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Gregor MORFILL
Plasma Sterilization

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Institute of Physics Press Release PR62 (09)
Thu, 26 November 2009

Plasma Produces KO cocktail for MRSA

MRSA (methicillin-resistant Straphylococcus Aureus) and other drug-resistant bacteria could face annihilation as low-temperature plasma prototype devices have been developed to offer safe, quick, easy and unfailing bactericidal cocktails.

Two prototype devices have been developed: one for efficient disinfection of healthy skin (e.g. hands and feet) in hospitals and public spaces where bacteria can pose a lethal threat; and another to shoot bacteria-killing agents into infested chronic wounds and enable a quicker healing process.

Two papers published today, Thursday 26 November, as part of a selection of papers on Plasma Medicine in New Journal of Physics (co-owned by the Institute of Physics and German Physical Society), demonstrate how far the design of equipment to harness the bacteria-killing power of low-temperature plasma has come.

Plasma, oft called the fourth state of matter after solid, liquid and gas, is defined by its ionized state. In space, stars are made up of high-energy plasma and, on Earth, it is researchers in high-energy plasma that are making significant strides towards limitless energy from nuclear fusion. The high energy of plasma stems from some atoms or molecules in a gas being stripped of their electrons, resulting in a mix of ionized and neutral species.

Also on Earth, scientists have been working on low-temperature and atmospheric-pressure plasma and have found applications in a range of industries, from plastic bag production to the manufacturing of streetlamps and semiconductor circuits.

In a low-temperature plasma, unlike its high-temperature counterparts, the temperature of ions and neutral particles stays low. The ‘recipe’ for producing such plasmas is simple: the fraction of atoms (molecules) that are ionized – and therefore are hot – is so low that collisions with cold neutral atoms (molecules) quickly reduce their temperature again. The analogy of adding a drop of hot water to a bucket of cold water gives a sense of how low-temperature plasma physicists are able to create plasmas without dramatically increasing the temperature of the overall molecules.

In medicine, low-temperature plasma is already used for the sterilization of surgical instruments as plasma works at the atomic level and is able to reach all surfaces, even the interior of hollow needle ends. Its ability to disinfect is due to the generation of biologically active bactericidal agents, such as free radicals and UV light, which can be delivered to specific locations. It is research into how and why these biologically active agents are generated that has led to the construction of medically invaluable devices.

One research group from the Max Planck Institute for Extraterrestrial Physics has built and trialed a device which is capable of disinfecting human skin safely and quickly (within seconds), annihilating drug-resistant kinds of bacteria that currently cause approximately 37 000 deaths from hospital induced infections every year in EU countries.

On the current disinfection challenge that medical staff face, and that their device will overcome, the researchers write, “The surgeons’ disinfection procedure – hand rubbing (3 minutes) or hand scrubbing (5 minutes) – has to be repeated many times a day, with a number of negative side-effects arising from the mechanical irritation, chemical and, possibly, allergic stress for the skin. For the hospital staff, the issue of hand disinfection is equally daunting. Over a typical working day, some 60 to 100 disinfections (in principle) are necessary – each requiring 3 minutes – i.e. a total of 3 to 5 hours!”

The new plasma devices under development cut this down dramatically – to around ten minutes a day. In addition, only electricity is needed, no fluids or containers.

Another device, an ‘argon plasma torch’, was developed by this group, together with ADTEC Plasma Technology Ltd in Japan, specifically for disinfecting chronic non-healing wounds. One advantage of the ‘argon plasma torch’ comes from regulating densities of biologically-active agents which are designed to ensure that the plasma is deadly for bacteria but harmless for human cells.

Cell biological studies, conducted together with partners from the Institute of Pathology, Technical University of Munich, are reported and interpreted in terms of chemical reactions which work differently in bacterial and human cells – deadly to the bacteria and supporting cell regeneration in human cells.

After successful trials that show how plasma can be manipulated to very beneficial ends, these researchers write, “One can treat plasmas like a medical cocktail, which contains new and established agents that can be applied at the molecular level to cells in prescribed intensities and overall doses.”

This work represents a first step in the direction of ‘plasma pharmacology’, a step along a path that will require considerable research efforts to harness the full potential of this new field of ‘plasma medicine’.

Both research papers describe the mechanics of their trials, the safety concerns they endeavour to overcome, the remarkable bactericidal effect they have successfully achieved, and the positive cell regeneration effects that can be stimulated using plasmas.

Contact

1. For further information, full drafts of the journal papers or contact with one of the research authors, contact IOP Press Officer, Joe Winters:
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2. To contact Professor Gregor Morfill, at the Max Planck Institute for Extraterrestrial Physics, call or email IOP press officer (as above) or email Professor Morfill directly on gem@mpe.mpg.de.

