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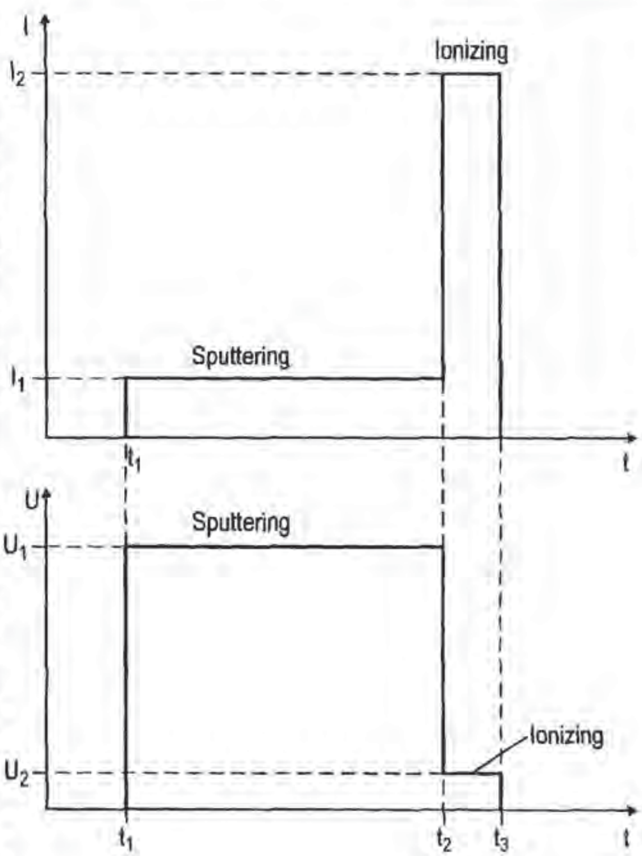
(54) Title: METHOD AND APPARATUS FOR PLASMA GENERATION



(57) Abstract: In a simple method and device for producing plasma flows of a metal and/or a gas electric discharges are periodically produced between the anode and a metal magnetron sputtering cathode in crossed electric and magnetic fields in a chamber having a low pressure of a gas. The discharges are produced so that each discharge comprises a first period with a low electrical current passing between the anode and cathode for producing a metal vapor by magnetron sputtering, and a second period with a high electrical current passing between the anode and cathode for producing an ionization of gas and the produced metal vapor. Instead of the first period a constant current discharge can be used. Intensive gas or metal plasma flows can be produced without forming contracted arc discharges. The selfsputtering phenomenon can be used.

WO 02/103078 A1

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METHOD AND APPARATUS FOR PLASMA GENERATION

TECHNICAL FIELD

The present invention relates to methods and apparatus for generating plasma flows and in particular metals plasma flows obtained by discharges in crossed electric and magnetic fields.

BACKGROUND OF THE INVENTION

Electrical discharges in crossed fields (**EXB** discharges) attract much attention due to their importance for science and technology. In science **EXB** discharges are important in the field of plasma physics and cosmic physics. In technology **EXB** discharges are used in devices for thermonuclear fusion, in vacuum technology such as in vacuum pumps, vacuum measurements, for coating work pieces using e.g. magnetron sputtering, in plasma accelerators, and as plasma emitters in ion sources.

The motion of charged particles in stationary crossed fields and quasi-stationary **EXB** discharges have been studied since 1921, see the article by A. W. Hull, "The effect of a uniform magnetic field on the motion of electrons between coaxial cylinders", Phys. Rev. 18, 1921, pp. 31 - 57, and by H. C. Early, W. G. Dow, "Supersonic Wind at Low Pressures Produced by Arc in Magnetic Field", Phys. Rev. 79, 1950, p. 186. Such discharges could be classified according to different parameters such as gas pressure, strength and configuration of the magnetic field used, electrode configuration etc. For the purposes herein these discharges are best classified according to the intensity or generally the behaviour of the discharge or driving current.

According to this classification using the driving current, quasi-stationary discharges in crossed fields could be divided in two classes: low intensity and high intensity current discharges. It is necessary to note that the transition current depends on many parameters, in particular on the dimensions of the apparatus used, and can vary for hundreds of amperes. Low intensity current discharges in crossed fields could be called such discharges which produce a plasma inside a magnetic configuration with a density less than 10^{18} m^{-3} and high intensity current discharges could be called such discharges which produce a plasma having a density of more than 10^{18} m^{-3}, the plasma density defined as the number of particles per unit volume.

Low intensity current discharges in crossed fields are widely used in vacuum technology such as in vacuum pumps, for coating work pieces, e.g. in magnetron sputter deposition. Typical discharge devices are Penning cells and cylindrical and planar DC-magnetrons. The low driving current results in a low-density plasma, less than 10^{18} m^{-3} as indicated above.

