Career Development Plan

I. Introduction

Much of this nation's technological infrastructure depends upon microelectronics. Our society continually demands the development of faster and more powerful consumer electronics. The fabrication of these devices requires methods that can create smaller and smaller features (sub-micron) on integrated circuits. Furthermore, these devices must be fabricated with a high degree of reliability and reproducibility with methods that are economically viable and environmentally friendly.

In the past decade the microelectronics and semiconductor industries have borrowed technologies from diverse fields such as fusion and astrophysical research to develop a technique to fabricate the present generation of microelectronic components; this technique is plasma processing. Using plasmas to process and fabricate these devices has become commonplace in all facets of the microelectronics industry.

Since plasmas are typically produced under vacuum conditions, plasma processing systems inherently provide the clean environment required for integrated circuit production. Additionally, the waste products produced by plasma processing techniques are minimal compared to traditional chemical processing techniques, thus making plasma processing an environmentally attractive method of production. As plasma processing techniques become applied to a larger fraction of semiconductor products, it is increasingly vital to understand the effect of the plasma parameters (density, ion temperature, electron temperature, etc.) on the thermal stability, electrical properties, and material and chemical characteristics of devices produced via plasma processing techniques.

At Fisk University, through the NASA-Fisk Center for Photonic Materials and Devices, the expertise and facilities exist to perform comprehensive studies of the growth of wide bandgap semiconductors and ion-implanted materials as well as complete analyses of the material, electronic and chemical properties of those materials. Thus, a natural extension of this research effort is a fundamental investigation of the effect of the plasma parameters on the surface morphology, surface chemistry and induced surface damage of materials.

This proposed work is a five-year plan that calls for the development of a new uniform plasma source at Fisk University, the Fisk Plasma Source (FPS), that will feature three methods of plasma generation. In collaboration with the NASA-Fisk Center, target materials will be provided for exposure to plasmas formed in the FPS. During the first eighteen months of this research program, while the Fisk Plasma Source is under development and construction, a linear plasma source at Auburn University will be used to perform initial experiments on plasma-materials interactions. The ultimate aims of this work are to develop plasma-processing techniques to enhance the existing device fabrication facilities at Fisk University and to compile a comprehensive experimental and theoretical database on the interaction of plasmas with materials.

The proposed research project is inherently multi-disciplinary covering topics of relevance to plasma physics, chemical physics, and materials science. This facilitates a wide range of educational and experimental opportunities for both the undergraduate and graduate students in the Physics Department of Fisk University. These research opportunities will be coupled with a new laboratory training course that focuses on experimental skills (such as vacuum and microwave technologies) that are vital for success in both the modern scientific workplace and in graduate studies. The goal of this course is to broaden the skills of the undergraduate physics major to make him or her more highly competitive in the global marketplace.

II. Motivation

Industrial applications of plasmas include:

(a) preparation and cleaning of surfaces [1],
(b) etching of electronic components [2,3],
(c) low energy ion implantation [4].

Most importantly, plasma processing techniques are capable of producing surface features of sizes ~ 1μm. However, problems related to the interaction of plasma particles with target materials remain. Fully understanding plasma-materials interactions will become increasingly important as the size of etched surface features becomes further reduced in size.

Two of the critical factors in the development of a plasma processing system are the plasma parameters that are required for a particular process and damage to the target material as a result of undesired plasma-surface processes. This project will address both of these factors.

II.A Plasmas and Plasma Sources

Plasma is commonly referred to as the “fourth state of matter”. A plasma is formed by ionizing and heating a gas. The plasma is formally defined as a quasi-neutral ensemble of the charged (ions and electrons) and neutral particles that exhibits a collective (i.e., fluid-like) behavior. Because a plasma consists of charged particles, it can be affected by applied electric and magnetic fields.

The commercially available plasma processing systems employ one of three techniques to produce a plasma. The first method uses an electron cyclotron resonance (ECR) source. These sources typically make use of standard 2.45 GHz microwave sources to initiate plasma formation and to raise the electron temperature [2, 5]. A second method uses radio frequency (RF) sources to form plasmas. In RF sources, typically the ions are heated by the applied RF electric fields [6]. In particular, recent studies indicate that helicon wave (a branch of the ion acoustic wave) RF sources are ideally suited for plasma processing applications [7]. Both ECR and helicon RF sources typically produce "high density" plasmas (plasma densities, $n \sim 10^{17}$ m^{-3}).