Designing plasmas for chronic wound disinfection

4. The published version of the paper "Designing plasmas for chronic wound disinfection" (Tetyana Nosenko, Tetsuji Shimizu and Gregor Morfill 2009 New J. Phys. 11 115013) will be freely available online from Thursday, 26 November. It will be available at http://stacks.iop.org/NJP/11/115013.

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http://news.bbc.co.uk/2/hi/technology/8379604.stm

Device Spells Doom for Superbugs

Max Planck Institute for Extraterrestrial Physics

Researchers have demonstrated a prototype device that can rid hands, feet, or even underarms of bacteria, including the hospital superbug MRSA.

The device works by creating something called a plasma, which produces a cocktail of chemicals in air that kill bacteria but are harmless to skin.

A related approach could see the use of plasmas to speed the healing of wounds.

Writing in the New Journal of Physics, the authors say plasmas could help solve gum disease or even body odour.

Plasmas are known as the fourth state of matter, after solid, liquid, and gas. They are a soup of atoms that have had their electrons stripped off by, for example, a high voltage.

Plasmas are common elsewhere in the cosmos, where high-energy processes produce them, and they are even posited as a potential source of fusion energy. Their properties have recently been harvested for use in plasma televisions.

Deadly cocktail

But the new research focuses on so-called cold atmospheric plasmas.

Rather than turning a whole group of atoms into plasma, a more delicate approach strips the electrons off just a few, sending them flying.

Collisions with nearby, unchanged atoms slows down the electrons and charged atoms or ions they leave behind.

It has been known for some time that the resulting plasma is harmful to bacteria, viruses, and fungi – the approach is already used to disinfect surgical tools.

"It's actually similar to what our own immune system does," said Gregor Morfill, of the Max Planck Institute for Extraterrestrial Physics, who led the research.

"The plasma produces a series of over 200 chemical reactions that involve the oxygen and nitrogen in air plus water vapour – there is a whole concotion of chemical species that can be lethal to bacteria," he told BBC News. …

"To produce plasmas efficiently at low cost so you can really mass produce these things for hospitals, that's the big breakthrough of the last year," Professor Morfill said.

The team says that an exposure to the plasma of only about 12 seconds reduces the incidence of bacteria, viruses, and fungi on hands by a factor of a million – a number that stands in sharp contrast to the several minutes hospital staff can take to wash using traditional soap and water.

More applications

Professor Morfill said that the approach can be used to kill the bacteria that lead to everything from gum disease to body odour.

Two prototype devices have been developed: one for efficient disinfection of healthy skin (e.g. hands and feet) in hospitals and public spaces where bacteria can pose a lethal threat; and another to shoot bacteria-killing agents into infested chronic wounds and enable a quicker healing process.

Two papers published today, Thursday 26 November, as part of a selection of papers on Plasma Medicine in New Journal of Physics (co-owned by the Institute of Physics and German Physical Society), demonstrate how far the design of equipment to harness the bacteria-killing power of low-temperature plasma has come.

Plasma, oft called the fourth state of matter after solid, liquid and gas, is defined by its ionized state. In space, stars are made up of high-energy plasma and, on Earth, it is researchers in high-energy plasma that are making significant strides towards limitless energy from nuclear fusion. The high energy of plasma stems from some atoms or molecules in a gas being stripped of their electrons, resulting in a mix of ionized and neutral species.

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http://physicsworld.com/cws/article/news/41072

Plasmas have Healing Powers

by

Jon Cartwright

Nov 26, 2009

Two related studies have demonstrated the effectiveness of low-temperature plasma for killing drug-resistant bacteria on human skin – one of the biggest challenges facing modern medicine. In one study, researchers in Germany describe a device that can disinfect hands in seconds, while in the other they reveal how low-temperature plasmas can safely disinfect open wounds.

Bacterial infection is a serious problem in hospitals. Studies show that the infamous superbug methicillin-resistant Straphylococcus Aureus (MRSA) alone infects 100,000 people every year in the US and results in about 18,000 deaths.

The best way to tackle the problem is disinfectant, but this can be laborious. Every day hospital staff must disinfect their hands on dozens of occasions, each taking up to several minutes. Keeping open wounds free from bacteria can be even harder.
Cool plasmas

In recent years, scientists have begun to investigate how plasmas – gases of ions and free electrons – can help. A fully ionized plasma can have a temperature in the region of 100,000°, which is far too hot for human tissue, but the temperature can be reduced if the degree of ionization is much lower, at say one part in a billion.

Gregor Morfill and colleagues at the Max-Planck Institute for Extraterrestrial Physics in Garching have shown how low-temperature plasmas can be used to clean hands conveniently in seconds. Their device contains a slab of dielectric material sandwiched between a solid electrode and a sheet of wire mesh. When they put a large voltage of 18 kV across the solid electrode and mesh, the resultant strong electric field generates numerous nano- and microsecond discharges that partially ionize the air. This ionization leaves ultraviolet radiation and a cocktail of chemical products – including ozone, nitrogen oxide, hydrogen peroxide and free radicals – which together kill bacteria.

