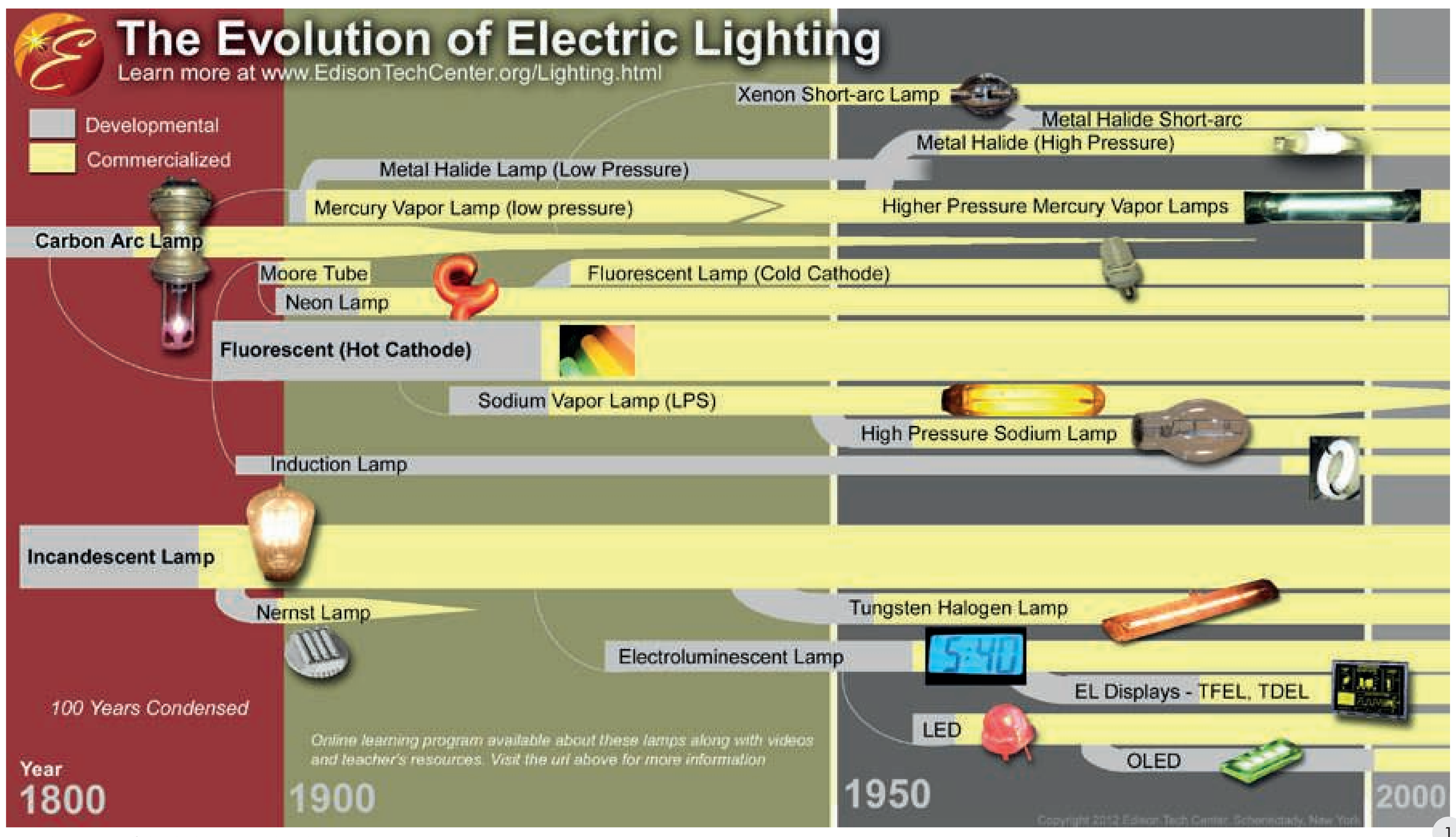
TECHNICAL APPLICATIONS OF THE PLASMA PHYSICS

– by Julia Cipo, Holger Kersten –

Lightning technology



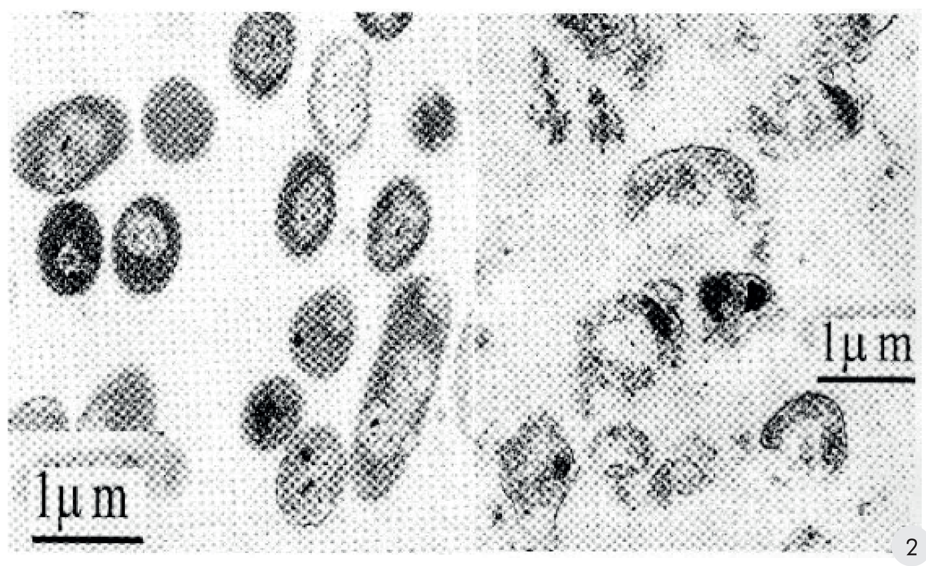
Development of the lightning technology 1

