Engineering and research education in Plasma technology

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INTRODUCTION

Plasma technology engineering is not very well-known by undergraduate students and very few engineering schools dedicate a complete semester to this subject. The plasma state is often considered as the fourth state of matter and basically consists of an ionized gas. 99.99 % of the Universe is made of plasma. They are also present in a natural state on earth (boreal aurora, lightning, and ionosphere).

Although they are not very well-known by the general public, plasmas are used for most of high technology devices. Indeed, one of the main applications of plasma technology is related to micro and nanotechnologies[1]. For instance, in a clean room of production of Integrated Circuits for memories or microprocessors, more than 50 % of the equipment consist of plasma reactors. Plasma technologies are also used for many other applications in materials industry (coating, functionalization), in chemical industry (gas abatement, gas production …), in medical industry (plasma sterilization, plasma treatment…) and in many other industries.At Polytech Orleans [2], a complete semester is dedicated to plasma technology in a master level within two courses of 120 hours each, called “Plasma Sources” and “Plasma Processing”. A strong collaboration with the GREMI lab[3] and different companies is very beneficial and necessary if we want the students to have access to expensive and state of the art equipment.

In the next sections, we introduce the different types of plasma sources and processing that are usually used in the industry and studied in this education program. We will detail the pedagogy. The last section is dedicated to the pedagogy by project which is followed in this educational program.

1 PLASMA SOURCES

1.1 Introduction to plasma physics education for engineers

A plasma is a very complex medium. Many different prerequisites are usually required in physics and chemistry to have a deep understanding of the mechanisms involved in such a medium. Most of the industrial plasmas are created by electrical discharges from various types of electrical excitations: Direct Current, Alternative Current, Radio Frequency, microwaves, pulsed power…[1].It is also important to teach the complex technology involved in plasma sources, which includes vacuum systems, gas injection, cooling, electrical power supply and optical and electrical diagnostics. Our educational program in plasma engineering comprises theoretical and practical aspects.

1.2 Different types of plasma sources

Different electrical excitations are used in the industry to produce plasmas. The simplest one is directcurrent discharges where a high voltage is applied between two electrodesin a gas at a low pressure (Fig. 1). This technology is usually used for lighting (Neon tubes, spectral lamps), for metal deposition by sputtering (DC magnetron) and for the production of arcs (torch plasmas, arcs).

Fig. 1: Picture of a DC discharge tube with Argon. Cylindrical probes are placed along the plasma to electrically characterize the plasma.

AC discharges at low frequency are also used for lighting and in Dielectric Barrier Discharge. The principle and mechanisms of such discharges are very close to those obtained in DC discharges.

Many industrial reactors operate at radio frequency discharges. The main advantage relies on the fact that such a plasma can be ignited through a dielectric window, which avoids metallic contamination from the cathode to the plasma. In such plasmas, the displacement current dominates. Electrons of the plasma which are light and mobile can follow the RF voltage fluctuation. This is not the case for ions, which are much heavier. In Fig.2, we show an inductively coupled plasma excited by a radio frequency current at 13.56 MHz flowing in an antenna mounted by the students of thePlasma Engineering option at Polytech Orleans. The antenna is placed on a Pyrex window. A metallic grid was placed around the antenna to form a Faraday cage and to reduce significantly the electromagnetic radiation outside the plasma reactor.

Fig 2: Example of an oxygen plasma created through a dielectric window by an antenna excited by a radiofrequency current.

Microwave and pulsed plasmas can also be used and offer different advantages for some processes. The discharges can operate in a very wide range of pressure from very low pressure (less than 1 Pa) to the atmospheric pressure (10^5 Pa). Atmospheric pressure plasmas usually do not need a complex vacuum system like at low pressure, which makes the system cost reduced. Among atmospheric pressure plasmas, dielectric barrier discharges, corona, arcs, torches and microplasmas are currently used and are presented within this course.

Both low pressure and atmospheric plasmas are of interest in industry. This is the reason why a special attention is given to the engineer students to teach them the relevance of each of these technologies depending on the targeted application.

1.3 Practical works

Practical works are very important in our education program on plasma engineering. Many different reactors are available for the students. Within the plasma source course, the students learn how to create and characterize DC and RF discharges. An experiment is also dedicated to vacuum systems to understand the different types of pumping systems and the different pressure gauges that are usually installed on low pressure plasma reactors. Moreover, in the same course, students learn the basics of atomic and molecular spectroscopy including active techniques and apply these techniques in practical work. For example, an experimental setup including a pulsed laser, a DC discharge and a spectrograph equipped with a photomultiplier is installed to study the Laser Induced Fluorescence of an argon plasma, which is an optical sophisticated and advanced technique to finely characterize a plasma. Optical Emission Spectroscopy is also carried out on an RF discharge in a mixture of Argon and Hydrogen (Fig. 3) to study the dissociation of H_2 molecules.

Fig 3: Picture of the experimental setup used for optical emission spectroscopy of an RF discharge in H_2/Ar plasma.

