Design of electron cyclotron resonance based reactive ion etching system

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Designs of the subsystems of the Electron Cyclotron Resonance (ECR) plasma stream source at frequency 2.45 GHz are explored. The assembled machine on this design has been evaluated using Langmuir probe and etching of Si based compound. The plasma densities have been found to be above the critical value at this frequency and etching rates are compatible to the reported values.

In recent years, there has been a growing interest in the technology of microwave-sustained plasmas in the semiconductor industry\textsuperscript{1-4}. Their electrode less nature together with their ability to create high densities of excited and charged species have made both high pressure and low-pressure microwave discharges an attractive technology for many plasma-processing applications. One of the applications, where such technology has gained ground in the recent past is processing of very large scale integrated (VLSI) circuits. This has lead to much improvement in such technologies in the global market. As the name ECR suggests, microwave energy is coupled to the natural resonant frequency of the electron gas in the presence of static magnetic field. This resonance occurs when electron cyclotron frequency \( \omega_{ce} = eB/m_e \)
equals the excitation frequency \( \omega \). In an actual discharge, this condition can be satisfied in a volume or surface layer within the discharge where the static magnetic field strength is adjusted to resonance, i.e. \( \omega = \omega_{ce} \), and a component of electric field perpendicular to the static magnetic field. The electrons are accelerated in this ECR volume and in turn ionize and excite the neutral gas. This plasma can be used in conventional RIE mode where control of ion energy from (50-500 eV) can be carried out with additional RF bias or grid system for Chemical Vapor Deposition System and for Reactive Ion Beam Etching System.

This article reviews the design parameters of the subsystem of ECR based Reactive Ion Etching System, its assembly, problems for optimization of the assembled system and technique for performance evaluation.

Design of Reactive Ion Beam Etching System

The system consists of five main sub-systems, viz.: (1) Plasma Source, (2) Process Chamber, (3) Vacuum system, (4) Flow Control and Monitoring System, and (5) Wafer Manipulator. Design philosophy of this instrument is to use sub-system available in the global market and in house fabrication of the critical components.

Plasma Source

Ultra large-scale integration (ULSI) of circuits on a chip puts stringent requirements on plasma source characteristics like plasma uniformity, anisotropy, selectivity damage control and throughput. To meet such specifications, there have been constant efforts to develop plasma source with high plasma density at low pressure \( (10^{-4} \text{ torr}) \) than conventional RF based plasma sources, having no contaminating filament like DC-discharges and to have separate plasma creation zone “source zone” from that of the etching operation (diffusion zone).

The high-density plasma at low pressure can be achieved by improving power absorption in discharges. The power absorption in different discharges is either by collision or collision less. The collision frequency is pressure dependent and at lower pressure, \( 10^{-4} \text{ torr} \) (pressure where plasma is to be generated). This becomes very small and, therefore, collision less absorption dominates. In collision less situation, an electron would oscillate in the oscillating...
electric field and would reach maximal velocity and energy. If an electron makes an elastic collision with an atom reversing its motion at the time the electric field changes its direction, it will continue to gain speed and energy. In this way, electron could gain enough energy to cause ionization even at low electric field. The average power absorbed by unit gas volume is given by:

\[ P_v = n_e e^2 E_0^2/2 \] 

The power absorbed by the plasma approaches zero for the conditions of rare collisions \((v \ll \omega)\) or frequent collisions \((v \gg \omega)\). The very high value of electric field is therefore required to sustain discharges at very low pressures. This situation can be resolved if magnetic field of specific strength is applied to a plasma system and it is rendered to execute gyro motion with frequency that of electric field so that charged particles will be in resonance with the electric field and absorption will be maximum. For a plasma density of \(10^{10}\) ions/cm\(^3\), the plasma frequency is \(9 \times 10^8\) Hz. Propagation of electric field into a plasma requires that field frequency should be greater than equal to plasma frequency. So, power source with field frequency \(2.45 \times 10^9\) Hz (microwave source) was taken as energy source. Mirror type magnetic field configuration was created in a cavity with the help of two solenoid coils (window/exit magnet) and varying current value to this coil can vary the field strength. The current to entrance coil can be varied from 0-200 ampere and that for exit magnet it is 0-130 ampere. In this way, one can pick up different field configurations for optimization of source. In our study, we have taken entrance coil 180 ampere for exit coil 120 ampere (as shown in Fig. 1 for this field strength). Field strength at \(z = 10\) cm and \(z = 27.5\) cm is 875 gauss and around this electron gyration frequency is \(2.45 \times 10^9\) Hz which is equivalent to field frequency of microwave source. Microwave source for this system is taken from M/s Astex USA with solenoid coil. Microwave generated by a magnetron are transported to cavity region through rectangular wave-guide WR-284. After passing through mode converter (Astex TEO1 to TM01), microwave is launched into a source region of the chamber through a quartz window. A three-stub tuner is used to tune the reflected power down to typically less than 1% of the forward power. The power supply for solenoid coil is form M/s Electronics & Measurements Inc., USA.