Fluorescent lamps

There are three main types of fluorescent lamps: cold cathode, hot cathode and electroluminescent. The cold and the hot cathode types of lamps are discharge tubes with a fluorescent coating on the inside like for example the energy saving lamps (compact fluorescent lamps), while the electroluminescent lamps consist of phosphor material which is being excited while an electric current passes through the phosphor material.

Arc lamps

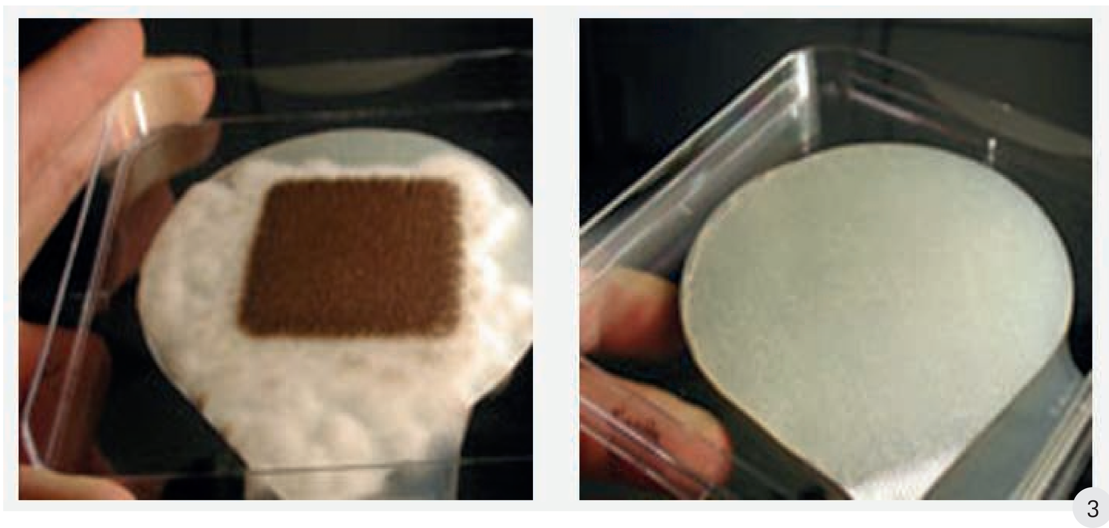
The first form of this type of lamp was the carbon arc lamp. The first to observe glowing gas discharges on a glass vessel was Francis Hauksbee in 1705. The phenomena of continuous arc discharges was seen und studied unaware of each other from Vasily Petrov and from Humphry Davy, which invents the first carbon arc lamp around 1800. The improvement of the carbon arc lamp was a long process, where Pavel Yablochkov and Charles F. Brush played an important role as they developed better carbon sticks which would be consumed slower. In 1875 the first carbon arc lamps were used as street lightning in Paris. The first public application in a department store was made in 1879 in Philadelphia, where Brush ran a number of the lamps in series. In the late 1980s the era of the carbon arc lamps ends and they got replaced by the high-pressure xenon arc lamps, which are more compact and with a light, that doesn't flicker.



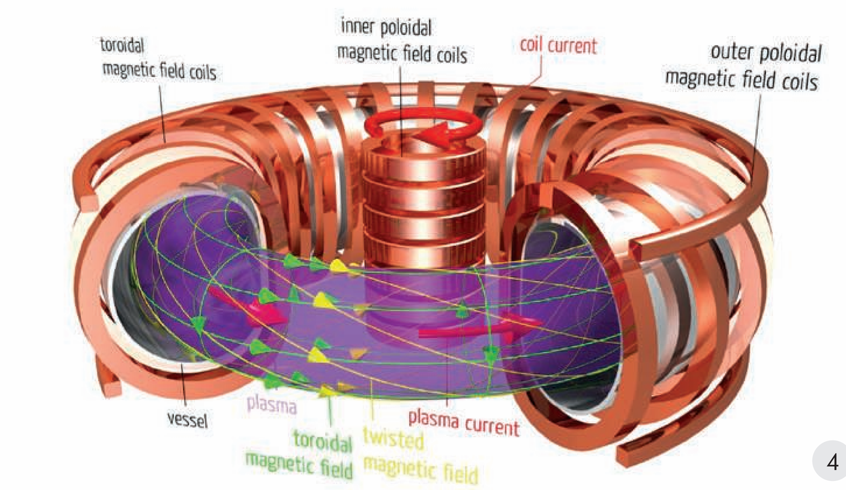
Scanning electron microscopy images of E.coli
(a) before and (b) after 30 seconds of exposure to plasma treatment 2

Plasma medicine

Besides removing layers of contamination from the surface of a material, plasma can also be used to completely kill micro-organisms. This method of plasma sterilization is especially effective in the medical branch, since it can sterilize a surface at room temperatures in a way shorter time that the commercial used methods. The micro-organisms include bacteria, fungi, spores, and viruses and can reach different sizes from 0,1 to 10 m. Some intermediate-pressure plasma sterilizers have been developed and use hydrogen peroxide or peracetic acid as their working gas. Another effective method is the OAUGDP (One Atmosphere Uniform Glow Discharge Plasma), where the working gas is the air itself. Through the present oxygen the basic molecular structure of the micro-organisms can be destroyed by oxidation. Another killing mechanism is in the form of active species of atmospheric plasmas and causes the disruption of the lipid cell wall. This way the cell content leaks in every direction by killing the micro-organisms and so by sterilizing the surface.