"It will even sterilize your socks, although you should probably wash them too" Gregor Morfill, Max-Planck Institute for Extraterrestrial Physics

Morfill told physicsworld.com that hospital staff could use the device routinely to clean hands and, if so desired, feet. "It will even sterilize your socks, although you should probably wash them too," he adds.

With other colleagues at the Max-Planck Institute, Morfill has examined the best way to use low-temperature plasma for cleaning open wounds. In some ways this is more difficult because ideally the plasma would not only kill bacteria but also prevent further growth of bacteria without having any negative side-effects on the living human cells.
Chemicals and plasma

The researchers performed a series of tests in which they subjected E. coli bacteria to both the chemical and UV products of plasma and, by shielding the bacteria with a quartz disc, just the UV products. They found that the UV radiation tended to kill bacteria in the short term, whereas the chemical products cause a lasting "after irradiation" inhibition of bacterial growth. With this knowledge, the researchers could determine the right composition and dosage of plasmas for future devices.

One of the group members, Tetyana Nosenko, said that the next step is to optimize the plasma composition for different types of wound, such as diabetic ulcers or those containing blood.

The research is described in two papers in the New Journal of Physics.

Patents

WO2008138504
PLASMA SOURCE
Inventor: MORFILL GREGOR [DE] ; STEFFES BERND
2008-11-20

US2008237484
Plasma Source
Inventor: MORFILL GREGOR [DE] ; SHIMIZU TETSUJI
2008-10-02
Abstract -- A plasma source, particularly for disinfection of wounds, comprising: an ionization chamber having an inlet for introducing a gas into the ionization chamber and further having an outlet for dispensing the ionized gas onto an object; several ionization electrodes being disposed within the ionization chamber for ionizing the gas and a predetermined ratio of the electrode-electrode distance on the one hand and the electrode-wall distance on the other hand, wherein the ratio is in a range approximately between about 1.8 and about 2.2.

EP1925190
PLASMA SOURCE
Inventor: MORFILL GREGOR [DE] ; SHIMIZU TETSUJI
2008-05-28

US2008136332
Method and Device For the Operation of a Plasma Device
Inventor: MORFILL GREGOR [DE] ; KONOPKA UWE
Abstract -- A method for the operation of a plasma device (100) is described in which particles (2) are arranged in a plasma, wherein a generation of electric travelling waves (1) is provided, under whose effective action the particles (2) in the plasma device (100) perform a directed movement to at least one pre-determined collection area (20, 20 A). A plasma device for carrying out the method is also described.
2008-06-12

US2003185983
Device for specific particle manipulation and deposition
Inventor: MORFILL GREGOR [DE] ; HUBERTUS THOMAS
2003-10-02

US2005147765
Method for producing particles with diamond structure
Inventor: DOSE VOLKER [DE] ; MORFILL GREGOR
2005-07-07

US6616987
Procedure and device for specific particle manipulation and deposition
Inventor: MORFILL GREGOR [DE] ; THOMAS HUBERTUS
2003-09-09

US6517912
Particle manipulation
Inventor: MORFILL GREGOR [DE] ; THOMAS HUBERTUS
2003-02-11

US Patent Application 20080237484
Plasma Source

October 2, 2008

Abstract -- A plasma source, particularly for disinfection of wounds, comprising: an ionization chamber having an inlet for introducing a gas into the ionization chamber and further having an outlet for dispensing the ionized gas onto an object; several ionization electrodes being disposed within the ionization chamber for ionizing the gas and a predetermined ratio of the electrode-electrode distance on the one hand and the electrode-wall distance on the other hand, wherein the ratio is in a range approximately between about 1.8 and about 2.2.

Inventors: Morfill; Gregor; (Munchen, DE) ; Shimizu; Tetsuji; (Garching, DE) ; Steffes; Bernd; (Garching, DE) ; Fujii; Shuitsu; (Hiroshima, JP)
U.S. Current Class: 250/427; 606/27
Intern'l Class: A61B 18/04 20060101 A61B018/04; H05H 1/26 20060101 H05H001/26

Description

BACKGROUND

[0003]The use of non-equilibrium plasmas for the in vivo sterilization of wounds has been discussed in Stoffels, E.; Stoffels, W.: "The healing touch of a micro-plasma", published on http://www.phys.tue.nl. However, the in vivo sterilization of wounds requires low temperatures of the plasma and a low electromagnetic irradiation, so that the conventional plasma sources are not suitable for the in vivo sterilization of wounds.

[0004]Further, U.S. Pat. No. 5,332,885 discloses a plasma spray apparatus for spraying powdery or gaseous material onto a substrate surface, e.g. for coating the substrate. However, due to the high temperature of the plasma output, this plasma spray apparatus is not suitable for the in vivo sterilisation of wounds.