### Process Chamber

Design of the chamber is as per wafer size and process requirements. We intend to process 6” wafer in the pressure range 0.1 to 1 mtorr with base pressure .0001 mtorr. Material of the chamber should have minimum degassing rate with easy machinability, no magnetic interference and cost effective. Chamber was built from non-magnetic 304 stainless steel. Chamber was designed to accommodate wafer manipulator with robotic arm. Chamber was provided with diagnostic port to put end point detector which views processed wafer directly and second diagnostic port near pumping port to install mass spectrometer for residual and process gases analysis. Exit port of the process chamber was so designed that it can accommodate throttle valve to adjust vacuum in desired range. Two ports are provided for pressure monitoring instrument like ionization gauge and capacitance diaphragm gauge. An additional port is provided to mount a small ion beam source to clean the wafer during process. Care has been taken that same chamber can be used for LPCVD system and Reactive Ion Beam Etching System. Complete design of the chamber is given in Fig. 2 and it is 300 mm in diameter & length 330 mm.

### Vacuum System

Design of the vacuum system depends upon ultimate vacuum (base pressure) requirements and process pressure requirements. In this case, it was desired that system should be in a position to give pressure about \(10^{-7}\) torr with process pressure of 0.1 to 1 mtorr when the flow rate is maintained between 0-20 standard cc per minute (sccm). Desired ultimate pressure can be achieved by turbo molecular pump or by cryo pump with pumping speed 1500 L/sec. As the cryo pump with this speed was available in the laboratory, so the same was used to build vacuum.

![Fig. 1—Schematic layout of the ECR system along with the distribution of the magnetic field](image-url)
 system. Throttle valve and capacitance diaphragm gauge combination was used to achieve constant process pressure during process. Pressure and flow requirements define the speed of the pump and in our case it is 1500 L/sec. Pressure monitoring is carried out by ion gauge and capacitance diaphragm gauge. Ion gauge is used to measure ultimate pressure while capacitance gauge is used to measure and control the pressure.

Flow System

Different etching processes are carried out at a different flow ratio of two or three gases at different pressure. So in this system, four channels are provided for flow of different gases. It is accomplished by using mass flow controller with mass flow transducer. System is provided with three different flow ranges 0-10, 0-100, and 0-1000 sccm with monitoring accuracy of 0.01, 0.1 and 1 sccm, respectively. Four independent channels are available for four gases and each can be controlled from its controller. In our system, we have provided channel for CF₄, SF₆, Cl₂, O₂ gases. These gases are taken to manifold for mixing and then taken to cavity to generate plasma. Complete flow line is built from ¼" stainless steel pipe with swagelok fitting. Two stage pressure regulators are used to monitor the pressure of the cylinder and the flow.

Wafer Manipulator

Substrate holder is provided to hold wafer up to 6 inches. As the system is designed for etching, therefore, provision for cooling the substrate was also provided. There is facility for tilt, substrate shutter and feed through for electrical input. For easy mounting of substrate, it is designed on O-ring based 150 mm flange. Special care has been taken to avoid microwave leakage from the flange.

System's Assembly, its problems & remedies

The layout of the system was so designed that working platform and control panel of all the electronic modules of the subsystems are approachable to the operator in sitting position. A special 19" rack was designed to house the microwave, magnets, ion source and cryo compressor power supply. As the weight of the solenoid coils and pumping system is around 250 kg, a rigid frame with 4" U-channel support was designed for its mounting. Most of the ports were designed with CF flanges to avoid microwave leakage. The microwave leakage test was carried out with Haladay microwave leak detector model No. HI-1510A.


Results and Discussion

Assembled system was characterized using Langmuir probe\(^5,6\) in the process chamber and plasma cavity. Performance optimization was carried out with the etching of the different materials such as silicon, silicon dioxide and silicon nitride. The \(I-V\) characteristics for different gases Ar, CF\(_4\), O\(_2\), CF\(_4\)/O\(_2\) (4:1) are shown in Fig. 3. These measurements have been made at 0.4-mtorr pressure, 500 watts input power, 15 secms flow with entrance and exit magnet at 180 and 120 ampere, respectively. It has been found that the plasma density obtained from the ion saturation current portion of the \(I-V\) curve (Fig. 3) is greater than critical value \(7.1 \times 10^{10} \text{cm}^{-3}\) for this frequency. The other plasma parameters such as floating potential, plasma potential, electron temperature are also obtained by using these \(I-V\) curves, as reported in Table 1. The etching rates for Si, SiO\(_2\) and Si\(_3\)N\(_4\) have also been evaluated and given in Fig. 4. System performance parameters are given in Table 1.

Conclusions

An Electron Cyclotron Resonance (ECR) stream source developed to generate the plasma of argon, O\(_2\), and CF\(_4\). Etching trials of Si, SiO\(_2\) and Si\(_3\)N\(_4\) were carried out. It was found that machine produces plasma with ion densities greater than the critical value \(7.1 \times 10^{10} \text{cm}^{-3}\) at 2.45 GHz with good plasma stability for long period.

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References