Germs killing through plasma treatment 3

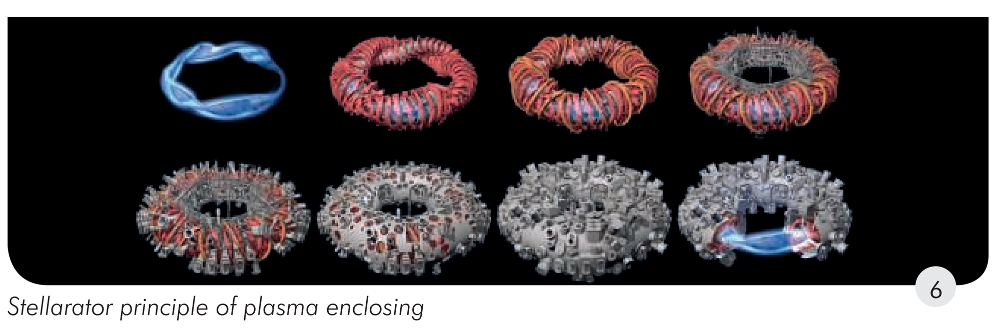
Fusion Research



Tokamak principle of plasma enclosing 4

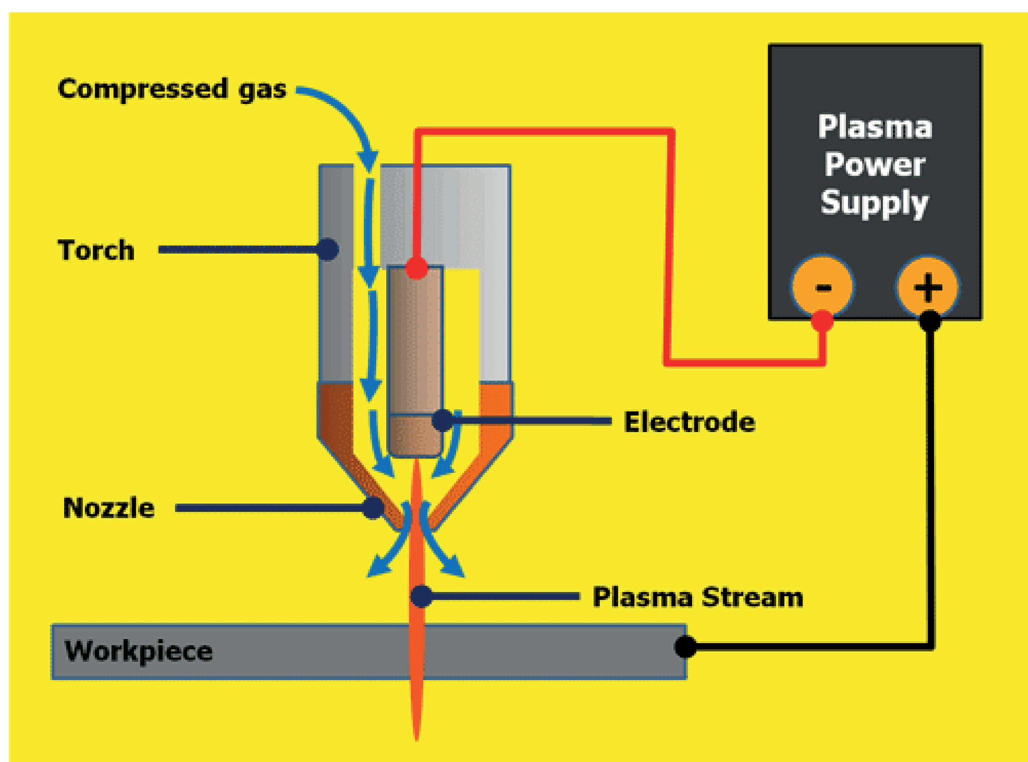
The benefits of the nuclear fusion are being studied since the 1950s. Unaware of each-other's work, the american and the soviet scientists developed two kinds of nuclear fusion reactors: Lyman Spitzer developed in 1951 at the Princeton University the first Stellarator and the soviet physicists Lev Andreevich Artsimovich, Igor Tamm and Andrei Sakharov developed the idea of the first Tokamak in 1952. Both nuclear fusion reactors are based on the encirclement of a high energetic hot plasma. The ionized gas is mostly a mixture of Deuterium and Tritium because the fusion reaction of these atoms is accompanied with a high energy release. This energy appears in form of kinetic energy of the released neutrons, which are later being detected in order to convert their energy into heat energy. It is planned to use the heat for the production of steam, which later can be used in steam turbines to generate electricity. The idea of producing eco-friendly energy with the purpose of creating a continuous energy source is theoretically feasible, but practically more difficult. The Tokamak (Toroidalnaja Kamera w Magnitnych Katuschkach) meaning 'toroidal chamber in magnetic coils' consists of a plasma inside of a toroidal reactor surrounded by magnetic coils. The flow of the plasma is maintained through three magnetic fields created by the plane coils, the round coils and the rotating plasma current. The disadvantage of a Tokamak is the pulsed energy generation, but scientists are optimistic to realize a continuous energy generation, since the results hereof were positive at the ASDEX Upgrade (Axially Symmetric Divertor EXperiment). Now they are working on constructing the largest Tokamak called ITER (International Thermonuclear Experimental Reactor). The first plasma there is expected to be generated in 2025.

