Ion impact etch anisotropy downstream from diffusion plasma sources

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Plasma processing in chambers located downstream from a source are gaining widespread use because they allow etching and deposition with minimal damage. This minimized damage, however, is achieved by using a low ion impact energy, which can lead to a poorer etch anisotropy. The best anisotropy for a given impact energy requires the lowest possible ion temperature. Laser-induced fluorescence measurements show that room temperature ions can be attained using a multidipole-confined discharge. In comparison, ion temperatures downstream from electron cyclotron resonance sources are much hotter, according to recent reports.

One aim of plasma processing research is the development of systems offering anisotropic etching with reduced surface damage. So-called diffusion plasma sources, which are decoupled from the substrate, provide independent control of ion energy and flux to the substrate. This control can be used to minimize surface damage or maximize etch anisotropy.

Two such plasmas are multidipole-confined and electron cyclotron resonance (ECR) discharges. They can be used as plasma sources for substrate etching and deposition.[1-8] Typically, they are configured with a source chamber that produces a plasma that flows downstream to a substrate. They provide what is desired in the fabrication of microelectronic circuits: good anisotropy, high etch rates, and little substrate damage.[1,5] In this letter, we compare our recent measurements of ion temperatures downstream of a multidipole source[9] to those made downstream of ECR sources.[1-3] These temperatures can be used to predict the expected etch anisotropy.

The etch anisotropy is limited by the distribution of ion impact angles at the substrate.[1] The impact angle is determined by the ion velocities perpendicular and parallel to the substrate normal, $v_\perp$ and $v_\parallel$. In a plasma there is a distribution of ion velocities, and thus a distribution of impact angles. The latter distribution can be characterized by a thermal impact angle θ

$$\tan\theta = \frac{v_\perp}{v_\parallel} \approx \sqrt{\frac{T_{i\perp}}{e\Delta\Phi_p}} . \tag{1}$$

Here e is the electron charge, $\Delta\Phi_p$ is the potential between the source and the substrate, and $T_{i\perp}$ is the ion temperature transverse to the substrate normal. For the best etch anisotropy, a small thermal impact angle θ is desired. A direct current (dc) or radio frequency (rf) substrate bias may be used to increase $\Delta\Phi_p$, and thus reduce θ. However, increasing $\Delta\Phi_p$ raises the ion impact energy, resulting in more substrate damage.[10] Equation (1) quantifies this trade-off between anisotropy and damage.

By using a discharge with a lower $T_{i\perp}$, etch anisotropy can be improved without increasing substrate damage. The coldest $T_{i\perp}$ that one might hope for is the temperature of the vacuum surfaces. This is because the ions are are produced from neutral gas atoms, which are in thermal contact with the chamber walls. There are several mechanisms that can lead to ions hotter than the surfaces, but none that can make them colder. Thus, the vacuum surface temperature is a lower limit on the ion temperature that can be attained. This means that there is an ideal ion temperature—the temperature of the surfaces. In this paper, we demonstrate that this ideal limit can be achieved in a downstream plasma configuration.

Laser-induced fluorescence (LIF) offers a nonintrusive and spatially resolved measurement of $T_{i\perp}$. Because of Doppler broadening, the spectral line shapes of the ions correspond to the shape of the ion velocity distribution.[1-3,9] The spectral line shape is measured by scanning the frequency of a narrow band tunable laser through the line while a photomultiplier tube is used to collect the resulting fluorescence. The ion temperature is computed[3] from the width of these lines, correcting[2] for the laser bandwidth. When the laser is directed transverse to the substrate surface,[9] the line width yields a measurement of $T_{i\perp}$.

We have reported LIF measurements downstream of a multidipole source in an argon plasma.[9] A sketch of our chamber is shown in Fig. 1. It consisted of a plasma source chamber and a larger downstream chamber, aligned along a common axis. These chambers were water cooled and maintained at room temperature, $T = 0.025$ eV. A grounded grid separated the chambers. A laser beam from a 400-MHz-bandwidth tunable dye laser was directed through the lower chamber to measure the transverse ion temperature there. Hot tungsten filaments were used to produce the plasma. Of course, one would not want to use hot filaments for semiconductor processing because of contamination. However, we found this system convenient for demonstrating that low ion temperatures are attainable with downstream configurations.

We found that $T_{i\perp} = 0.028 \pm 0.007$ eV, which is nearly room temperature. This was determined from the width of

