Recent Advances in Microwave Plasma Sources for Materials Processing

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Microwave plasma sources are unique among the variety of plasma sources that are available in that they operate in the collisionless regime, $\nu/\omega < 1$, where ν is the total electron collision frequency and ω is the microwave frequency. In this regime of collisionality, the electrons oscillating in the electric field are able to acquire the maximum energy per cycle before undergoing a collision. This results in a higher degree of ionization and dissociation of the plasma than is possible with lower frequency excitation.

The simplest type of microwave discharge can be made by passing a quartz tube through the end of a terminated waveguide, as shown in Figure 1. The plasma is formed in the portion of the tube inside the waveguide and is transported away by the flow of gas in the tube. The flow of ions and radicals from the tube can be used for either etch or deposition of thin films on a substrate which is located "downstream" from the region where the plasma is formed.

Downstream sources typically operate in the range of 1-10 Torr depending on the gas being excited. The plasma equilibrium is maintained when the rate of plasma loss is balanced by the rate of plasma generation.
At high pressures, plasma is lost due to volume recombination of ions or radicals, while at low pressure the predominant loss mechanism is surface recombination. Recent advances in microwave plasma source design have extended the range of operating pressure from atmospheric to as low as 10^{-5} Torr.

Atmospheric Torch

The operation of the downstream source can be extended to atmospheric pressure by producing a region of low pressure behind an obstruction in the tube. The wake within the flowing gas stream provides an environment for a stable microwave discharge over a wide range of conditions. The plasma formed in the region of wake circulation does not contact the reactor walls which are cooled by the colder gas surrounding the plasma. The microwave atmospheric torch has several advantages over other types of plasma torches including reactive gas compatibility due to the absence of electrodes and improved stability with hydrogen and helium. The microwave atmospheric torch is being investigated as a new tool for plasma pyrolysis and atomic emission spectroscopy.

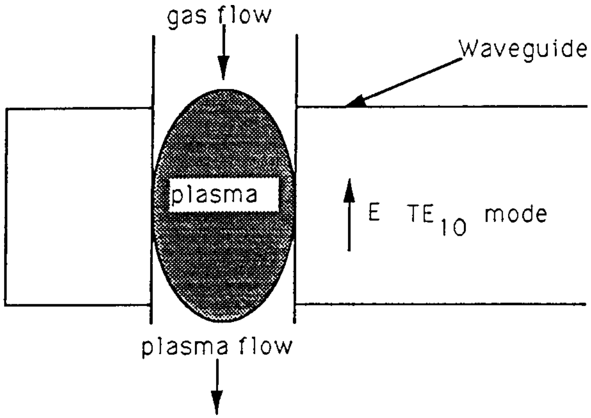

Figure 1. Microwave downstream plasma source

Electron Cyclotron Resonance (ECR) Plasma Sources

Plasma loss due to surface recombination at low pressure is easily overcome by applying a magnetic field to the plasma. The magnetic field causes the ion and electrons in the plasma to gyrate in circular orbits about the magnetic field lines at a characteristic frequency called the cyclotron frequency. At a magnetic field strength of 875 Gauss, the electrons gyrate about the magnetic field lines at a frequency of 2.45 GHz, the same frequency used in commercial microwave generators. The electron cyclotron resonance (ECR) which occurs when the electron cyclotron frequency matches the frequency of the microwave field leads to an enhanced absorption of the microwave energy, as well as an increased electron energy due to the resonant absorption of microwave energy. The distribution of electron energy in an ECR discharge contains a low energy component (~5 eV) and a low density, high energy tail (10-30 eV). The high energy tail is largely responsible for the high flux of dissociated and ionized species which exit the source. ECR discharges can operate effectively anywhere in the range from 10^{-5} Torr to several hundred milliTorr.

ECR Plasma Sources for PECVD

The features of the free streaming ECR source are shown in Figure 2. Microwaves are launched from the microwave network (consisting of the microwave generator, isolator, tuner, and coupler) through a quartz microwave window located at the center of a large electromagnet. The microwaves propagate in the plasma without loss of power to the resonance zone where the microwaves are strongly absorbed. The hot plasma in the resonance serves to ionize gas that is fed in at the microwave window. Initially, the hot electrons formed in the resonance zone tend to escape faster than the ions until a positive potential is formed. The positive potential retards the loss of electrons and expels the ions until the flow of ions and electrons is equalized. The ions exiting the source gain the energy of the positive potential which is typically 10-30 eV, depending on the microwave power, gas pressure, and the type of gas used (eg. molecular vs. monoatomic). The high flux (> 10 mA/cm^2) of low energy ions makes ECR sources particularly attractive in deposition applications where ion flux can be used to reduce the substrate temperature required to obtain dense, stoichiometric films.