By a Stellarator the plasma flow is maintained through the helical complicated formed magnetic coils, which are responsible for the twisting of the magnetic field. Differently from the Tokamak there isn't a current in the plasma to be maintained, making the Stellarator a good option of generating constantly energy. Stellarators have a discrete symmetry and are worldwide used for nuclear fusion research like in Germany at the Wendelstein 7-X or the Large Helical Device in Japan.

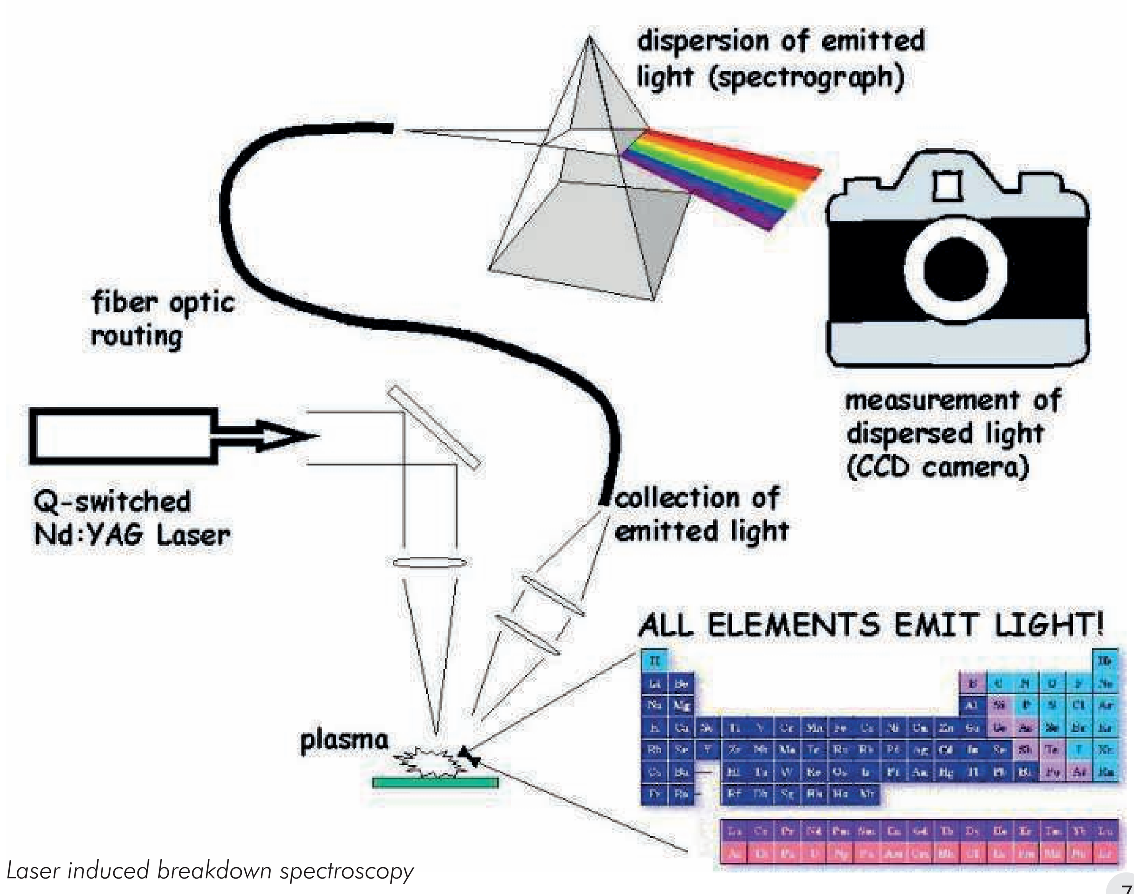

Stellarator principle of plasma enclosing 6

Plasma cutting and welding

Plasma cutting is a process, where a jet of hot plasma is applied to cut conductive materials like steel, copper, brass, aluminium, titanium and more. The first plasma cutting processes have been applied in the 1960s and became popular in the metal industry in the 1980s. The new method brought a lot of advantages with it compared to the "metal-cutting-metal-methode". It did not produce metal splinter, was more precise, cheap and flexible at cutting different shapes. This process uses a plasma torch, which is created by constricting the plasma stream through a small -mostly made of copper- opening. The created plasma arc makes a fast motion from the electrode in the torch to the conductive material being cut. The most used material for the electrode in the opening is tungsten, while the most common gases in the plasma torch are oxygen, nitrogen, argon, hydrogen, methane and compressed air. The plasma cutting process is applied in the automotive industry, fabrication shops and scrapping operations. Another purpose of using plasma torches can be the plasma arc welding process. In this method two inert gases are involved: the shielding gas, that is placed around the outer nozzle in order to shield the molten weld from the atmosphere and the plasma gas, that gets ionized and flows through the opening to create the plasma arc. Here it can be differed between two kinds of arc processes: the non-transferred arcs, where the arc discharge takes place between the electrode and the confining nozzle and the transferred arcs, which is formed between the electrode and the material to be treated. The transferred arcs possess a larger energy density, so they are mostly used for metal cutting and welding. The non-transferred arcs are usually only used for welding. The process of plasma arc welding and cutting was developed by Robert M.Gage in 1953 and later patented by him in 1957.