[0005]A so-called plasma needle is disclosed in Stoffels, E. et al.: "Plasma needle: a non-destructive atmospheric plasma source for fine surface treatment of (bio)materials", Plasma Source Sci. Technol. 11 (2002) 383-388. This plasma needle comprises a single electrode being disposed within a grounded metal cylinder with 1 cm inner diameter. However, the aforementioned plasma needle is not suitable for a large-area sterilisation of wounds since the outlet of the metal cylinder is very small.

[0006]Moreover, US 2004/0138527 A1 discloses a tubular suction tool for accessing an anatomic surface or anatomic space and particularly the pericardium to access pericardial space and the epicardial surface of the heart to implant cardiac leads in a minimally invasive manner are disclosed. Therefore, this reference is not pertinent to the present application.

SUMMARY

[0007]It is therefore an aspect of an exemplary embodiment the invention to improve the afore-mentioned plasma source.

[0008]As an example, an embodiment provides a plasma source, which is suitable for the large-area in vivo sterilization of wounds.

[0009]According to an illustrative example, a plasma source is provided comprising an ionization chamber having an inlet for introducing a gas into the ionization chamber and further having an outlet for dispensing the ionized gas onto an object, e.g. a wound of a patient. Further, the plasma source comprises several ionization electrodes being disposed within the ionization chamber for ionizing the gas. In the plasma source there is a specified distance between adjacent ionization electrodes and also a specified distance between each ionization electrode and the inner wall of the ionization chamber. Further, the plasma source is characterized by a specified ratio of the electrode-electrode distance on the one hand and the electrode-wall distance on the other end, wherein the ratio is in a range between 1.8 and 2.2. In one embodiment, the ratio of the electrode-electrode distance on the one hand and the electrode-wall distance on the other hand is substantially 2, i.e. the electrode-electrode distance is two times bigger than the electrode-wall distance.

[0010]This ratio advantageously results in both an easy discharge trigger and a steady operation of all ionization electrodes. Therefore, the plasma source provides a large plasma output with a low energy input, so that the plasma source is well suitable for in vivo applications, e.g. sterilization of wounds, treatment of bacteriological, fungicidal and viral skin disorders, since it combines a comparatively low temperature of the plasma with a low electromagnetic irradiation.

[0011]It should be noted that the afore-mentioned values for the ratio between the electrode-electrode distance on the one hand and the electrode-wall distance on the other end may refer to the end o the ionization electrodes, where the plasma is actually generated. For example, the inner diameter of the ionization chamber might vary along the ionization electrodes, so that the aforementioned ratio accordingly varies even in case of a constant electrode-electrode distance. In such a case, a ratio is defined between the electrode-electrode distance and the electrode-wall distance at the end of the ionization electrodes.

[0012]However, it is possible that the ratio between the electrode-electrode distance and the electrode-wall distance is within the specified range (e.g. 1.8-2.2) over the entire length of the ionization electrodes and not only at the end of the ionization electrodes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013]FIG. 1 is a perspective view of a plasma source according to an exemplary embodiment of the invention.

[0014]FIG. 2 is a longitudinal sectional view of the plasma source of FIG. 1.

[0015]FIG. 3 is a top view of the plasma source of FIGS. 1 and 2.

[0016]FIG. 4 is a side view of the plasma source of FIGS. 1 to 3.

[0017]FIG. 5 is a perspective view of an exemplary ionization chamber of the plasma source of FIGS. 1 to 4.

[0018]FIG. 6 is a cross-sectional view of the ionization chamber of FIG. 5.

[0019]FIG. 7 is a schematic cross-sectional view of exemplary ionization electrodes in the ionization chamber of the plasma source of FIGS. 1 to 4.

[0020]FIG. 8 is a schematic view of an exemplary plasma source of FIGS. 1 to 4 connected to a gas source, a coolant pump and a D.C. voltage source.

[0021]FIG. 9 is a side view of a medical device using the plasma source of FIGS. 1 to 4.

[0022]In an exemplary embodiment of the invention, the plasma source comprises six ionization electrodes. Experiments using argon for the generation of the plasma have shown that the conversion efficiency (plasma output per electrode) increases with the number of ionization electrodes approximately linearly up to a number of six ionization electrodes. Then, the efficiency flattens out and eventually decreases. Therefore, a plasma torch with six ionization electrodes is the optimum for argon gas. However, the invention is not restricted to plasma sources having six electrodes. For example, it is also possible to provide 3, 4, 5, 7, 8, 9, 10, 11 or 12 ionization electrodes within the ionization chamber.

