubscript{2}, which do not etch
spontaneously, a high ion density is necessary to produce a
high etch rate. For this reason we have also conducted ex-
periments in which solenoidal confinement was used in the
chamber. With this field configuration the diffusion of the
plasma from the source is controlled by the axial magnetic
field in the processing chamber, hence when the field
strengths in the source and chamber are comparable the ra-
dial density distribution in the source is mapped onto the
substrate in the processing chamber. A radial profile of the
ion current density in CHF\textsubscript{3}, obtained with this form of con-
finement is shown in Fig. 13. It is important not to rely solely
on radial density distribution measurements when judging
the performance of a processing reactor since the actual etch
process is a complex sputter-enhanced chemical reaction. In
Fig. 14 is shown the results of measurements of the etch rate
of SiO\textsubscript{2} [plasma enhanced chemical vapor deposition
(PECVD)] in a strongly confined plasma. The etch is rea-
sonably uniform to a radius of 65 mm and this performance
could easily be improved by increasing the size of the source.
The etch rate can simply be increased by increasing the plas-
ma density.

VI. CONCLUSIONS

Our research into the helicon source and its applications
has continued to confirm its advantages for the production
of high-density plasmas for plasma research and plasma pro-
cessing. In this paper we have presented results of funda-
mental studies of the performance of the source when it is
used in a complete plasma etching system. These studies
were made using argon as a working gas because of the diffi-
culties involved in the interpretation of data from electro-
static probes and microwave interferometry in the electro-
negative plasmas produced with the etch gases SF\textsubscript{6} and
CHF\textsubscript{3}. It should be noted, however, that the plasmas pro-
duced with the electronegative etching gases exhibit mode
behavior similar to that observed in argon.

These studies of how the plasma breaks down during
pulsed operation and the behavior of the density jumps have
provided a greater understanding of the mechanisms by
which the plasma is produced and maintained in the source.

Using the source and allowing the plasma to diffuse into a
processing chamber with multipole confinement we have
produced high-density plasmas in SF\textsubscript{6} and CHF\textsubscript{3} uniform
over 200-mm diameters.

There is a great deal of interesting physics still to be
gleaned from studies of the source and the optimization of
the diffusion plasmas used in plasma processing machines.

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