How a plasma arc cutting torch works 5



Laser induced breakdown spectroscopy 7

Mass spectroscopy

Another application of plasma gases is found in the spectroscopy, especially during the ICP-MS (Inductively Coupled Plasma Mass Spectrometry) and the LIBS (Laser-Induced Breakdown Spectroscopy). With ICP mass spectroscopy the different elements of a mixture can be detected. The exception of this method is that also elements with a very low concentration (about 10^{-15}ppq - part per quadrillion) can be determined. Therefore an inductively coupled plasma is preserved in a torch and can be generated by heating inductively the working gas with an electromagnetic coil. The torch consists of three tubes and between the outer tubes a gas discharge takes place. The most used gas therefore is argon and it flows in phases between the outermost tubes, between the central tube and the intermediate tube and inside the central tube. The last gas flow passes through the plasma centre forming a channel, where the sample is placed into. The molecules of the sample break apart and the single atoms ionize. Then a mass spectrometer is used to separate the ions from each-other.

The laser-induced breakdown spectroscopy (LIBS) is form of atomic emission spectroscopy, where the excitation source is the highly energetic laser beam. When the laser passes the limit for optical breakdown, a highly ionized plasma can be generated. Because of the high temperature plasma (up to 100000 K) the sample dissociates into ions, electrons and excited atoms. After that the plasma emits continuously radiation and cools. The characteristic atomic emission lines are now visible for each containing element. Since the LIBS is experimentally simple and one of the cheapest analytical techniques, it is applied in different branches. In 2012 the Mars Science Laboratory sent the ChemCam, a measuring device including a LIBS to the Mars with the purpose to obtain elemental composition of rock and soil.

Sources: 1- Edison Tech Center in Schenectady, New York 2- "Industrial Plasma Engineering: Volume 2: Applications to Nonthermal Plasma Processing by J.Reece Roth 3- plasmatreat.de 4- engineering.com 5- ESAB (swedish: Elektriska Svetsnings-Aktiebolaget) knowledge center - esabna.com 6- expeditersonline.com 7- Courtesy of US Army Research Laboratory - http://www.arl.army.mil/www/default.cfm?page=247

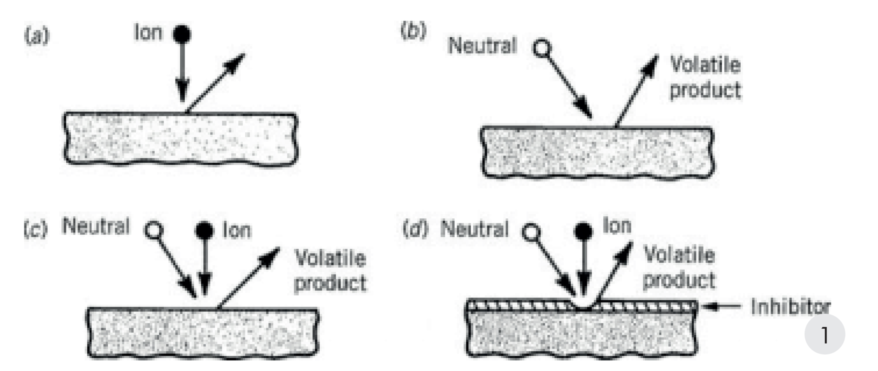
TECHNICAL APPLICATIONS OF THE PLASMA PHYSICS

– by Julia Cipo, Holger Kersten –

Surface technology and materials processing

Plasma etching

Plasma etching is an universal tool for material removal based on chemical reactions. The first applications of plasma etching are going back to the 1985, since it was still an unknown process in the beginning of the 1980s.
There are four main processes of plasma etching: sputtering, pure chemical etching, ion energy driven etching and ion inhibitor driven etching.
The sputtering is the process, where the atoms of a surface can be emitted due to an ion bombardment generated by the high energetic discharge. The process is not selective, anisotropic and can be very sensitive to the incidence angle of the ion. It is also the only one of these four processes, that can remove non-fleeting material from a surface.
The second etching process is the pure chemical etching, where the discharge delivers gas-phase atoms or molecule, which interact with the processing surface. The interaction supplies gas-phase products, which should be volatile. The gas-phase particles arrive in an almost constant angle to the surface, which makes the process isotropic.
The ion energy driven etching is the third process of this kind. The difference to the previous process is that the discharge supplies not only the etchants, but also the high energetic ions. Due to this increased production, a higher rate of etch products can be achieved. Even if here are two factors that play a role in the generation of the etch products, the etch rate is directly depending from the ion energy. The ions collide with a high angular distribution on the surface, making this process anisotropic and less selective. As in the pure chemical etching the etch products here are also volatile.
In the fourth type of etching -ion inhibitor driven etching- an inhibitor is needed. Here the discharge is responsible for the etchants, the energetic ions and the inhibitor molecules. Independently from the rest, the etchant can produce a high rate of etch products. The inhibitor forms a deposition layer. The ion bombardment that falls on the created layer clears it as it forms. So the untreated layer remains to protect the surface from the etchant. This process turns to be selective with volatile etch products.