[0023]Further, the ionization electrodes may be rod-shaped and arranged parallel to each other forming an equilateral polygon in cross-section. In such an embodiment the distance between adjacent ionization electrodes, i.e. the electrode-electrode distance, is uniform within the electrode arrangement. However, the invention is not restricted to electrode arrangements having a uniform electrode-electrode distance. Instead, the electrode-electrode distance might vary within the electrode arrangement from electrode to electrode. Further, the distance between the ionization electrodes and the inner wall of the ionization chamber may be uniform within the entire electrode arrangement. However, the invention is not restricted to such embodiments having a uniform electrode-wall distance. Instead, the electrode-wall distance might vary within the electrode arrangement from electrode to electrode.

[0024]Further, the ionization electrodes may have an at least partially serrated surface, which can be realized by using screws having an external thread as the ionization electrodes. In this manner, an easy discharge trigger and a steady operation of the ionization electrodes is facilitated.

[0025]The ionization electrodes may be made from aluminium. An advantage of aluminium is that it does not develop a polymerized coating, which might "flake off". Further, ionization electrodes consisting of aluminium have a better plasma efficiency.

[0026]However, it is also possible to use ionization electrodes made from stainless steel. An advantage of lionization electrodes consisting of stainless steel is that they are particularly suitable for sterilisation purposes.

[0027]The ionization electrodes may ionize the gas within the ionization chamber by emitting microwaves. Therefore, the plasma source may comprises an electrical terminal for externally connecting the ionization electrodes to a micro wave generator. However, the invention is not restricted to plasma sources in which the plasma is generated by microwaves. Instead, it is possible to use radio frequency (R.F.) or even direct current for ionizing the gas within the ionization chamber.

[0028]However, if the plasma is generated by microwaves, the length of the ionization electrodes may be matched to the wavelength of the microwaves. For example, the length l of the ionization electrodes might correspond to the wavelength .lamda. of the microwaves. Alternatively, the length l of the ionization electrodes might correspond to half the wavelength .lamda./2.

[0029]In an exemplary embodiment of the plasma source the walls of the ionization chamber are made from an electrically conductive material, e.g. aluminium, so that the walls of the ionization chamber are shielding the microwaves emitted by the ionization electrodes. In this manner, the electromagnetic radiation leaving the ionization chamber is reduced, which allows in vivo plasma applications.

[0030]Further, the outlet of the ionization chamber may be covered by a mesh to avoid an unwanted accidental contact with the ionization electrodes.

[0031]Further, the mesh covering the outlet of the ionization chamber may be made from an electrically conductive material, e.g. stainless steel, so that the mesh is shielding microwaves emitted by the ionization electrodes. In this manner, the electromagnetic radiation leaving the ionization chamber through the outlet of the ionization chamber is further reduced.

[0032]Finally, a positive direct-current voltage can be applied to the mesh to enhance plasma output and efficiency. In this manner, the electrons of the plasma within the ionization chamber are accelerated towards the mesh, so that the positively charged ions are following the electrons towards the outlet of the ionization in order to maintain an electrically neutral plasma.

[0033]Further, the mesh covering the outlet of the ionization chamber may have a mesh size of less than 5 mm or even less than 4 mm.

[0034]In accordance with exemplary embodiments of the invention, the plasma source comprises a protective cap, which is detachably attached to the outlet of the ionization chamber for preventing an over heating of the object. Therefore, the protective cap comprises at least one spacer projecting axially from the protective cap to ensure a safety distance between the outlet of the ionization chamber and the surface of the object, e.g. a wound.

[0035]In operation, the plasma source provides a flow of plasma having a comparatively low temperature, which may be below 100.degree. C., 75.degree. C. or even 50.degree. C., measured on the surface of the object.

[0036]It should further be mentioned that the operating pressure within the ionization chamber is substantially equal to the ambient pressure outside the ionization chamber, so that the plasma source does not need any pressure control within the ionization chamber.

[0037]In an exemplary embodiment the outlet of the ionization chamber has a cross-section of at least 10 cm.sup.2, which allows an application of the plasma to a comparatively large surface.

[0038]Further, the plasma source may be operated with a gas flow rate in the range of 1-10 l/min. However, the invention is not restricted to plasma sources operating with a gas flow rate within the aforementioned range.

[0039]In an exemplary embodiment of the invention, the plasma source further comprises a cooling means for convectively cooling the ionization chamber. The cooling means comprises at least one hollow cooling channel being disposed in the wall of the ionization chamber. During operation of the plasma source, a cooling agent, e.g. ambient air, can be pumped through the hollow cooling channels. In this manner, the temperature of the plasma is further reduced allowing in vivo plasma applications.

[0040]Further, it has to be mentioned that the plasma source may use argon to generate the plasma. However, the invention is not restricted to plasma sources using argon. For example, a mixture of argon and a few percent of nitrogen or oxygen might be used to generate the plasma, so that radicals are generated from the nitrogen/oxygen molecules.

[0041]In an exemplary embodiment the plasma source further comprises a handle on the outside of the ionization chamber for manually positioning the plasma source relative to the object, e.g. above a wound.