A third method of producing a plasma is to form a DC discharge. This requires the formation of a large enough static electric field to cause a neutral gas to "break down". Plasma generation systems such as the hollow cathode discharge (HCD) have used this method to produce plasmas for many years [8].

The main challenge in designing plasma sources for plasma processing applications is the production of a high-density, low temperature plasma ($T_e \leq 15$ eV and $T_i \leq 2$ eV). Magnetic fields are often used to provide control of the plasma density and temperature profiles. Nonetheless, there does not exist a single plasma production scheme that satisfies all of the requirements for an “ideal” plasma source.

The plasma source proposed in this project is a unique source for investigating the physics of plasma-materials interactions. It will incorporate all three of the aforementioned plasma production systems on a single device. As a result, this experimental program will be able to perform studies over a wide range of plasma parameters. Furthermore, this research can develop techniques for optimizing the plasma parameters necessary for plasma processing systems.

II.B Previous Studies of Wide Bandgap Semiconductors at Fisk University

The study of wide bandgap semiconductors at Fisk University is carried out by the Material Science and Applications Group, led by Dr. Arnold Burger. The research program has produced more than 33 publications, 64 conference presentations, one patent [9] and two book chapters [10]. A vigorous research effort is being carried out in the purification of electronic materials and growth and characterization of semiconducting crystals such as HgI_2, PbI_2, ZnCdTe and ZnSe.

The research program at Fisk has extensive capabilities including: crystal growth of mercuric iodide by physical vapor transport, processing novel heavy metal iodides and II-VI compound binary and ternary single crystals; characterization of electrical, optical and thermal properties of these compounds; design, fabrication and evaluation of electronic devices, such as room temperature x-ray and gamma-ray detectors, photodetectors. Selected materials studied by this research group are wide bandgap semiconducting and semi-insulating crystals having found numerous photonic applications including radiation detectors, solid-state lasers and photovoltaic junctions.

New instrumentation was acquired, and special equipment was designed and built for the purification, synthesis and crystal growth of photonic materials, and for their characterization. As a result, the Material Science group has become internationally recognized as one of the major institutions conducting research in the area of wide bandgap semiconductors for room temperature X-ray and gamma-ray detectors.

Specific capabilities of the lab to characterize grown crystals include:

a) Low temperature photoluminescence measurements help us understand the mechanisms of point defect formation in crystals grown under different growth conditions.

b) Differential Scanning Calorimetry measurements aimed at adding complementary quantitative evidence of compositional deviations from stoichiometry.

c) Measurements of the electrical properties using short laser pulses or X-ray for the purpose of obtaining useful parameters on mobilities and lifetimes of electric charge carriers.

d) High resolution Atomic Force Microscopy, for determining the surface morphology of grown crystals. The data may provide micro and nano scale evidence of the modifications induced during plasma modification. The research will provide assessment tools that may help establish the relationship between convection and perfection and homogeneity of the crystals.

For this proposed project, cadmium zinc telluride (CdZnTe) semiconductors will be used as a target material. CdZnTe has been developed as a room temperature radiation detector in recent years due to its better performance and portability compared to CdTe and HgI_2. In the detector fabrication process, surface modification, such as passivation, etching and oxidation, play an important role in subsequent detector performance by means of reducing surface leakage current.

It is proposed therefore to investigate the incorporation of a plasma processing step in the fabrication of radiation detectors. Plasmas will be used to etch and form oxide layers on prepared samples. The aforementioned characterization techniques will compare chemical and plasma etching techniques. The study will be directed towards finding the conditions that will lead to the optimization of surfaces prior to their metallization by reducing the concentration of surface defects (recombination centers, impurities, etc.). The use of plasma etching treatments will be first applied to single element detectors and will be later applied to the detector array technology. Improvements in the detector fabrication technology are anticipated which may benefit several of the U. S. private companies maintaining the lead in this field.