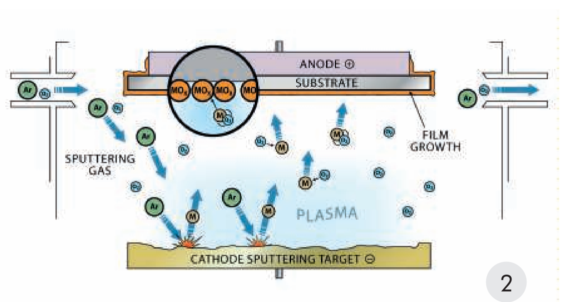


Four basic plasma etching processes: (a) sputtering, (b) pure chemical etching, (c) ion energy-driven etching, (d) ion-enhanced inhibitor etching (Flamm and Herb, 1989)

Plasma deposition

Two plasma-assisted deposition examples based on two different processes:

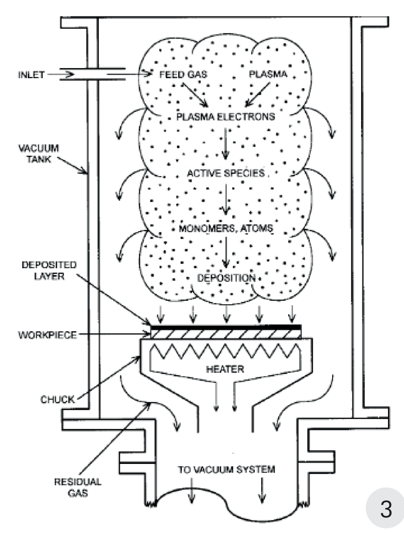
Sputter deposition for the production of thin aluminum films (actually Al/Cu or Al/Si): The sputter deposition method can be classified in physical sputtering and in reactive sputtering processes.
During a physical sputtering the ions are headed straight to a sputter target, causing the motion of the target atoms to the substrate, where they are deposited. An excellent film uniformity and surface smoothness can be achieved through physical sputtering. The film morphology was first studied by John A. Thornton in 1986 and depends on the deposition pressure as well as on the substrate temperature. John A.Thornton made great contributions in the study of thin films and magnetron sputtering, while working close with the American Vacuum Society (AVS).
The method of reactive sputtering is based not only on the ion bombardment, but on an additionally reactive gas as well. The film deposition on the substrate is created by the sputtered target material and the additionally gas, which reacts chemically with the target. A widespread application of this sputtering method is the deposition of films whose components have different vapour pressures. Mostly deposited are dielectrics such as oxides and nitrides. The most common reactive gases are O_2 and H_2O for O target atoms, N_2 and NH_3 for N atoms, CH_4 and C_2H_2 for C atoms as well as $SiH_4$for Si atoms. Because of the high sensitivity of oxide, nitride or carbide towards high-power fluxes, metal targets are mostly used for deposition.



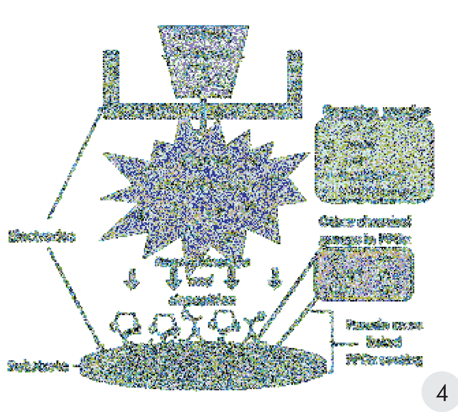
Sputter deposition

Plasma enhanced chemical vapour deposition (PECVD) at temperatures around 300°C for the insulating layer on silicon nitride surfaces: This method is applied on sensitive materials, which could melt by the higher temperatures around 900°C in a CVD (nonplasma chemical vapour deposition). The PECVD method consists of a plasma controlled gas-phase set and surface reactions that lead to a solid layer on surfaces. A problem of this process is the uniformity of the deposited films, since the PECVD is associated with high pressures, high flow rates, high gas-phase reaction rates and high sticking probability of gas-phase depositions. Even though the method is still being used widely for amorphous silicon thin films in solar cells, flat panel displays and for exposure devices in the xerography. The characteristics of the films depend on the concentration of the hydrogen, which is used extra in the process for eliminating the drooping bonds of the amorphous material. This way the dangling bonds would not carry the charged particles.
A special version of the PECVD method is the **plasma polymerization**. This method uses plasma sources with the attention of generating a gas discharge, which otherwise will activate the needed monomers. The grouping of the monomers forms the polymers, which are highly adhere to the coating surface. For the plasma polymerization the glow discharge method is used, because it generates free electrons that later collide with neutral molecules. This creates many reactive species such as monomers of different kinds. The most common monomers are thiophenes, pyridines, acetylenes and acrylonitriles. These monomers create polymers such as the polystyrenes, polyacrylates and polyethylenes. The difference to the normal polymerization is that the plasma polymers do not consist of regular repeating units. The ease of their application makes them usable for adhesion, protecting coatings, printings and biomedical applications.