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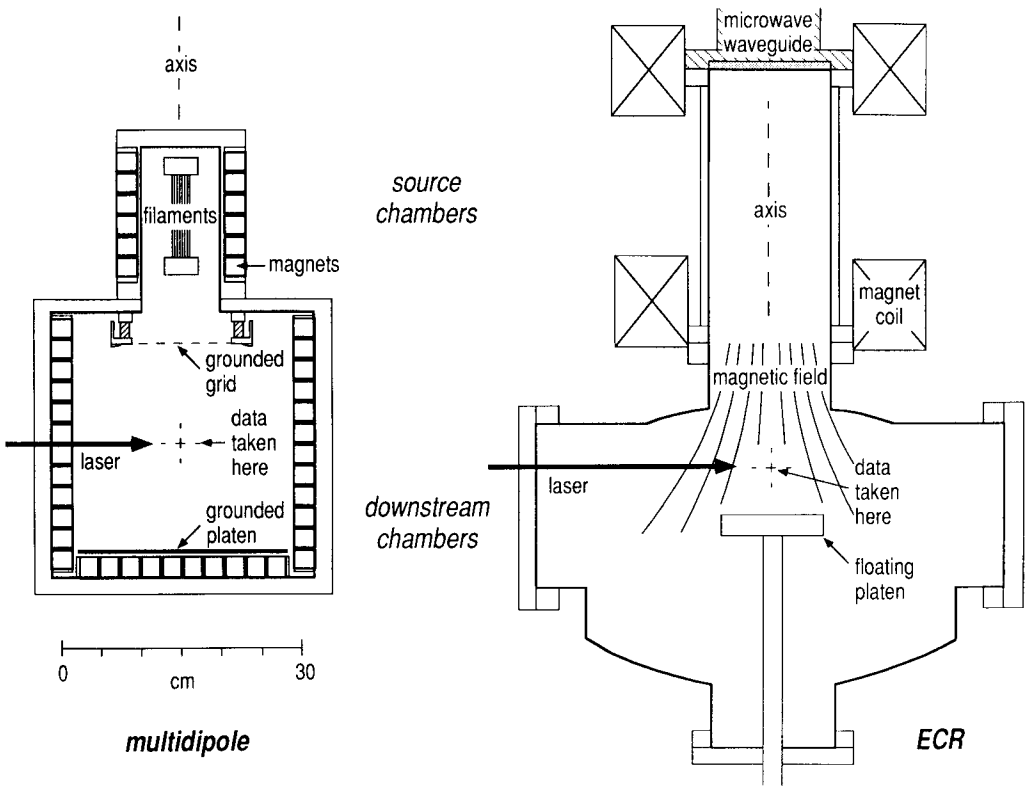

FIG. 1. Multidipole and ECR plasma chambers drawn to the same scale. Our multidipole system is shown on the left. On the right, we have copied a drawing of the ECR chamber used by Trevor *et al.* (Ref. 2). Both systems consisted of a plasma source chamber and a larger downstream chamber, aligned along a common axis. The laser beams originated from tunable dye lasers and were used to measure the ion temperature $T_{i\perp}$ transverse to the axis. For etching, substrates could be placed on the platens, although there were no substrates in any of the experiments compared here.

the LIF line shape, recorded by probing the 611.492 nm argon ion line. Typical data is shown in Fig. 2. This measurement was made on the axis of the downstream chamber, 25 cm from the source. Additional measurements show that this temperature was independent of the neutral pressure (varied from 0.002 to 0.170 Pa), the discharge current (0.12–6 A), and filament bias (20–80 V). Further details of our results, as well as detailed descriptions of the chamber and LIF apparatus, are presented in Ref. 9.

For ECR sources, $T_{i\perp}$ has been reported by Den Hartog *et al.*,[1] Trevor *et al.*,[2] and Nakano *et al.*[3] Those three experiments closely resemble our multidipole experiment, except that they used commercial ECR sources, without a multidipole field. They all used vacuum vessel configurations and LIF methods similar to ours. For example, in Fig. 1 we compare our setup to the chamber used by both Trevor *et al.*[2] and Nakano, *et al.*[3] In an argon discharge, Trevor *et al.*[2] found that $T_{i\perp} \leqslant 0.46$ eV at a neutral gas pressure of 0.046 Pa. In a nitrogen plasma, Den Hartog *et al.*[1] found that $T_{i\perp}$ ranged from 0.12 to 0.24 eV, for pressures from 0.069 to

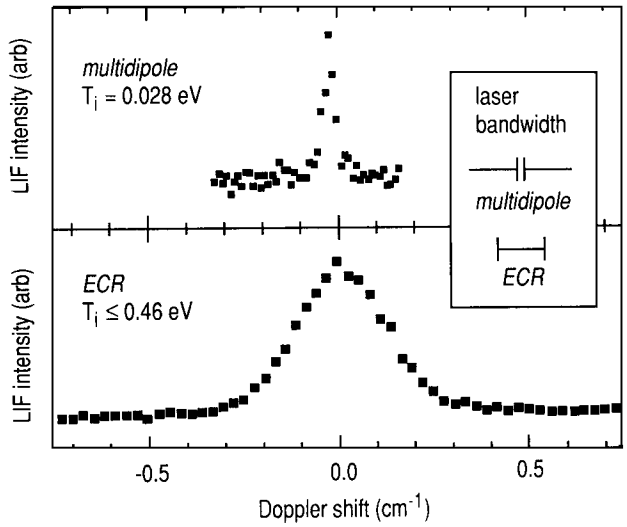

FIG. 2. Laser-induced fluorescence (LIF) line shapes, obtained experimentally. The upper curve is the line shape from our measurements in the multidipole discharge. The lower curve for the ECR discharge is reprinted from Trevor *et al.* (Ref. 2). Based on the linewidth, the transverse ion temperature is $T_{i\perp} = 0.028$ eV in the multidipole discharge, which is nearly room temperature. In the ECR discharge it is hotter, $T_{i\perp} \leqslant 0.46$ eV. Both temperatures have been corrected for the finite laser bandwidths, shown in the inset. Because of the lower $T_{i\perp}$, the multidipole discharge should offer a better ion impact anisotropy.