High intensity current discharges have been mostly used for generating dense plasma for the goals of thermonuclear fusion. Typical discharge devices include Homopolar I, Ixion and F I devices. The typical plasma density is about 10^{18} - 10^{23} m^{-3}.

The second important characteristic of discharges in crossed fields is the voltage drop between the electrodes.

For a low intensity driving current the rate of neutral gas ionization is low and balances the plasma losses to form an equilibrium plasma density at a low level. The electrical resistance of the anode-cathode gap is high resulting in a high anode-cathode potential drop. As soon as an opposite process becomes energetically possible a strongly enhanced ionization process should arise.

Two methods have been described for plasma ionization in systems using with discharges in crossed electric and magnetic fields. Their practical applicability depends on system dimensions and the strength of the magnetic field. The method generally accepted in systems of sufficiently large dimensions using a strong magnetic field is the so called "Rotating Plasma Approach". This approach is based on the fact that the electric field penetrates into the plasma and that the plasma is magnetized, see B. Lehnert, "Rotating Plasmas", Nuclear Fusion 11, 1971, pp. 485 - 533. Another approach is based on fact that the electric field is concentrated preferably near the cathode of the discharge. This approach is used for processes in systems using a low magnetic field and non-magnetized ions. This approach could be called e.g. "Secondary Electron Approach", see B. S. Danilin and B. K. Sirchin, Magnetron Sputtering Systems, Moskva, Radio i Sviaz, 1982. As will be obvious from the following this invention deals with both kinds of systems and therefore both plasma approaches will be used.

Alfvén has postulated, see H. Alfvén, "On the Origin of the Solar System", Clarendon Press, Oxford, 1954, that a strongly enhanced ionization process should arise when the mutual plasma-neutral gas velocity reaches the critical value v_c, the Alfvén limit, given by

$$v_c=(2e\phi_i/m_i)^{1/2}$$

where ϕ_i is the ionization potential, e is the charge of the electron and m_i is the ion mass.

For devices having a low sputtering rate and low plasma losses it results in an anode-cathode voltage drop limitation during the starting period of the discharge. For devices having a high sputtering rate it results in an anode-cathode voltage drop limitation during all of the discharge time. The voltage drop or critical voltage V_c is given by

$$V_c= Cv_cB$$

where C is a constant and B is the strength of magnetic field in the discharge device. In the case of a high sputtering rate, the ionization potential ϕ_i of the sputtered atoms creates the metal vapor. It means that the discharge voltage has to depend on the sputtering cathode material.

This phenomenon was demonstrated both by investigation of plasma motion through a neutral gas and by experiments with planar magnetron sputtering devices, see U. V. Fahleson, "Experiments with Plasma Moving through Neutral Gas", Physics Fluids, Vol. 4, 1961, pp. 123 - 127, and D. V. Mozgrin, I. K. Fetisov, and G. V. Khodachenko, "High-Current Low-Pressure Quasi-Stationary Discharge in a Magnetic Field: Experimental Research", Plasma Physics Reports, Vol. 21, No. 5, 1995, pp. 400 - 409. In the latter publication the high current, low voltage discharge in a magnetron magnetic configuration is called as a "high-current diffuse regime".

It means that the transition from a low intensity current **EXB** discharge to a high intensity current discharge has to be followed by a decrease of the discharge voltage. Typical anode-cathode potential drops for low intensity current, quasi-stationary discharges are in the range of about 10 – 0.3 kV and for high intensity current discharges in the range of about 300 – 10 V.

If quasi-stationary discharges are implemented in magnetron sputtering devices, in a first regime effective cathode sputtering is obtained but a low ionization rate of the sputtering gas and metal vapor. In a second regime an opposite state occurs having a low sputtering rate but a high ionization rate of the sputtering gas. Thus, it can be said that it is impossible to generate, by a separate low intensity current quasi-stationary discharge, or by a separate high intensity current discharge in crossed fields, highly ionized metal plasma fluxes.

The devices using **EXB** discharges can operate for a short time in the transient, i.e. the non-quasi-stationary, regime. In this regime it is possible to overcome the Alfvén limit of discharge voltage as well for high current discharges, see the article by B. Lehnert cited above. High current, high voltage non-quasi-stationary discharges occur in magnetron sputtering devices and are very important for magnetron sputtering applications because those discharges allow obtaining a fully ionized impermeable plasma in the magnetron magnetic configuration. But, as will be shown hereinafter, if transient discharges are implemented in magnetron sputtering devices by either high intensity current discharges or by low intensity current discharges it is impossible to generate highly ionized intensive metal plasma fluxes.

Metal plasma fluxes can be produced by low current quasi-stationary **EXB** discharges in a magnetron configuration for sputtering atoms in a moderate pressure, of e.g. 1 - 100 mTorr, and with a low-density plasma. In this case the plasma is produced by an RF-induction coil mounted in the deposition chamber. The electron density produced in induction plasmas is about 10^{17}-10^{18} m^{-3}.

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