Similar to the PECVD method is the **plasma impulsed chemical vapour deposition method (PICVD)**. This technique is newer and -compared to the PECVD method- it has a pulsed clocking (pace) of the ignition. Here the substrates are placed in a chamber filled with a mixture of mostly nitrogen and oxygen combined with reactive titanium and silicon dioxide carrier gases. The cleavage products as titanium and silicon dioxide are being deposited immediately on the surface of the substrate. This method enables the deposition of homogenous tightly packed layers, also known as multilayer-systems and is used often for gas-proof coatings in the inside of plastic bottles.

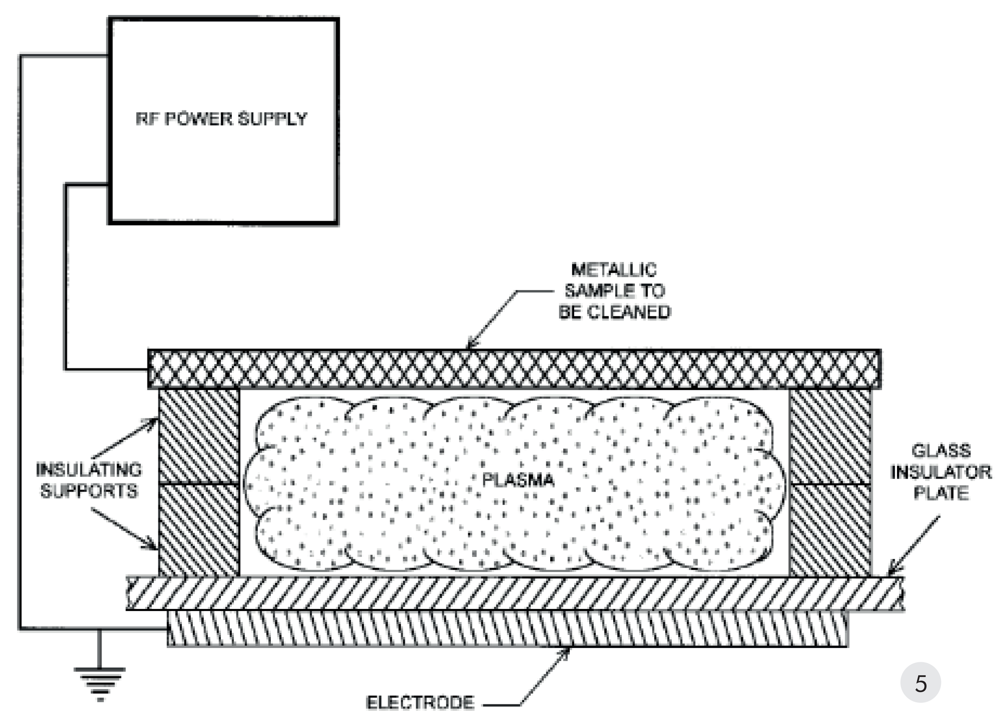


A schematic illustration of apparatus for plasma-assisted chemical vapor deposition (PCVD).



Plasma polymerization.

Plasma cleaning

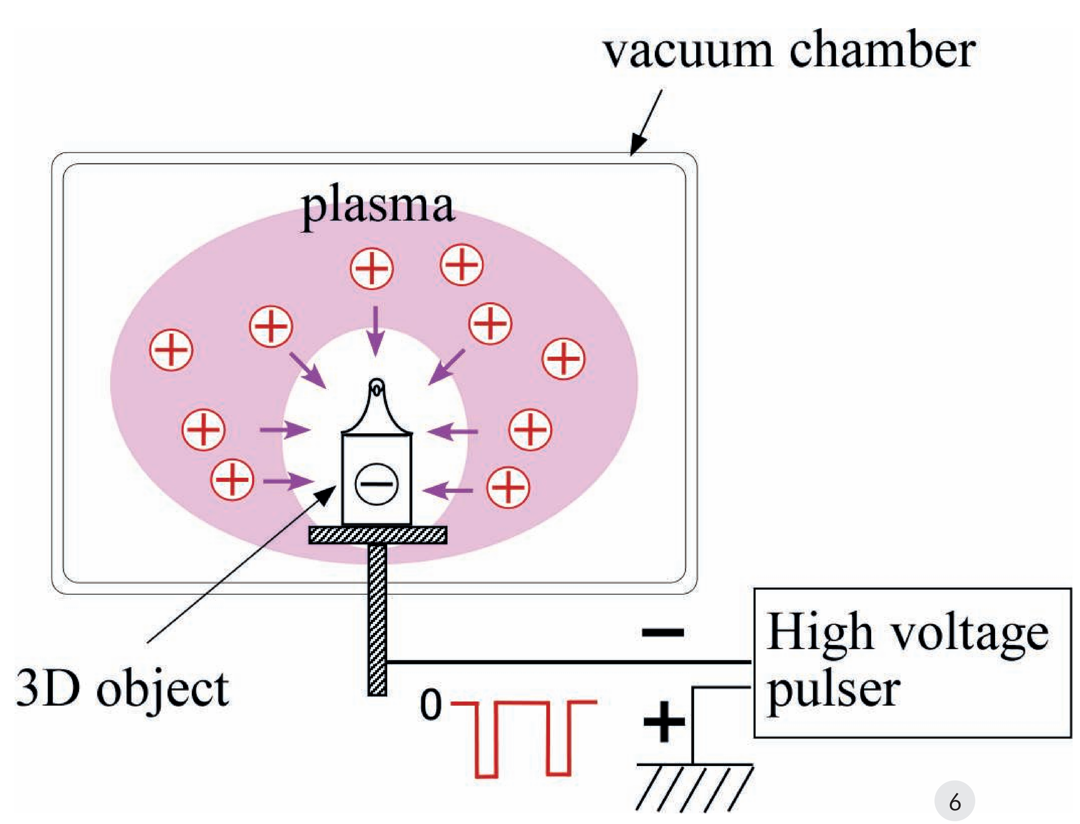


A configuration used to clean metal surfaces in the plasma science laboratory with the surface to be cleaned as a bare electrode of the OAUGDP.

