ABSTRACT
Plasma sources used for etching and deposition are usually of two types: Capacitively Coupled Plasmas (CCPs) and Inductively Coupled Plasmas (ICPs). A new type of ICP, a helicon discharge, can produce higher plasma densities at the same power and would be useful for such applications as optical coating. Helicons require a dc magnetic field, which greatly complicates the physics of how they work. They have been studied theoretically and experimentally for over 20 years and are now well understood. However, they have not been universally adopted for commercial use, partly because the magnetic field increases the complexity and cost of industrial units. This obstacle has been overcome by the use of permanent magnets in a novel configuration. Experimental results will be shown both for single discharges and for arrays of tubes to cover large areas.

INTRODUCTION
Helicon discharges differ from other radiofrequency (rf) plasmas in that they require a dc magnetic field (B-field). The range of plasma motions is greatly increased by this field, spawning many theoretical papers on how helicons work. These plasmas are probably the best understood of any gas discharges. Reviews have been written by Boswell [1] and Chen [2]. The high ionization efficiency of helicons is caused by rf absorption by the so-called Trivelpiece-Gould (TG) mode, which is an electrostatic electron cyclotron wave in a thin layer near the boundary. Calculation of the wave fields and absorption profiles requires solving two simultaneous partial differential equations for hundreds of values of the axial propagation constant $k$. Fortunately, Arnush [3] has written the code HELIC to do this, and it is available on our website [4]. For helicon design the most important output of HELIC is “RnB”, the plasma resistance, which is proportional to the rf energy absorbed. A typical scan of RnB vs. plasma density $n$ is shown in Figure 1.

Note first that RnB has a peak, and this peak moves to higher $n$ at higher $B$. Second, RnB is very low, in the 1Ω range. To overcome the stray resistances of cables, we wish to operate with RnB higher than 1 or 2 ohms. Third, the right-hand side of each curve, past the peak, is the stable region of operation because if the density drops, RnB rises to increase the power absorption. The fact that RnB has a peak rather than rising monotonically is due to constructive interference of the wave reflected from the back plate when $H$, $n$, and $B$ are just right. This is called the Low Field Peak [5]. This peak is not normally used but is used in the present design.

The most successful commercial helicon source was the MÖRI (M = 0 Reactive Ion etcher) source made by Plasma Materials Technologies, Inc. of Chatsworth, CA. PMT was merged into Trikon, Ltd. of England. A diagram of this source is shown in Figure 2. The B-field is generated by two large magnet coils, concentric and with opposite polarities to spread the field so that it is minimal at the substrate. The antenna consists of two rings at the top and bottom of the discharge tube, with currents in the same or opposite directions. The matching circuit for 13.56 MHz operation is at the top. The process chamber has small permanent magnets covering the sides to slow the diffusive loss of plasma.
The electromagnets of this source weigh over 100 lbs. and require a large dc power supply. After several years of design and experiment, we have replaced the electromagnet with annular permanent magnets, thus permitting the construction of a much smaller, lighter, and cost-effective source producing more plasma. The latest configuration is shown in Figure 3. The magnet here is an off-the-shelf neodymium (NdFeB) magnet of 2 in. ID, 4 in. OD, and 0.5 in. thick. The designs of the discharge tube and the magnet will be described next.

**PERMANENT-MAGNET SOURCE DESIGN**

Figure 4 is a drawing of the discharge tube, designed after extensive calculation and experiment. Its diameter is set by the inductance of the antenna, which is three turns of 1/8-in. OD copper tubing for 13.56 MHz and one turn for 27.12 MHz. The resulting inductances permit rf matching with reasonably sized vacuum capacitors. The height of the tube, with an aluminum top plate, is determined by the condition for the Low Field Peak. The tube has a “skirt” at the bottom for separation from the flange on which it is mounted in order to reduce canceling currents induced in the flange.

With a quartz tube the plasma can run at 1 kW continuously without overheating the tube. In commercial use, the viton O-rings would be replaced with a ceramic-to-metal braze. Gas is normally fed from below. A top feed is not necessary even at 1 kW. The antenna must be located at the bottom to minimize loss of plasma to the sidewalls.