2 PLASMA PROCESSES

2.1 Introduction to plasma processing

Plasma process engineers are currently hired in companies to propose and optimize recipes from a plasma source to treat or modify a material or a surface. For example, in the microelectronic industry, plasmas are used for thin film layer deposition, pattern etching and surface modification at the nanometric scale. This is a different job from the plasma source designer, but plasma engineers of the two activities usually work in close collaboration. As mentioned in the introduction, many different high technology products require several plasma processes to be fabricated. This is why plasma processing is a very important part of the plasma engineering education program. Physical and chemical treatment are both carried out on materials, gases, liquids or biological matter to modify them or provide them the wanted properties.

2.2 Examples of plasma processing

Lectures are given on non-thermal plasma processes applied to the plasma treatment of effluents (gas, liquid), to the decontamination of surfaces and biological matter and on plasma medicine.
Non-thermal plasma processing is used to generate active species such as O, OH, HO_2, O_3 which can efficiently oxidize organic compounds. Operating parameters of the plasma as high-voltage values, HV type (pulsed, alternative), and pulse repetition rates are all important parameters in order to control, for example, the destruction of pollutants and the produced species. Chemical kinetics is used to explain the chemical pathways and to obtain a better understanding of the chemical reactions implied in the plasma bulk. Examples used in the courses deal with automotive exhaust gas for NOx abatement and Volatile Organic Compounds, industrial liquid effluents, ozone production and biological treatment (bacteria decomposition for the sterilization).

Corona and Dielectric Barrier Discharges are currently used for such applications. Various configurations of these plasma are possible as shown in Fig. 4.

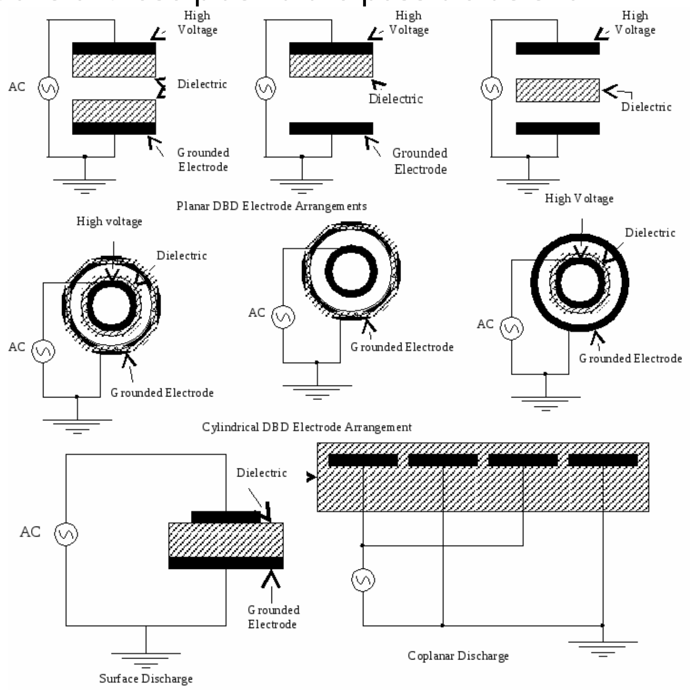

Fig 4: Different configurations of DBD and surface discharges (from [5]).

The use of the plasmas for medicine is extensively studied worldwide and this aspect is also taught at Polytech Orleans. Plasma jet technology developed at GREMI lab offer many perspectives to directly treat different diseases (plasma healing, tumour treatment…) [6].

An important part of the “plasma processes” course is dedicated to deposition plasma processes such as physical vapour deposition and Plasma Enhanced Chemical VaporDeposition and to etching processes. These two applications are very current in the industry, in particular in micro and nanotechnology. Students have access to a clean room at Polytech and GREMI for their project to use the available plasmaequipments. After the plasma process, this is of course important to be able to characterize the effect of the plasma on the treated material. This is why a good part of the course is dedicated to material characterisation.

Another important part of the “plasma processes” course is dedicated to plasma simulation, wherenumerical methods are presented to the students in order to make them capable of simulating a plasma or a process. To illustrate this part, students are given a problem and have to try to solve it by simulation.

2.3 Practical work

Students also perform practical works within the “plasma processes” course. One of the experimental setup consists of creating ozone by dielectric barrier discharge, optimize its production and study its production kinetic. Ozone is then used to oxidize a liquid solution to illustrate the liquid treatment part of plasma technology. Etching and deposition reactors are also available at Polytech. Fig. 5 shows the plasma created in an RF capacitively coupled plasma discharge for thin film deposition. Chemical reactions are also studied using a mass spectrometer in reactive plasmas.

Fig. 5: Plasma deposition process by cathodic sputtering.

3 PROJECTS IN PLASMA ENGINEERING

During the whole semester dedicated to plasma engineering, students carry out a project in parallel to their courses. They all work on the same project, which is divided into different tasks that are managed individually by small groups of students. The previous project was consisting in creating a new plasma reactor following specifications imposed at the beginning of the project. The students need to elaborate a file containing all relevant information on the design of the reactor and their choice for each part of the reactor fabrication taking into account the robustness, the cost and the eco-design of their project. At the very end of the project, the students make a public presentation in front of a jury including specialists of plasma sources. The objective is to make them practice their future job they will carry out in the industry.

4 SUMMARY AND ACKNOWLEDGMENTS

Plasma engineering is not a very well-known activity in the general public. However, more and more advanced technologies require plasma reactors and processes for their fabrication. At Polytech Orleans, a complete semester is dedicated to this option for engineer students who are interested in this fascinating area.

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