II.C Previous Studies of Ion-Implanted Materials at Fisk University

The study of ion-implanted materials at Fisk University is carried out by the Chemical Physics Laboratory led by Dr. Don Henderson. This research program has led to the publication of more than 20 scientific articles and has received considerable visibility in the field of nanophase materials. The research effort at Fisk benefits greatly from a strong research collaboration with the Solid State Division at the Oak Ridge National Laboratory (ORNL). Ion implantation is performed at ORNL while characterization of the ion-implanted materials is performed at Fisk. This group is pursuing studies of a variety of nanocrystals including Au, C, Cu, Pb, and other metal colloids into CaF_2, MgO, Al_2O_3, mica and amorphous SiO_2.

Metal colloids and semiconductor nanocrystals (quantum dots) have recently drawn considerable attention from the scientific community. This interest originates from the potential application of these materials for optical devices based optical bistability. The technological importance of these materials covers a broad range of applications: (1) all-optical switching devices that operate on the femtosecond time scale; (2) ultra-high density memory storage media; (3) waveguide lasers; (4) phase conjugate devices for correcting aberrations in optics; and (5) electroluminescent devices. On other hand, these materials, studied from a fundamental perspective, allow for evaluating and verifying quantum and dielectric confinement models developed for quantum dots and metal colloids.

Recently it has been demonstrated that ion implantation is a versatile method for fabricating quantum dots and metal colloids [11-13]. This method is direct and chemically clean as compared to other approaches that have been taken for fabricating metal colloids and quantum dots. In addition, one has the freedom to select a dielectric host that is particularly suited for probing the optical properties of the quantum dots and metal colloids. This becomes particularly relevant when the research reaches the stage of device design.

The technique of ion implantation does suffer from the problem of producing quantum dots and metal colloids that have narrow size distributions. Additional problems arise from the structural damage caused by the implantation process. These difficulties are also intrinsic to other fabrication methods. The dispersion in the size distribution of quantum dots and metal colloids formed by ion implantation originates from the concentration profile that is developed by the implantation process itself. A process that leads to increasing the size dispersion of quantum dots and metal colloids is the thermal annealing process. Unfortunately, the resulting dispersion in particle size often washes out the interesting structure that is predicted from quantum and dielectric confinement theories. Accordingly, new process methods must be explored for controlling the size distribution of quantum dots and metal colloids while reducing the structural damage caused during implantation.

It is proposed that the thermal annealing process be replaced by a short (≤ 50 ms) plasma pulse. By controlling the plasma temperature and density this plasma pulse can rapidly deposit energy onto a substrate. Recent experiments using pulsed DC plasma sources with current densities of up to 10 A/cm^2 have shown that plasmas can be used effectively to induce recrystallization of material surfaces [14]. Of particular interest is the use of plasma annealing to remove the damage caused by high energy ion implantation. It may also be possible, for rapid and large temperature rises, to develop techniques for controlling the size distribution of quantum dots and metal colloids.

Specific diagnostic capabilities of the Chemical Physics Laboratory to analyze plasma processed materials includes:

a) Hitachi UV-Vis-NIR spectrophotometer with scan range of 185 - 3,200 nm and resolution of 0.1 - 8 nm. It allows us to investigate structural defects due to ion beam damage and band gap of quantum dots and surface plasma resonance of metal colloids formed in dielectric hosts.

b) Continuum Model PY61C picosecond Nd:YAG laser with 2nd, 3rd and 4th harmonics together with to be installed dye laser and UV extension can cover 200 - 1064 nm wavelength region. With it, we can conduct both time resolved and nonlinear spectroscopies on variety of nanophase materials.

c) DI Nanoscope III scanning probe microscope (SPM) which operates in both contact and tapping mode of atomic force microscopy (AFM) and scanning tunneling microscopy (STM). This equipment allows us to study surface morphology and certain types of surface chemical composition via lateral force measurement.

d) Rudolf Ellipsometer can measure the optical constants of various substrates. Multi-angle measurements allows us to do depth profiling with the precision of a fraction of an angstrom.