The magnet in most of the measurements (not the one in Figure 3) is a NdFeB ring of 3 in. (7.6 cm) ID and 5 in. (12.7 cm) OD, and 1 in. (2.5 cm) thick, of rectangular cross section and polarized vertically. As shown in Figure 5, such magnets have a stagnation point not far from the magnet. Below the stagnation point, the B-field is reversed from that inside the ring and is quite uniform. If the discharge tube is placed inside the hole of the magnet, the plasma cannot be ejected to the substrate, and therefore the external field is used. A diagram of the system is shown in Figure 6, and a photograph of it in Figure 7. A vertical extension had been added to house a thin vertical probe for measurements inside the discharge (given elsewhere [6, 7]).
SINGLE-TUBE MEASUREMENTS

Plasma created by this source is efficiently ejected toward the substrate, keeping the density in the source below $5 \times 10^{12} \text{ cm}^{-3}$ at rf powers at which $n$ would be 10 times higher in a long cylinder. Downstream measurements are made in the large chamber shown in Figure 8. Langmuir probes are inserted in the three ports. Port 1 measures plasma soon after leaving the source. Port 2 is at normal substrate level. Port 3 sees low-density, more uniform plasmas. A brief summary is given here; details are found in References 6 and 7. Figure 9 shows the radial density profiles at the three ports at 400W of 27.12 MHz rf power. Pressure is 15 mTorr of argon.

The small source effectively fills the chamber with plasma. At substrate level (Port 2), peak density vs. rf power is shown in Figure 10. The density reaches almost $5 \times 10^{13} \text{ cm}^{-3}$ at 1000W, while electron temperature $kT_e$ stays below 2 eV. Figure 11 compares 27.12 MHz with 13.56 MHz under the same conditions. The higher density at 13 MHz is contrary to expectations. HELIC calculations like those in Figure 1 showed that higher plasma resistance is obtained at 27 MHz. Perhaps antenna coupling is better at 13 MHz because a three-turn antenna is used. However, breakdown at 13 MHz requires higher pressures, after which the pressure can be reduced. At 27 MHz, breakdown occurs at any pressure. The density advantage of helicons over ICPs (same tube without magnet) varies from 16 % at 200W to 42 % at 1kW. The discharge can operate from below 1 mTorr to above 100 mTorr.
HELICON ARRAYS

Figure 12 shows an array of eight tubes, each with a 3" x 5" x 1" magnet, mounted on the conducting top plate of a processing chamber for optical coating, or silicon etching or deposition.
A distributor at the center connects the rf power from a matching circuit via suitable cables (one is shown) or transmission lines to each tube. The tubes are connected in parallel. All will ignite equally if each tube gets 400W or more. For water cooling, the antennas are connected in pairs, so that water enters and leaves the pair at ground potential. A recent theory shows that no center tube is needed for uniform density [8, 9].

A large linear array, Medusa 2, was constructed and tested for roll-to-roll processing. A schematic is shown in Figure 13. Although there are eight holes in each row, only four are occupied in each configuration tested. The B-field is adjusted by changing the height of the magnet support. There are four ports for Langmuir probes.

In the experiment, the magnets were held in a wooden tray, shown in Figure 14. The magnets are very strong and are prevented by bars from vertical motions, which would flip them onto each other. There is no vertical force when they are in the same plane. A distributor box (not shown) lies on top of the magnet tray. Input to the distributor comes from the matching network, and the output consists of eight Teflon-insulated cables of equal length to each tube. To reduce the circuit resistance, we designed a 50Ω rectangular transmission line, shown in Figure 15, in which the center ¼-in. OD copper pipe carries both the rf current and the cooling water. The water return is soldered to the top and bottom grounded plates of the transmission line. Figure 16 shows the all eight tubes equally lit from the transmission line.
Measurements of plasma density were made with Langmuir probes in the ports shown in Figure 13. The “radial” profile in the lower right port in Figure 13 is shown in Figure 17. The density is quite uniform between the rows of tubes and falls towards the walls. The electron temperature hovers around 1.5 eV. The ion current uniformity at the bottom of the chamber was measured by a row of 22 ion collectors movable along the chamber length. Some results are shown in Figure 18. The curves for collectors that lie beneath the rows (in staggered configuration) show peaks and dips as they pass under a tube or a space. The curve for the centerline between rows shows ±3 % uniformity. For a moving substrate, the coverage is uniform except near the walls.

Further data on this system can be found in References 10, 11, 12, and 13 and in the Ph.D. thesis of H. Torreblanca [14].

**SUMMARY**

The advantage of higher ionization efficiency in helicon sources can be obtained easily by using permanent magnets. The use of PMs and the Low Field Peak for this purpose is covered by U.S. Patent [15].

**REFERENCES**


