A low energy multi-purpose implanter based on ECR plasma

G. S. Taki
Dept. of Electronics and Communication Engineering
Institute of Engineering and Management
Saltlake, Kolkata, India
e-mail:gstaki@gmail.com

K. K. Ghosh
Dept. of Electronics and Communication Engineering
Institute of Engineering and Management
Saltlake, Kolkata, India
e-mail:kk_ghosh@rediffmail.com

***Abstract*-A multipurpose implantation facility has been designed based on Electron Cyclotron Resonance (ECR) ion source. It can easily be configured online for surface modification by ion beams, neutral particles and ECR plasma. The set up can be used for preparing thin films of nanometer thickness following the route of a plasma assisted chemical vapor deposition. The facility mentioned here, uses a specially designed 2.45 GHz singly charged ECR ion source floating at users' configured small potential. The potential varies from zero to a few tens of volts for extracting particles from the source. Energy of the impinging particle lies in the range suitable for efficient deposition below the sputtering energy level of the substrate. At zero source potential, the ions come out at an energy equivalent to the plasma potential. In ECR plasma, the electrons are heated up by microwave power at resonance condition. The resonance condition is sustained by a solenoid magnetic field created by a precision constant current flowing through a coil. A magnetron tube supplies microwave power into the plasma through vacuum and voltage isolating windows with the help of a specially designed microwave feeding system. A 500 l/s turbo molecular pump is used to create the desired base vacuum ~1x10^{-7}Torr. The substrate/targets will be assembled on an electrically isolated target ladder assembly. Facility will be provided to elevate the temperature of the substrate up to a desired value during carrying out plasma enhanced chemical vapor deposition process. The experiments will be carried out in a multiport cylindrical chamber. The set up facilitates nitriding (e.g. SiN, Si_3N_4, GaN, AlN, GaAsN), oxidation (e.g. transparent optical anti reflection coating of SiOx, TiOx , ZnO and ITO), coating of dielectrics and superconductors, ion beam assisted deposition in vacuum, hydrogen cleaning, in-situ etching and sputter cleaning etc. The basic design feature of the facility and its uses has been discussed here.**

Keywords-ECR ion source; extraction; implantation; sputtering; surface modification.

I. INTRODUCTION

Various research tools have been utilized so-far to carry out studies on Zinc oxide semiconductors, indium tin oxide and silicon photonic devices to develop photo voltaic cell, LED, PSD and image sensors.The material properties of the produced film or the implanted substrate widely differs depending upon the deposition or implantation methods used in the production process. The research tools have their own advantages and disadvantages depending upon the methodology and the ambient conditions of the experimental set-up like the temperature, pressure and the presence of gaseous elements in the experimental chambers. The properties of the implanted/deposited film also depend upon the mass and energy of the impinging atoms and ions. It has also been observed that in some special cases the material property changes even with the charge state of the ions. The important factors for precise experimental studies are many. A versatile experimental facility, which can satisfy major experimental requirements, is usually preferred. The conceptual design of such a multipurpose low energy implantation facility will be discussed here which can deliver very low energy ions, neutral molecules or plasma. The facility serves both the purpose of using a very low energy implanter and producing ultra-thin films at a comparatively lower substrate temperature. It will usually work below the sputtering energy level of most of the elements to achieve maximum deposition yield. This facility basically utilizes a 2.45 GHz electron cyclotron resonance ion source which produces the low charged state positive ions and cold plasma. Low energy ions, extracted from the source by applying suitable electrostatic field, can be utilized for surface modification studies and the plasma diffusing out of the source assists the chemical vapor deposition process at lower substrate temperature. By utilizing suitable electrode configuration, the facility can be used for very low energy neutral particle implantation. In essence, the elegance of such a facility can be realized in implanting ions or neutral molecules on this methodology-based Nano-metric film following the process of cleaning its top layers by subsequent sputtering.

II. DESCRIPTION OF THE FACILITY

ECR plasma is generated here in a multimode cavity that acts as a plasma chamber. Basically a retro-fittable, three electrode accel-decel extraction assembly will be used to satisfy users' configured extraction field to extract ions, neutrals, electrons and plasma as a whole. The experiments are carried out in a multi-facility multiport chamber to place the substrate or target within a few centimeter distances from the ECR plasma. The combined volume of plasma chamber and the experimental chamber is pumped by a turbo-molecular

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pump and the extraction assembly controls the differential pumping speed imparted to the plasma chamber. The resonance magnetic field is created by a solenoid magnet keeping outside the plasma chamber [Figure 1].