II.D Plasma-Induced Damage to Materials

Materials exposed to plasmas can suffer several types of damage due to plasma-materials interactions. These include: (a) sputtering and defect production, due to the impact of energetic particles from the plasma; (b) unwanted chemical reactions with the various plasma species; (c) impurity deposition from the plasma; and, (d) charging due to the flux of charged particles from the plasma to the material surface. These forms of plasma-induced damage can have many effects on the properties of the target material.

Defect production is perhaps the most serious form of damage resulting from plasma processing[15]. This is a consequence of direct plasma particle impacts onto the surface of a material which causes the displacement of atoms in the material. In high density plasmas, lateral notching, which is another form of physical degradation of the material structure can occur [16]. This type of damage can produce damage in etched structures $\sim 1\ \mu\text{m}$ across and may pose a serious limitation in further reducing the size of etched structures. Oxide charging (a degradation of the band gap in semiconductors) results from the flow of charged particles from the plasma to the target material [17]. This form of plasma damage alters the electrical characteristics of a material and reduces the reliability of electronic components made from those materials.

Through the collaboration with the NASA-Fisk Center for Photonic Materials and Devices, wide bandgap cadmium zinc telluride (CdZnTe) semiconductors (produced by the Center’s Material Science group) and ion-implanted silica glass (produced by the Center’s Chemical Physics group) will be exposed to plasmas generated by the Fisk Plasma Source. The facilities of the Surface Science group, X-ray photoelectron/Auger spectroscopy (XPS/AUGER) and associated UHV equipment, will also be used to determine the surface morphology and surface chemistry of plasma processed samples.

Studies will focus on control of plasma-materials interactions. The plasma parameters will be modified via the magnetic field strength, gas fill pressures, and simultaneous operation of the various plasma generation systems. The plasma parameters will be iterated in order to obtain a balance between an efficient rate of processing (e.g., etching or oxide removal) and the type and level of plasma-induced damage (e.g., charge buildup or defect production).

II.E Development of Educational Programs at Fisk University

An essential component to all university-based research is the education of graduate and undergraduate students. With the well-documented difficulties in the physics job market [18] and evidence indicating a decline of the physics undergraduate population [19], it is vital that current physics students be given the necessary skills to succeed in an increasingly competitive marketplace. This is particularly important for students at one of the predominantly African-American universities, such as Fisk University.

At Fisk University, there is a strong tradition of excellence in both research and education. Some 60% of Fisk undergraduates pursue advanced degrees. Although Fisk University is a small (total enrollment is approximately 850 students), liberal arts university, there is a strong emphasis on research. Students working in the Fisk Physics Department have produced over a dozen publication and presentations in the past two years. Current research projects in the physical and biological sciences receive funding through NSF, NASA, DoEd, DOE, DHHS, ONR and the EG&G Corporation. Also, Fisk University is a designated NASA research center on photonic materials.

As part of this proposal, a new course, titled *Modern Laboratory Techniques,* is to be developed for upper-level undergraduate students (juniors and seniors) and first-year graduate students in the physical sciences that will enhance their skills as researchers. Lectures, experiments, and computer-based activities are combined into a single course that focuses on introducing these students to laboratory techniques relevant to the modern scientific workplace.

III. Proposed Work

This proposal aims to develop plasma-processing techniques to enhance the existing device fabrication facilities at Fisk University and to compile a comprehensive experimental and theoretical database on the interaction of plasmas with materials. There are three main tasks for this proposed project. First, is the development of a new high density, uniform plasma source at Fisk University, the Fisk Plasma Source (FPS), that has the capabilities to produce plasmas using electron cyclotron resonance (ECR) heating, a hollow cathode system, and a helicon wave system. The second task is to introduce semiconductor and ion-implanted materials produced in collaboration with the NASA-Fisk Center for Photonic Materials and Devices into hydrogen, helium and argon plasmas generated by FPS. Here, an investigation into the electrical, chemical and optical properties of plasma-exposed materials will be performed. The third task of this proposed project is to provide the graduate and undergraduate physics students at Fisk University the opportunity to participate in research and educational activities that will help prepare them for careers in the modern scientific workplace.

Brief descriptions of the experimental and educational phases of this project are presented in the following sections. Fig. 1 shows the time table for the experimental and educational objectives for this project.