TABLE I. Comparison to other experiments. Using LIF, we found that the ions are at room temperature in the multidipole discharge. The authors of Refs. 1–3 used commercial ASTeX ECR sources; the model numbers are indicated.

	This work	Ref. 1	Ref. 2	Ref. 3
Discharge	Multidipole	ECR	ECR	ECR
Model no.		S1000	S1500	S1500
Gas	Ar	N_2	Ar	Ar,Ar/Ne, Ar/He
P (Pa)	0.020–0.150	0.069–0.553	0.046	0.023–0.037
$T_{i\perp}$ (eV)	0.028 ± 0.007	0.24–0.12	$\leqslant 0.46$	0.54–0.22

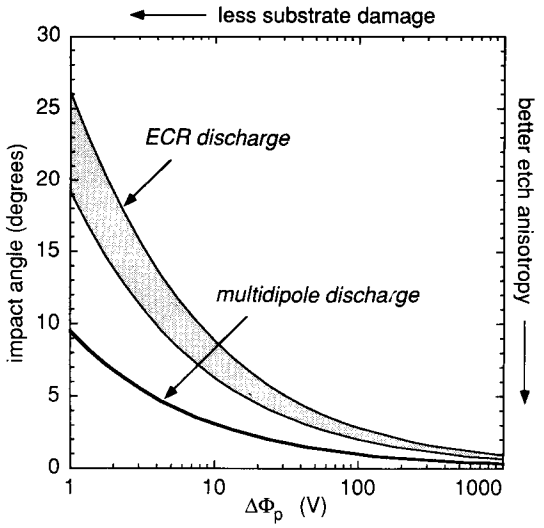

FIG. 3. Thermal impact angle θ vs $\Delta\Phi_p$ for multidipole and ECR discharges. Here, $\Delta\Phi_p$ is the bias between the source and the substrate. The impact angle was computed from Eq. (1) using the temperatures reported by Den Hartog *et al.* (Ref. 1) for the ECR source and our result for the multidipole discharge. Lower impact angles yield better etch anisotropy, while lower biases result in less substrate damage. Thus, one should ideally attempt to operate a discharge with parameters toward the lower-left-hand corner of this graph.

0.553 Pa, respectively. Similar temperatures were reported by Nakano *et al.*[3] for a variety of gas combinations. We can summarize that the ECR sources used in Refs. 1–3 are characterized by temperatures in the range $0.12 \leqslant T_{i\perp} \leqslant 0.54$ eV. These results are compared to ours in Table I.

Because the multidipole discharge has a lower $T_{i\perp}$, it should provide a more anisotropic etch than can be attained with the ECR sources reported in Refs. 1–3. In Fig. 3 we compare the impact angles predicted by Eq. (1) as a function of bias $\Delta\Phi_p$.

The best possible etch should offer good anisotropy and low substrate damage. To achieve this, a small impact angle and a low bias are desirable. This ideal region of parameter space corresponds to the lower-left-hand corner of the graph in Fig. 3.

Clearly, the multidipole discharge operates closer to this ideal region than does the ECR discharge. One can determine how much closer by drawing lines of constant bias or constant impact angle in Fig. 3. For a line of constant $\Delta\Phi_p$, the thermal impact angle is at least 2 times smaller for the multidipole source. Likewise, for a line of constant impact angle, the bias for an ECR source must be 5–10 times higher than for a multidipole discharge. Because the ions are at room temperature in the multidipole discharge, it exhibits the smallest thermal pitch angle that can be obtained for a given bias $\Delta\Phi_p$.

Finally, we note that for plasma etching, a high ion density is important because it provides a high ion flux, which contributes to a high etch rate. It is reassuring to know that one can attain comparable plasma densities in multidipole and ECR discharges. Our LIF experiments were carried out for various densities[9] ranging from 0.1 to 6×10^9 cm^{-3}. The ion temperature was always the same, regardless of the ion density. Other researchers[11] using multidipole discharges reported achieving a density as high as 10^{12} cm^{-3}. These densities are comparable to those found downstream from ECR sources,[2] 10^9–10^{11} cm^{-3}.

In summary, one should attempt to operate diffusion discharges with the smallest possible $T_{i\perp}$, to attain the best etch anisotropy. We have demonstrated that temperatures as low as room temperature are attainable in a multidipole-confined discharge. ECR discharges, in contrast, have much higher ion temperatures.[1-3] Consequently, multidipole-confined discharges should yield better etch anisotropy than the ECR discharges reported in Refs. 1–3.

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