[0042]Finally, exemplary embodiments may include a medical device for the plasma treatment of a patient comprising the aforementioned novel plasma source. In such a medical device, the plasma torch may be mounted to a moveable arm allowing a user-defined positioning of the plasma source above the patient, wherein the moveable arm supports the plasma source, so that the plasma source need not be manually held by a therapist. The moveable arm preferably comprises several degrees of freedom of motion

[0043]The embodiments and its particular features and advantages will become more apparent from the following detailed description considered with reference to the accompanying drawings.

[0044]FIGS. 1 to 4 and FIG. 8 show an exemplary embodiment of a plasma source 1, which is suitable for the in vivo sterilization of wounds.

[0045]The plasma source 1 comprises an ionization chamber 2 having an inlet 3 for introducing an argon gas into the ionization chamber 2, where the argon gas is ionized by six ionization electrodes 4 (see FIGS. 2, 7 and 8). The ionization electrodes 4 are rod-shaped and arranged parallel to each other forming an equilateral polygon in cross-section (see FIG. 7). The ionization electrodes 4 are connected via a HF connector 5, a coaxial cable 6 and an auto tuner 7 with a conventional microwave generator 8. During operation, the microwave generator 8 generates microwaves having a specified wavelength .lamda., wherein the length of the ionization electrodes 4 is matched to the wavelength .lamda. of the microwaves in such a way that the length of the ionization electrodes 4 corresponds to the wavelength .lamda.. However, in other embodiments it is possible that the length of the ionization electrodes 4 corresponds to half the wavelength .lamda. of the microwaves.

[0046]Further, it should be noted that there is a uniform electrode-electrode distance d.sub.EE between adjacent ionization electrodes 4 and also a uniform distance d.sub.EW between the ionization electrodes 4 and the inner wall of the ionization chamber 2. Accordingly, the ionization electrodes 4 are arranged in such a way that the ratio between the electrode-electrode distance d.sub.EE on the one hand and the electrode-wall-distance d.sub.EW is substantially 2, which results in an easy discharge trigger and a steady operation of all the ionization electrodes 4. Therefore, the plasma generation is extremely efficient, which results in a large plasma output for a low energy input, so that in vivo plasma applications are possible with low temperatures of the generated plasma and low electromagnetic irradiation.

[0047]In this embodiment, the rod-shaped ionization electrodes 4 each consist of a screw having an external thread. Therefore, the surface of the ionization electrodes 4 is serrated, which enhances the plasma generation.

[0048]Further, it should be noted that the ionization electrodes 4 are made from aluminium. An advantage of aluminium is that it does not develop a polymerized coating, which might "flake-off".

[0049]Further, the ionization chamber 2 comprises an outlet 9 (see FIG. 2) at the bottom end face of the ionization chamber 2. The outlet 9 is covered by a mesh 10 made from an electrically conductive material. The mesh 10 serves three purposes. Firstly, the mesh 10 prevents an unwanted, accidental contact with the ionization electrodes 4 within the ionization chamber 2. Secondly, the mesh 10 is shielding the microwaves generated within the ionization chamber 2, so that the electromagnetic irradiation outside the ionization chamber 2 is reduced. Finally, the mesh 10 can be electrically contacted with a direct-current voltage source 11 (see FIG. 8) to enhance plasma output and efficiency.

[0050]It should further be noted that the plasma source 1 comprises a protective cap 12, which is detachably attached to the bottom of the ionization chamber 2. The protective cap 12 comprises a central opening below the outlet 9 of the ionization chamber 2, so that the dispensing of the plasma through the outlet 9 is not interfered by the protective cap 12. The protective cap 12 comprises several spacers 13 projecting axially from the protective cap 12 to ensure a safety distance between the bottom surface of the ionization chamber 2 and the outlet 9 on the one hand and the object, e.g. a wound, on the other hand.

[0051]Further, a handle 14 is attached to the peripheral surface of the cylindrical ionization chamber 2. The handle 14 allows a manual positioning of the plasma source 1 above a wound, which will be described later.

[0052]In this embodiment, the plasma source 1 further comprises several cooling channels 15 (see FIGS. 5, 6 and 8) extending coaxially and parallel to each other within the wall of the ionization chamber 2. At the bottom of the plasma source 1, the cooling channels 15 meet in several suction holes 16, which are evenly distributed along the circumferential surface of the ionization chamber 2. At the top of the ionization chamber 2, the cooling channels 15 meet in a common outlet 17, which is connected to a coolant pump 18 (see FIG. 8). The coolant pump 18 sucks ambient air through the suction holes 16 into the cooling channels 15 thereby effectively cooling the walls of the ionization chamber 2 and also the plasma generated within the ionization chamber 2. Therefore, the cooling further reduces the temperature of the generated plasma allowing in vivo plasma applications, e.g. sterilization of wounds, treatment of bacteriological, fungicidal and viral skin disorders.