III.A Phase I: Design and Construction of the Fisk Plasma Source

The first phase of the proposed project is to design and construct a new class of linear plasma source, the Fisk Plasma Source (FPS). This source will combine a 2.45 GHz ECR microwave source, a helicon wave RF source, and a hollow cathode discharge configuration for plasma generation. This combination of plasma generation systems facilitates greater control of the plasma parameters. The objective is to develop the techniques necessary to produce a stable, uniform plasma over a four to six inch diameter target area. The initial target parameters of the plasma source will be:

(1) Plasma Density (n): ~ 10^{17} m^{-3}
(2) Electron Temperature (T_e): < 5 eV
(3) Ion Temperature (T_i): < 2 eV
(4) Magnetic Field Strength (B_0) 1 kG (on axis, typ.)

Plasmas are to be formed using argon, hydrogen, and helium gases. The primary goal of the first phase of this project is to make “first plasma”, using the ECR configuration, by the end of the first year.

The FPS will be constructed from standard five-way and six-way stainless-steel crosses. This allows standard vacuum components to be purchased thereby reducing overall costs facilitating ease of maintenance and repair to vacuum hardware. The FPS will be a high-vacuum system that uses diffusion pumps rated at an ultimate pressure of 4×10^{-9} torr, thus ensuring a minimum of non-plasma particulate contamination to experiments.

The plasma source will be magnetized. Solenoid electromagnets will surround the main vacuum vessel. These magnets will produce an on-axis magnetic field strength of up to 2 kG. This will allow experiments to be performed using both first and second harmonic ECR heating (the required magnetic field strength for first harmonic ECR at 2.45 GHz is 875 Gauss; for second harmonic ECR, 1750 Gauss). Fig. 2 shows the preliminary configuration of the FPS.

Upon completing the assembly and “first plasma” studies of the FPS, a careful characterization of the plasma parameters will begin. Initial measurements of the plasma parameters will begin around the 13th month of this project and be performed routinely throughout the course of this project. Single and double Langmuir probes, an emissive probe, a gridded-energy analyzer, and optical spectroscopy will be used to measure the plasma parameters. These diagnostics will measure the plasma density, ion and electron temperatures and plasma potential. During the second year, the helicon wave and hollow cathode plasma sources are also expected to become operational, greatly expanding the parameter space over which plasmas can be generated in the FPS.

Concurrent with the development of the plasma generation systems, the hardware needed to place target materials into the FPS will be designed and constructed. By the end of the second year of this proposed project, the first plasma-material interaction experiments using the FPS will be performed.

III.B Phase II: Characterization of Plasma-Induced Damage to Photonic Materials

The second phase of the project will be performed in collaboration with the NASA-Fisk Center for Photonic Materials Research in the Physics Department of

Fisk University and with the Auburn University Physics Department. Experimental studies will focus on exposing CdZnTe semiconductors and gold implanted silica glass to plasmas.

During the first eighteen months of this research program a linear plasma column at Auburn University will be used as a plasma source. This is the period of time during which the FPS will be under construction at Fisk University. The plasma source at Auburn University will be used to provide preliminary data on the interaction of plasma with the target materials and to highlight experimental difficulties that may arise in performing these experiments. Thus, granting us the opportunity to refine the experimental techniques that will be used on the FPS. However, the plasma source at Auburn uses solely a 2.45 GHz, ECR plasma generation system thus limiting the range of plasma parameters that can be investigated.

Beginning in the third year, and throughout the remainder of the project, the material production facilities of the Center will be used to provide target materials for exposure to plasmas produced in the FPS. The Center facilities will also be used to make a detailed and comprehensive analysis of plasma-induced damage to the target materials.

Initial experiments will involve targeting both semiconductor and ion-implanted materials with non-chemically reactive plasmas; e.g., helium and argon. These studies will examine the role of sputtering damage and defect production due to different ion species and ion energies. In particular, experiments will be performed that will examine the transfer of energy and momentum from plasma ions to the substrate. Experimental measurements of the penetration of plasma ions into the substrate will be compared against Monte Carlo simulations of plasma-materials interactions.