A. *ECR ion source*

One of the basic components of the facility described here is the Electron Cyclotron Resonance ion source [1, 2, 3]. In ECR ion source the electrons gain energy from microwave power under cyclotron resonance condition. Here, plasma electrons revolve in a circular path maintaining a particular frequency under the action of the Lorentz force due to a static magnetic field. This frequency is called the cyclotron frequency (ω). Efficient energy transfer takes place in resonance, when the revolution frequency of the particle becomes equal to the EM wave frequency. In case of ECR source it is in the microwave frequency range.

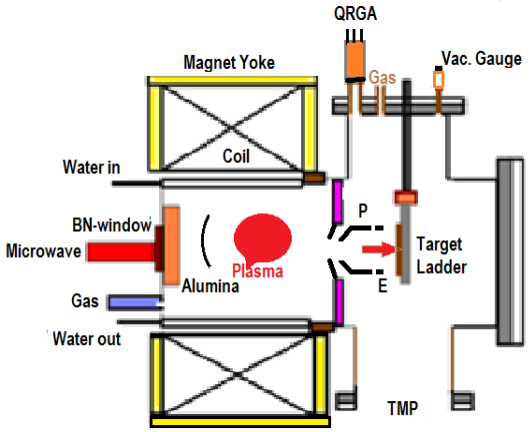

Figure1. Schematic diagram of the multi-facility implanter

The equation of motion may be written as

$$Bev = \frac{m_e v^2}{r}$$

where B is the magnetic field, v is the velocity component of electron perpendicular to the static magnetic field, e and m_e are the electronic charge and mass respectively. The resonance condition with the wave may be expressed as:

$$\omega = \frac{eB}{m_e} = 2\pi f$$

Higher frequency microwave generators are extremely costly equipments. The microwave generators used for microwave ovens are the best choice for generating cold or moderately hot plasma. These 2.45 GHz magnetron driven generators are easily available and cheaper. 875 gauss is the resonance magnetic field corresponding to this frequency. A plasma temperature of 8 to 70 eV is a good choice for generating singly charged ion. The power ranges from 450 to 1000 Watts is suitable to produce good amount of ion and electron flux at higher operating pressure. Larger power will be specifically needed for operating at higher vacuum pressure during development of thin films of different elements on substrates utilizing the ECR enhanced chemical vapor deposition. Low operating pressure and high microwave power will be needed for implantation and material modification work.

B. *Microwave system*

The schematic diagram of the microwave system is shown in figure 2. A magnetron delivers power to the plasma through a ceramic (Boron Nitride) or quartz window and a ridged rectangular waveguide. A multi stub tuner will take care of the initial mismatch between the generator and the plasma load. To protect the magnetron from the large reflected power caused due to severe mismatch between the waveguide and the plasma, a circulator with water cooled dummy load is used. A bidirectional coupler provides the overall protection by constant monitoring the incident and reflected power. The large difference between the impedances of the waveguide and the ECR plasma is due to the extreme dynamic nature of the dielectric properties of plasma.This mismatch has been taken care by using two blocks of Boron-nitride and Alumina. Basically the composite dielectric will slow down the waves for further matching. For the ease of fine tuning, the injected microwave power is to be varied from 100 watts to maximum value as and whenever needed.

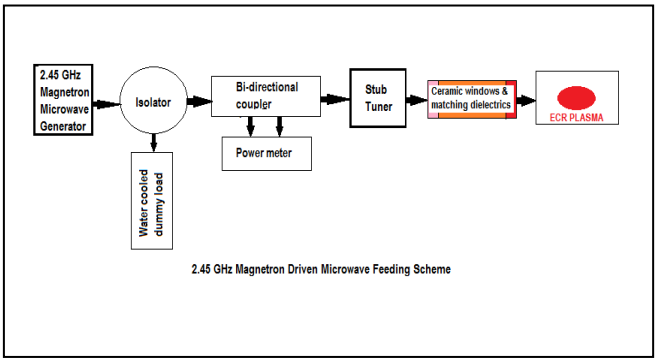

Figure 2. Microwave feeding scheme

To facilitate ion extraction from the ECR plasma, the ionization cavity floats at some potential, higher than the plasma potential. So the electrical isolation of the cavity is extremely important. As very high vacuum is maintained inside the cavity to avoid contamination and impurity during implantation, a microwave vacuum interface is essential for the facility to allow microwave power with minimum attenuation. For the electrical isolator i.e., the DC-cut, Teflon (PTFE) may be used due to its low loss angle and higher dielectric strength. As the outgassing property of the Teflon is not very good, boron nitride is the best choice for the vacuum window. Usually a single thin dielectric plate pressed between a choke flange and a flat cover flange is used as a vacuum window. The vacuum sealing is achieved by pressing indium wire on both sides of the dielectric plate. It is found that two dielectric plates sandwiched together produce a better window configuration with a minimum power reflection co-efficient less than 0.8% [4, 5].