Plasma cleaning is a surface treatment process used for removing impurities from solid or thin films. It removes only thin layers of the surfaces and does not change the chemical state of the material underneath the surface. The layers to be removed can be of different kinds: hydrocarbons, microorganisms, dirt, radioactive contamination or a layer of chemical reaction products. The plasma cleaning process can be classified in active and passive plasma cleaning. The active plasma cleaning includes real plasma currents, which are achieved because of an electrically conductive tool serving as an electrode during the discharge. In the passive plasma cleaning the tool does not conduct any plasma current. Both mechanisms remove efficiently impurities of metallic surfaces. A difference can be noticed during the removal of thin oil films: the passive plasma cleaning method is here about 1000 times faster than the active cleaning process. The mostly used gases for plasma cleaning are argon and oxygen, as well as air and hydrogen-nitrogen mixture. The gas which is ionized by high frequency voltages creates the glowing plasma. When oxygen is used, organic bonds can be broken and hydrocarbon layers on the surface can be removed. For removing easily oxidized materials gases like argon or helium are used. When only carbon has to be removed, the plasma cleaning process gets the name 'plasma ashing'. Therefore only oxygen is used.

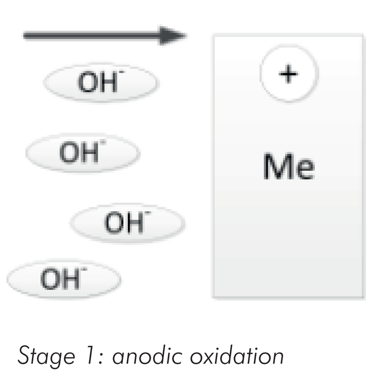
Plasma implantation

Another important process for semiconductor doping or even for surface hardening is the ion implantation. It is a process, where the ion bombardment impinges upon the surface of a solid by changing its atomic composition and the material properties on the surface area. The ion implantation is used for low-flux and high-energy implants, while for high-flux implants one other process is more common: plasma immersion ion implantation (PIII). The PIII processes are mostly characterised by low-pressure discharges and a secondary emission of electrons during the ion implantation. The target here is located inside a plasma environment and the ions of the plasma are moving with a high velocity towards the target. These processes are getting applied for hardening tools and medical hip implants, as well as for semiconductor doping or selective copper plating. It can also be used for improving the wear and the corrosion resistance of metallurgical surfaces. In this case the process is known as plasma source ion implantation (PSII), where the target is mostly immersed into a nitrogen plasma.

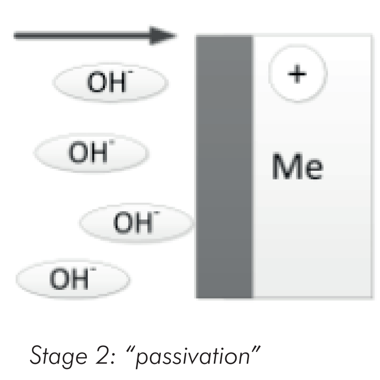


Plasma Immersion Ion Implantation (PIII) scheme.

Plasma Coating

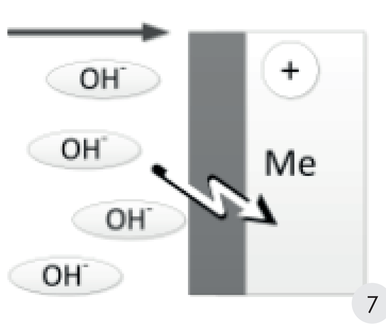


Stage 1: anodic oxidation



Stage 2: "passivation"

Plasma electrolytic oxidation (PEO) is another plasma coating process, which is used for creating thick layers of oxide on the surface of different metals such as magnesium, titanium and aluminium. Therefore the material that has to be coated is immersed in an electrolyte medium, while a high potential is applied. Because of the high applied voltage a dielectric breakdown potential can be achieved and a series of discharges takes place between the immersed material and the counter-electrode. These discharges modify the growing oxides, which are known for their hardness and corrosion resistance.



Stage 3: dielectric breakdown

Sources: 1- "Principles of Plasma Discharges and Materials Processing", Second Edition by Michael A. Lieberman and Allan J. Lichtenberg 2- Lurie Nanofabrication Facility (LNF) of University of Michigan - http://lnf-wiki.eecs.umich.edu/wiki/File:Sputter_Deposition.png 3- "Industrial Plasma Engineering: Volume 2: Applications to Nonthermal Plasma Processing by J.Reece Roth 4- Royal Society of Chemistry Publication - http://pubs.rsc.org/en/content/articlelanding/2015/tb/c5tb00901d/unauth#!divAbstract 5- "Industrial Plasma Engineering: Volume 2: Applications to Nonthermal Plasma Processing by J.Reece Roth 6- mawi.tu-darmstadt.de 7- "Plasma Electrolytic Oxidation of Valve Metals" by Alex Lugovskoy and Michael Zinigrad