Further experiments will also investigate how a chemically reactive plasma, hydrogen, induces damage to a substrate. Comparisons will be made against similar plasma parameters in used in helium and argon plasmas. Experiments will also be performed to optimize the plasma parameters of a hydrogen plasma so as to maximize the etching rate of CdZnTe semiconductors while minimizing the induced plasma damage. The design of the FPS is uniquely suited to this task since its three plasma generation systems and flexible magnetic field systems will facilitate a large degree of control over the plasma parameters.

In a related series of experiments, the hollow cathode configuration will be used to produce a fast plasma pulse to perform plasma annealing experiments. Here, the plasma will be used to induce surface melting and recrystallization of the surfaces of ion-implanted materials. These experiments have only recently been attempted [17] and have been shown to yield positive results at inducing recrystallization of the upper layers ($\leq$ 100 nm) of substrates with defects. It is then desirable to explore the use of the pulsed plasma source to evaluate its capability of controlling the size and size distribution of quantum dots and metal colloids. The systems we intend to investigate are those that have best characterized and include gold colloids in MgO, SiO_2, CaF_2 and InP and GaAs quantum dots in amorphous SiO_2. The parameter space of pulse length and plasma energy will be evaluated to produce the optimal configuration for best controlling the size of the metal colloids and quantum dots while minimizing plasma-induced perturbations to the substrate. The diagnostic equipment required to analyze the electrical, chemical, and optical properties of plasma exposed materials are readily available in the Chemical Physics and Surface Science Laboratories at Fisk University.

III.C Phase III: Student Participation in Research and Educational Activities

Student participation and mentoring will be strong components of this research project. Both undergraduate and graduate students will be actively recruited to participate in the design and construction of the FPS. It is expected that during the first phase of this project, the design, construction, and characterization of the plasma source, up to 3 graduate students will receive Master's degrees (the highest degree offered by Fisk University) in Physics based upon the development of the microwave plasma generation system, the design and modeling of the magnetic field system, and the development of the plasma diagnostics. An additional 3 to 5 undergraduate students are expected to participate in this phase of the project as well.

During the second phase of the proposed work, students from the Chemistry, Biology and Physics departments are expected to participate in the continuing studies of plasma parameter control as well as plasma-material interactions. It is also expected that graduate students will be involved in the development of Monte Carlo simulations of plasma particle behavior and plasma-material interactions. During all phases of this proposed work, students will be encouraged to present the results of their research at regional and national conferences.

The new *Modern Laboratory Techniques* course will begin during the third year of this project. This will allow the PI the time to complete his first three-year cycle of courses at Fisk University. Although the course will be open to all qualified students, those students who are directly involved with research on the FPS will be strongly encouraged to participate in the course. Topics to be discussed in this course include:

(a) vacuum technologies,
(b) materials growth and processing,
(c) microwave and radio-frequency produced plasmas,
(d) computerized data acquisition systems,
(e) integrated circuits,
(f) optical spectroscopy.

The course is designed for a small class, typically 7 to 10 students, to facilitate strong student-teacher interactions. The class will alternate weekly between lectures and laboratory activities. The objective is to provide the student with a setting in which he or she can actively participate in the laboratory activities and gain those abilities which are most sought out by the employers whose companies engage in scientific activities or to give the student a head start on the experimental skills that are needed to pursue an advanced degree. It is believed that this course will be of such a great value to the students that it will become a regularly offered class of the Physics department.

IV. Summary of Prior Research and Education Accomplishments

The Principal Investigator of this project is Dr. Edward Thomas, Jr., a recent recipient of the doctorate in Physics (August, 1996) and a new Assistant Professor of Physics at Fisk University. Dr. Thomas has research experience in the areas of experimental and computational plasma physics with seven publications and a dozen conference presentations, including 4 poster presentations at the American Physical Society - Division of Plasma Physics Conference.