The ECR plasma is highly anisotropic in nature due to the large variation in the magnetic field gradient. The dielectric constant and the impedance of the plasma also widely vary inside the plasma cavity. A matching of the plasma impedance with the impedance of the external microwave feeding network

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is dynamically obtained by adjusting the operating pressure, gas flow, magnetic field and injected microwave power into the plasma.

However, in practice an appreciable amount of reflected power is frequently found in ECR ion source due to the high impedance of the low ionized media between the microwave vacuum window interface and the ECR plasma surface. Several studies have been carried out on microwave coupling into the ECR plasma for its efficient injection [6, 7, 8, 9]. Many microwave and antenna structures have been studied to slow down the waves for better absorption efficiency. Devices like antenna horn and slow wave structure, rectangular to circular transition, dielectric loaded wave guide, ridged wave-guide etc. have been tested to obtain high density plasma [9].

It has been planned to use dielectric plates of boron nitride and alumina at the microwave injection point where the BN acts as a vacuum window and the alumina plate faces the ECR plasma. The dielectric slabs with high dielectric constant work like the dielectric resonators. The high dielectric constants of the resonator ensure that most of the fields are contained within the dielectric, only some of the fields fringing or leaking out from the sides and ends of the dielectric plates [10]. The BN and Alumina are low loss and high dielectric constant material. The dielectric constants are 4.6 and 9.5 respectively which are in increasing order to match the dielectric properties of plasma. In an experiment, it has been observed that the dielectric constant of plasma varies from ~20 to 100 depending upon the plasma density [5]. Besides the impedance matching, the alumina plate will play another major advantageous roll towards the stability of the plasma. As its secondary electron emission co-efficient is very high (~9), each axially escaping electron will produce nine times electrons when strikes the alumina plate. Electrons thus produce will increase the cold electron density in the plasma. This mechanism basically removes the instability due to starvation of electrons.

C. Magnetic field

Ion confinement has a little role on the singly charged ion production. The radial confinement of the plasma and the strong axial magnetic mirror with large mirror ratio are less important in this case.

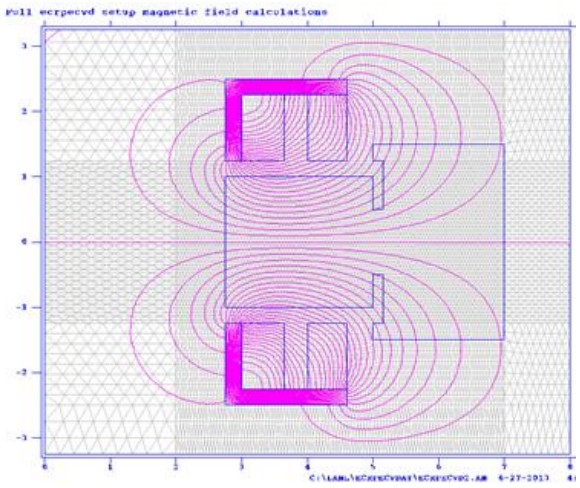

Figure 3a. Configuration of solenoid magnet and field lines

A single peak field suitable for this purpose. The magnetic field in the transitional region between the cavity and the experimental stage should be uniform and parallel to the axis of propagation of the particle. The magnet design has been carried out with the help of SUPERFISH-code. The design of the coil along with its yoke, field lines and the profile of the magnetic field are shown in figure 3a and 3b respectively.