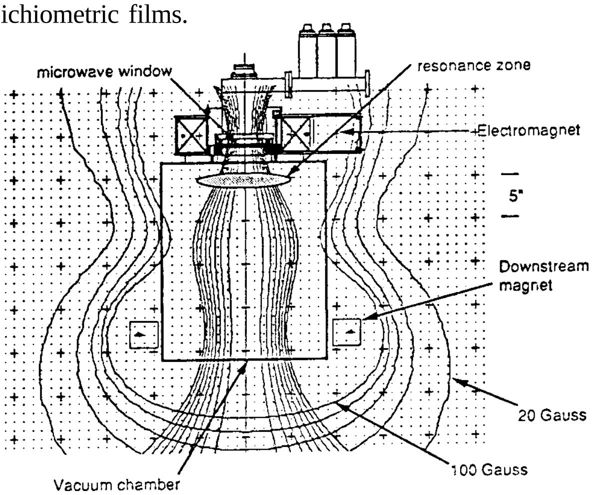

Figure 2. Streaming ECR Plasma Source

Since the magnetic flux and ion flux are both conserved quantities, it follows that the ion flux is proportional to the magnetic flux. This can be used to advantage in etch and deposition applications by using a downstream magnet. If the downstream magnet adds to the flux of the window magnet, then the magnetic flux at the substrate is increased and the ion flux to the substrate is also increased. Conversely, if the downstream magnet acts in opposition to the window magnet the magnetic flux and ion current at the substrate are reduced. Thus, the ion flux and ion energy in an ECR source can be independently controlled which provides a means of controlling the stress in deposited films. Downstream magnets have also proven effective in controlling the ion current density profiles to improve process unformity.

Most commercially available ECR plasma reactors employ a configuration similar to that shown in Figure 2 because of the added flexibility in the ability to control the plasma flow to the substrate. Because the microwaves are introduced through a relatively small window and the vacuum chamber can be made quite large, surface interactions can be minimized for higher plasma efficiency and reduced contamination.

ECR plasma sources have been demonstrated to produce high quality films of SiO_xN_y, diamond-like-carbon, and diamond at reduced substrate temperatures. At ASTeX, we have used ECR technology to produce free standing SiC membranes for x-ray lithography[1]. Recently, this work was extended to multilayer membranes consisting of alternating layers of SiC and SiN_x. The multiple layers could be optimized for increased burst strength (1.1 GPa), low reflectance (<2% at 633 nm), and improved chemical etch resistance.

High Pressure Microwave Sources for Diamond Deposition

High pressure microwave (HPM) sources have been used by researchers to deposit high quality polycrystalline diamond for nearly five years. The HPM source is shown schematically in Figure 3. A single mode cavity (TM_{01}) is used to form a cylindrically symmetric microwave discharge at high pressure. The plasma is primarily hydrogen with a small amount of methane added. Methyl radicals dissociated in the plasma ball diffuse down to the heated substrate where the diamond film is formed.

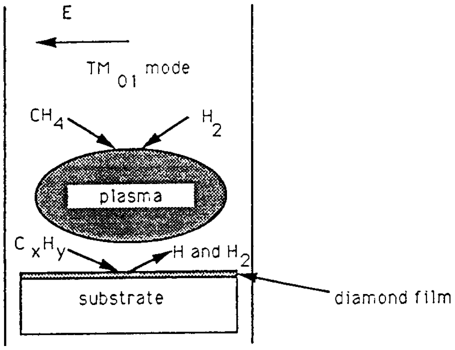

Figure 3. High Pressure Microwave Reactor

Data taken in the HPM reactors has shown a strong scaling of deposition rate with microwave power. This has led to higher power density reactors where linear growth rates as high as 15 µ/hr have been reported[2]. Scaling this technology to commercial scale is currently under way at ASTeX. A new reactor operating at 75 kW is targeted to provide diamond deposition capabilities at 10,000 to 30,000 carats/year. The reactor uses a 915 MHz generator to take advantage of the reduced cost of microwave generation and the natural increase in size of the plasma due to the increased wavelength. The reactor will be used to deposit thick (1 mm) diamond films on substrates up to 6 inches in diameter for the production of diamond multi-chip modules.

References

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