Of particular relevance to this project, the PI has performed experiments with hydrogen, helium and argon plasmas produced by both a Hollow Cathode Discharge (HCD) device and by an ECR microwave source. He is experienced at designing, constructing, and operating various plasma diagnostic tools including: Langmuir probes, emissive probes, Mach probes, **E** x **B** probes (omegatrons), ion and electron guns, and gridded-energy analyzers. Dr. Thomas is experienced at performing experiments which can characterize and modify plasma parameters. The PI also has extensive computational experience in modeling vacuum magnetic fields (for stellarator devices), single particle trajectories in toroidal devices, and Monte Carlo simulations of particle emission from ion and electron guns. Further details are given in Sec. E of this proposal.

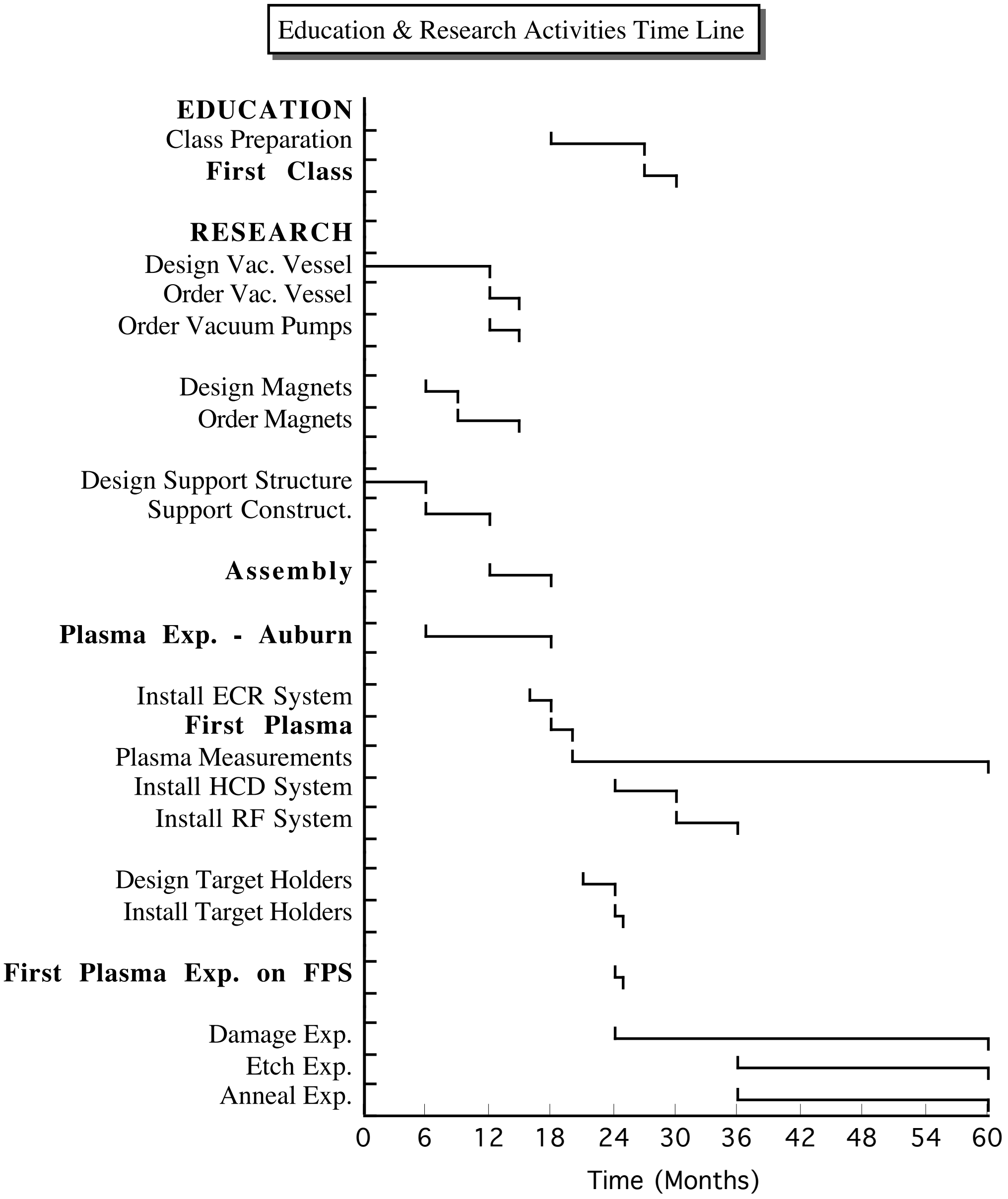
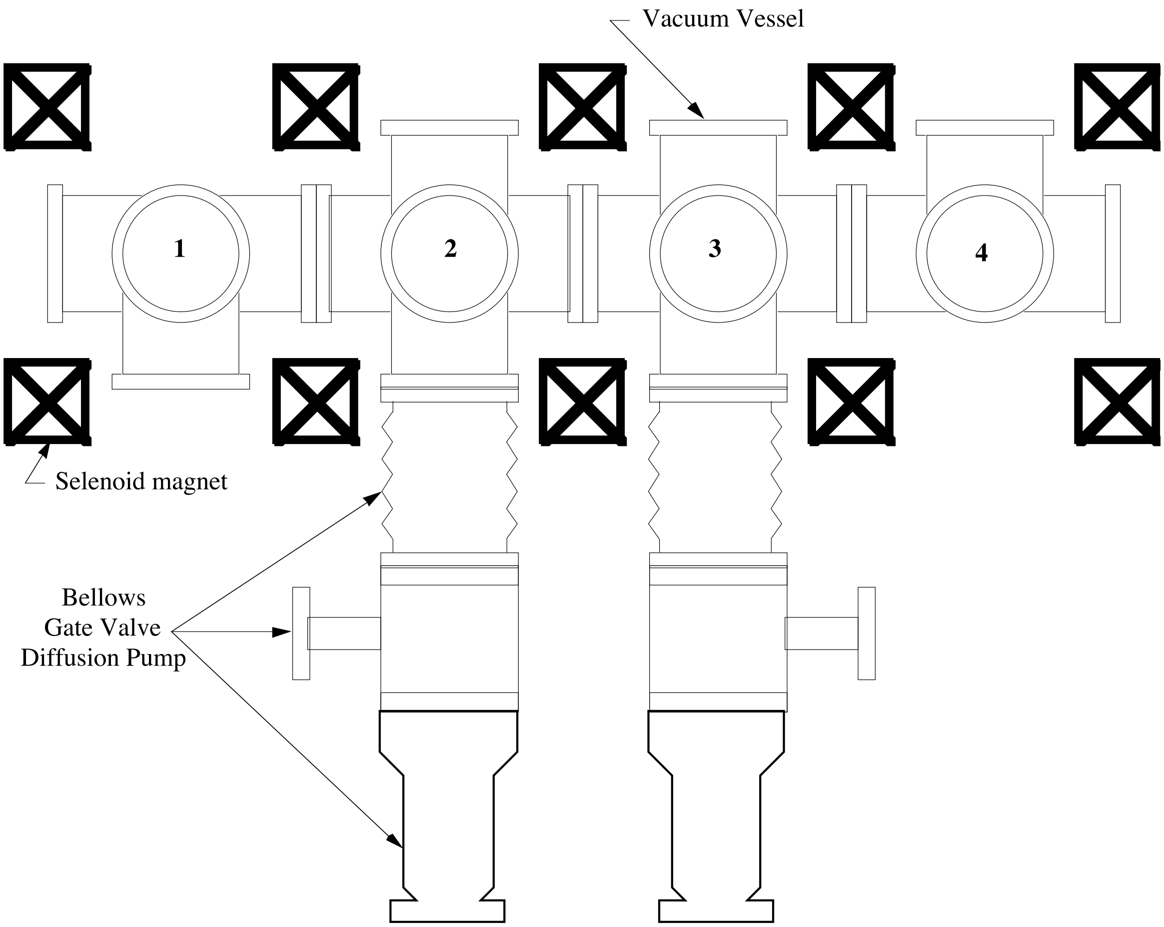


Fig. 1: Time line of activities



Sec. 1: Hollow Cathode Source, Helicon Antenna
Sec. 2: Microwave Source, Langmuir Probes
Sec. 3: Langmuir Probes, Emissive Probes, Energy Analyzer
Sec. 4: Sample Holder, Langmuir Probes, Optical Spectrometer

Fig. 2: Preliminary Design of the Fisk Plasma Source

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