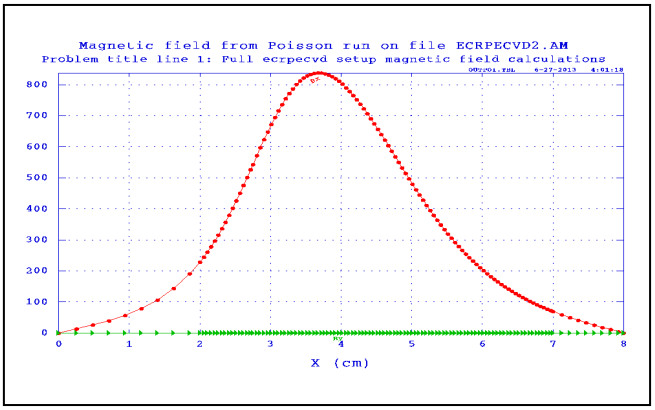

Figure 3b. Solenoid magnet field plot in Gauss

D. Plasma cavity and extraction system

The plasma chamber is a water cooled double wall cylindrical multimode microwave cavity. It is made of non-magnetic stainless steel cylinder, with a gas inlet port. The microwave matching network is connected in the injector side. The other side of the cavity is connected with the multi facility experimental chamber through an alumina insulator.

A demountable beam extraction assembly is suitably placed and biased to extract singly charged extremely low energy ion beam. Here, the plasma cavity is positively biased to 5-10 Volts and the puller is kept at negative 200 volts to prohibit the escaping of energetic electrons.

A modified extraction assembly will be used in case of neutral and plasma extraction.

In case of extraction of neutral atoms/molecules, a specially designed aperture plate inhibits the ions to escape from the plasma, but allows reactive neutrals to escape and form the dominant beam fraction. The emitted neutral particles are largely thermalized through multiple collisions on passing through the aperture. The residual ion content from the beam can be removed by using a suitable ion trap.

Normally, a larger proportion of the charged particles of the plasma escape through the extraction aperture when the electrodes are kept at ground potential. So, the plasma reaches the target assembly without applying any accelerating potential to the electrodes. Here the total flux will be more than that of extracted neutrals. Obviously, the sample will be kept at a few centimeters from the source. Here the ion energy will be equal to the plasma potential and the electron energy depends upon the microwave power density and operating pressure. The electron energy and the microwave power relation is expressed as:

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$$\frac{P}{V} = n_e k T_e$$

where P=microwave power

V=Volume of the plasma cavity
N_e=electron density
T_e =Temperature of the electron and
k= Boltzmann constant.

The ion simulation has been carried out by SIMION code as shown in figure 4. In the simulation, the plasma cavity and the puller potential are taken as +5 Volts and -200 Volts respectively. The final electrode is kept at ground potential. The positive ions are extracted by the electrical force under the influence of the falling solenoidal magnetic field. Here, the magnetic field has been applied in the simulation using a special configuration of a set of poles as shown in figure. The simulation shows that a parallel uniform circular beam travelling towards the target.

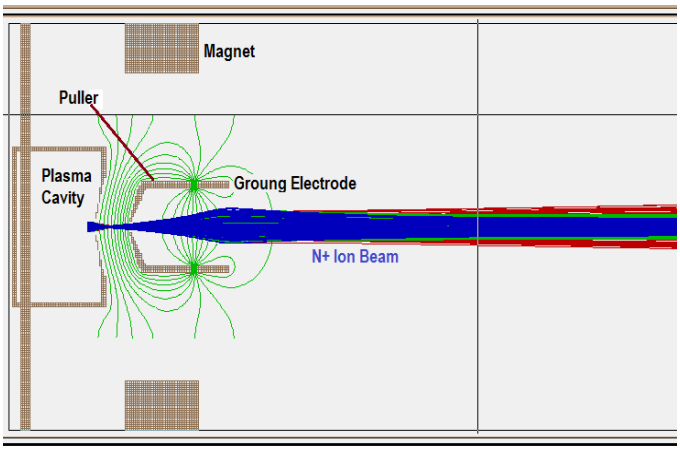

Figure 4. Extracted ion trajectory under electric and magnetic field in the implanter

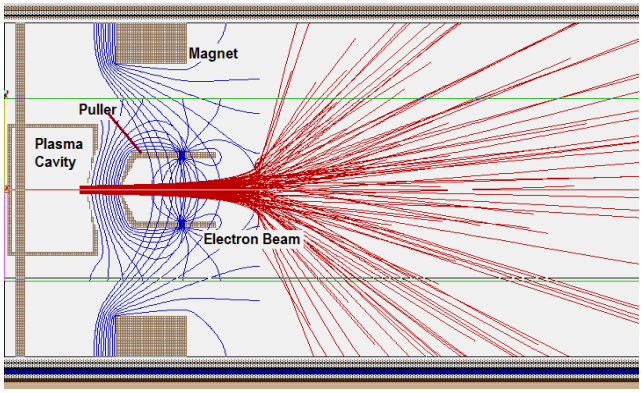

Figure 5. Extracted electron trajectory under the influence of electric and magnetic field