[0053]It should further be noted that the inlet 3 of the ionization chamber 2 is connected to a gas source 19 (see FIGS. 8, 9) providing an argon gas flow.

[0054]Finally, FIG. 9 shows a side view of an exemplary medical device for the plasma treatment of wounds.

[0055]The medical device comprises a carriage 20 supported on rollers 21. The carriage 20 houses the auto tuner 7, the microwave generator 8 and the gas source 19 mentioned above. Further, the carriage 20 houses an uninterruptible power supply (UPS) 22, a transformer 23, a personal computer (PC) 24 and a mass flow controller 25.

[0056]At the top of the carriage 20 there is a rotatable column 26 supporting a moveable and pivotable arm 27 having several degrees of freedom of motion. The plasma source 1 is mounted at the and of the arm 27 so that the plasma source 1 can be easily positioned above a wound by gripping the handle 14 of the plasma source 1. In the desired position the therapist can release the handle 14 of the plasma source 1, so that the arm 27 will bear the weight of the plasma source 1 during the plasma application, which may take a couple of minutes.

[0057]Although the invention has been described with reference to the particular arrangement of parts, features and the like, these are not intended to exhaust all possible arrangements of features, and indeed many other modifications and variations will be ascertainable to those of skill in the art.

US Patent Application 20080136332
Method and Device For the Operation of a Plasma Device

Morfill; Gregor ;   et al.
June 12, 2008

Abstract -- A method for the operation of a plasma device (100) is described in which particles (2) are arranged in a plasma, wherein a generation of electric travelling waves (1) is provided, under whose effective action the particles (2) in the plasma device (100) perform a directed movement to at least one pre-determined collection area (20, 20A). A plasma device for carrying out the method is also described.

Inventors: Morfill; Gregor; (Munchen, DE) ; Konopka; Uwe; (Neufahrn, DE) ; Thomas; Hubertus M.; (Pfaffenhofen/Ilm, DE) ; Jacob; Wolfgang; (Garching, DE) ; Annaratone; Beatrice; (Munchen, DE) ; Fink; Martin; (Mintraching, DE) ; Sato; Noriyoshi; (Sendai, JP) ; Shimizu; Tetsuji; (Garching, DE) ; Stuffler; Timo; (Seefeld, DE)
U.S. Current Class: 315/111.21
U.S. Class at Publication: 315/111.21

Intern'l Class: H05H 1/00 20060101 H05H001/00

Description

[0001]The present invention relates to methods for the operation of a plasma device, as for example for the plasma-based material deposition or surface processing, and in particular to methods for the manipulation of particles in a plasma device. The present invention also relates to plasma devices which are configured for the implementation of such methods.

[0002]It is generally known that there can be particles in a gas in which a plasma condition is generated by means of an electric discharge. The particles are, for example, specifically introduced into the plasma from the outside or are generated in the said plasma by means of a pre-determined process sequence (refer to, e.g. "Dusty Plasmas: Physics, Chemistry and Technological Impact in Plasma Processing" (ed. A. Bouchoule), J. Wiley & Sons, 1999). In this case, particularly an examination or manipulation of the particles in the plasma can be desirable. During the examination of the particles, for example, an interaction of particles (e.g. during the generation of so-called plasma crystals) or the development or the growth of the particles are to be characterised. The manipulation of particles can comprise, for example, a particle processing in the plasma (surface removal or surface separation) or the deposition of the particles on substrates, as is the case during the controlled deposition of polymorphic layers (Cabarrocas et al. J. of Non-Crystalline Solids 227-230 (1998) 871-875). In the deposition of polymorphic layers, the separation or the deposition of particles in a certain particle size distribution can be of interest. However, a practical method for the setting of a particle size distribution has not been available up to the present time.

[0003]Alternatively, the particles in the plasma or on a substrate can represent an undesirable contamination. As an example, during the manufacture of solar cells, wafers or components for the flat screen technology by plasma deposition, the quality and the failure rate of the products can be substantially determined by the capability to keep away the disturbing particles from the substrates to be coated. Particles can cause local discharges on the substrate and, subsequently, holes in the layer through which the image quality, for example, of a flat screen is diminished.

[0004]One cause of the substrate contamination is that, after a coating operation when the plasma is switched off in a plasma reactor, the particles formed in the plasma with typical dimensions in the nm range to the um range carry an electric net charge (typically a negative charge), whereas the substrate surface has an opposing charge. This leads to a previously unavoidable particle movement to the substrate surface, even if the plasma coating is performed on vertically aligned substrates (Ivlev et al. "Decharging of Complex Plasmas: First Kinetic Observations" in "Phys. Rev. Lett.", Volume 90, Page 5). The problems mentioned here occur particularly with the plasma deposition on large substrates with typical diameters in the dm range to the m range.