A small fraction of electron beam may be extracted from the source by floating the source at a small negative potential. One can carry out experiments with low energy electron beam keeping the target at a few centimeter distances from the extraction area. In this case the produced positive ions are stopped by applying positive potential to the puller electrode which is higher than the equivalent ion energy. Figure 5 shows a SIMION plot where electrons are drawn from the source under the influence of the magnetic field and also by applying -5Volts and +200 volts on the ionization plasma cavity and the puller electrode respectively. The final electrode of the extraction system is always kept at ground potential.

E. Vacuum

The vacuum plays a major role producing ions in the source. The purity of the coated material depends upon the initial vacuum condition of the experimental chamber. After attaining a good base pressure ~1x10-7 Torr, the precursor is allowed to enter into the test chamber in plasma assisted CVD mode. The total volume of the plasma chamber and the test chamber is 25 litres approximately and a 500 l/s turbo pump is a good choice to facilitate several experimental requirements. A differential pumping speed has been provided through the electrostatic extraction assembly in case of ion implantation. The selection of apertures and conductance allows the optimum balance between gas flow, working pressure and extracted beam current. The pressure in the chamber has been monitored continuously with the help of a inverted magnetron type pressure gauge and the elemental species are analyzed on regular basis by installing a residual gas analyzer.

F. Multiport Experimental Chamber

Besides an Electron Cyclotron Resonance (ECR) ion source, the facility consists of a multi-port cylindrical implantation chamber with a suitable vacuum pumping system. The pumping system is preferably a turbo molecular pump with a dry type rotary backing pump [Figure.1]. An electrically isolated substrate holder with the heating facility is housed at the end of a manipulator hanging from the top flange of the implantation chamber. The target or substrate holder must be placed within a few centimeters from the extraction assembly. The electrostatic extraction assembly draws the ion/neutral flux from the ECR plasma and allows falling on the temperature controlled substrate for surface modifications. The total dose/ion flux can be measured by measuring current and time of the implantation or by measuring total flux from the integrator. Here, the feed gas in ECR source is used for generating plasma and producing ions of the particles to be implanted. The ion source will be floating at a positive potential for extracting positive ions needed to carry out extremely low energy implantation or surface modification work. The voltage is less than 100 volt to avoid the surface sputtering by the ions. Otherwise the sputtering from the surface will dominate and the resultant yield of the thin film will be much less.

III. IMPORTANT PROCESSES AND ADVANTAGES

- Equal number of ions and electrons together with the neutral atoms or molecules are present in plasma. In case of plasma assisted chemical vapor deposition, the precursor reactive feed gas is directly introduced into the implantation chamber to achieve much lesser degree of ionization (~10^{-5} / 10^{-4}). In this process, plasma acts as the source of energy to create dissociation of the reactive gases at a temperature less than its thermal dissociation temperature. The processes take place in ECR cold plasma are listed below:

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1. The heating of electrons by microwave energy in the electron cyclotron resonance condition

2. Ionization of available neutral atoms by collision of the energetic electrons (primary ionization process)

3. Ionization of neutral atoms due to atom-ion collision (secondary ionization process)

4. Increase of energy of neutral atoms by the collision of energetic electrons having energy below the minimum ionization potential

5. The radiative loss by way of electrons-ion recombination

- The first three processes are essentially related to the ionization in an ECR source and the fourth process plays major role to reduce the level of much higher thermal dissociation temperature for a coating gas / vapor during the thin film preparation process. As the degree of ionization is very less, a non-equilibrium condition exists in the experimental chamber and the temperature of the mixed plasma gas is almost equal to that of the neutral molecules. So, in both the cases the resultant accumulation of the projectile particle on the substrate will be more due to less sputtering.

- Another important feature of this proposed set up is the purity of the implanted material and the produced thin film. The impurity in the film is caused due to the sputtering of the surface material of the chamber and the material sputtered out from the extraction grid or electrode of the source. The low particle / ion energy and the low operating temperature of the substrate are the other important factors. The major contribution towards purity is the low operating vacuum pressure. Specifically the buried residual neutral molecule causes the major impurity and change in the crystallographic and optical material properties.

A precisely uniform implantation or deposition of the ion /element can be obtained by the proposed set up. The effective exposed area of the target and substrate may be finely tuned by the beam optical manipulation. The temperature of the substrate may be varied from outside by using proportional temperature control system and an accurate infrared temperature gun. Multiple numbers of small targets /substrates may be placed on the target ladder assembly at any desired angle essentially needed for the specific experiment. The vacuum pressure inside the experimental chamber is continuously monitored by a vacuum pressure gauge. The composition and the purity of the coating, during implantation / coating are preferably to be measured by a quadrupole residual gas analyzer (QRGA).

IV. SCOPE OF RESEARCH

Low pressure plasmas have a lot of applications in the field of materials processing. Such plasmas are unique in terms of generation of chemically reactive species at low temperature. This is basically due to the non-equilibrium nature of the plasma state. The internal energy of low pressure plasma is very high because of the presence of the charged particles. The thermodynamically allowed but kinetically hindered in a conventional process, proceed with a high rate under plasma conditions. Such plasmas find wide uses in several industrial processes including developing thin films by Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD), Magnetron Sputtering and also the manufacturing of semiconductors. Because of the inherent advantages, the studies on the following areas of surface physics and engineering may be carried out utilizing low pressure plasma:

- Utilizing such facility, it is possible to deposit a broad range of silicon rich silicon dioxide with varied silicon to oxygen ratio, silicon oxynitride, cerium doped silicon oxynitride which are the major ingredients of photonic research. The ability to grow silicon carbide based materials creates a great impact to the related scope of the above research [11, 12].

- In this method, suitable films of Silicon dioxide, Silicon Nitride and amorphous silicon may be synthesized at controlled temperature. So, the synthesis related to solar cell produced from amorphous silicon and the two sides hetero-junction solar cell produced from SiH_4, N_2, Ar and organo metallic precursors are the direct application oriented works to be mentioned. Recent findings show that the solar cells produced by silicon nano wires gives very high conversion efficiency (44.5%) of the solar power. So, developing nano structured devices by this route will yield superior result in the renewable energy research [13].

- With suitable arrangement, nano structures e.g., ZnO nanowire, diamond like carbon film, the nanometer thickness thin film of Al doped silicon oxide, nitrogen rich silicon nitride Si_3N_4 may be developed in this method. Synthesis of nano structured super hard thin films/materials composition region of the ternary (C-B-N) system i.e., C_3N_4, SiC, BN are the subject of concerned work [14, 15].

- The deposition of oxides like Y_2O_3 and Yttria stabilized Zirconia (YSZ) may be developed by ECR plasma assisted metal organic chemical vapour deposition (MOCVD). These oxides are suitable for use in specialized high temperature and nuclear environment.

- ECR plasma assisted chemical vapour deposition of oriented diamond films can be carried out. This appears to be a specific candidate for nuclear detector applications [16].This kind of set up facilitate the chemical vapor deposition of Diamond like Carbon (DLC) containing nano-composite films.

- The semiconducting compound of YBaCuO [$Y1Ba_2Cu_3C_6$ at $>900^0$C &$Y1Ba_2Cu_3C_7$ at $>400^0$C] can be produced at controlled temperature and the deposition of Niobium thin film inside the superconducting cavity may be one of the best suitable and typical work to be carried out. The inner surface of any uncommon shaped cavity can be coated with the

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desired superconducting material may be carried out in the ECR plasma enhanced CVD process [17, 18].

- Currently ITO indium tin oxide-based materials are used in electro optic modulators, window heaters, solar cells, electro-chromic mirrors, and flat-panel displays. In addition, indium oxide nanostructures are promising device materials for chemical sensors in the upcoming nano-electronic era.

V. CONCLUSIONS

The design of an ECR plasma based multipurpose implantation facility is discussed here.The low pressure plasma has very high internal energy due to the presence of the charged particles. The thermodynamically allowed but kinetically hindered in a conventional processes are viable at a very high rate under plasma conditions. The proposed set up can be widely used in several industrial processes e.g., developing thin films by Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD), magnetron Sputtering etc [19, 20]. This set up is also suitable for modern semiconductor development and research. Moreover, the facility can easily be configured online for surface modification by ion beams, neutral particles and ECR plasma. So, the setup is very much suitable for preparing thin films of nanometer thickness and also for developing nanostructure in the route of plasma assisted chemical vapor deposition. Finally, it can be concluded that with the invent of a variety of dopants, the tools will ensure its uses for continued research in the world of nano science and technology.

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