[0005]With the applications for the examination or manipulation of particles in the plasma as well as with the particle contamination, there is generally an interest in exerting influence on the location, distribution and/or movement of the particles in a pre-determined manner. It is proposed in WO 99/52125, in a plasma reactor with additional electrodes or with the use of a so-called adaptive electrode with a plurality of partial electrodes, to set or to change the electric field statically or with low frequency in such a way that the particles assume a certain spatial distribution over the substrate in the plasma reactor. However, this technique can be disadvantageous in that the defined objectives of examining or manipulating particles in the plasma can only be solved to a limited extent and that the deposition on the substrate reproduces the structure of the electrodes.

[0006]The objective of the invention is to present an improved method for the operation of a plasma device with which the disadvantages of the conventional technologies for examining or manipulating particles in the plasma are overcome and that in particular a reliable and specific movement of particles in the plasma is made possible. The method according to the invention should have in particular an extended application range and open the way to new options for influencing the particles in the plasma. It is also the objective of the invention to present an improved plasma device with which the disadvantages of the conventional plasma reactors are overcome and which is suitable for influencing particles in the plasma.

[0007]This objective is solved by a method and a plasma device with the features of claims 1 and 19. Advantageous embodiments and applications of the invention result from the dependent claims.

[0008]With reference to the method, the invention is based on the general technical teaching of generating electric travelling waves in a plasma device through which waves forces are exerted on particles in the plasma, so that the particles are moved in a directed manner to at least one pre-determined collection area in the plasma device. The electric travelling waves advantageously cause a particle transport with a net flow of particles towards the collection area. As opposed to conventional techniques where merely a positioning or redistribution of particles without a net flow was envisaged, the travelling waves enable a continual particle movement during and/or after the formation of the plasma. With this, particles which are continually and subsequently formed in the plasma during a plasma deposition, for example, can be removed advantageously and constantly from a plasma area, particularly from the vicinity of a substrate that is to be coated. In the result, contaminations can be avoided and layers with a considerably improved homogeneity can be generated. The above-mentioned quality losses and equipment failures of the resulting products can be reduced and/or the plasma conditions for a manufacturing process can be optimised.

[0009]The electric travelling waves can advantageously run through the entire plasma area without restriction, so that the particle transport reliably takes place over extended substrates also, as coated for example in the semiconductor or solar cell technology.

[0010]The plasma device generally comprises a device with an evacuation-capable inner zone, in particular with a plasma chamber, which is filled with an operating gas for generating plasma and where electric fields can be applied for the ignition of a plasma discharge. An electric travelling wave is generated by an electric field distribution (travelling field) moving in the time sequence, preferably periodically repeated in a certain direction. According to the invention, a travelling wave can be generated with a pre-determined direction or several travelling waves with pre-determined directions, for example two travelling waves running oppositely relative to one another. By means of the interaction with the field of the travelling wave the particles perform a directed movement, meaning, they are shifted in a direction parallel to the running direction of the travelling wave. The term "directed movement" can include movements at least of parts of a particle quantity in several directions in each case when several travelling waves with various running directions are generated.

[0011]According to a preferred embodiment of the invention the electric travelling waves are generated with a plurality of strip electrodes which are arranged next to one another in the plasma device and are loaded with one or several alternating voltages (collection alternating voltage). The use of strip electrodes has the advantage of a high degree of flexibility with the generation of the travelling waves. The parameters of the electric travelling waves, particularly the wave form as well as the frequency and amplitudes, can be adapted with a minor work effort to the characteristics of the particles which are to be transported or deposited (separated), such as for example to their size or dielectric characteristics. Furthermore, the strip electrodes can be arranged without any problems in an existing plasma device without having any detrimental effect on its function, such as for example the coating of a substrate. In an advantageous manner, travelling waves can be generated with the strip electrodes which waves are uniform along the longitudinal course of the strip electrodes and the running direction of which is determined by the arrangement direction of the strip electrodes.

[0012]Further advantages for the generation of travelling waves can result if all strip electrodes are loaded with a common collection alternating voltage, this however with a pre-determined delay or phase shift in each case. The loading of the strip electrodes with specific phase shifts in each case means that strip electrodes, which are arranged in sequence and adjacent to one another in accordance with the desired movement direction of the particles to the collection area, are charged with the collection alternating voltage with a time lag so that the continuing travelling wave is generated in the desired direction of movement of the particles.

[0013]The method according to the invention has advantageously a high degree of variability with the selection of the collection alternating voltage or its adaptation to the conditions of the individual practical application. According to a first variant, the collection alternating voltage can be established with a symmetrical voltage characteristic. The time-dependency of the collection alternating voltage is characterised in this case by two edges mirror-symmetrical to one another within one period. This embodiment of the invention enables in an advantageous manner that available alternating voltage sources can be used for the provision of the collection alternating voltage. The migration velocity of the amplitude maxima of the collection alternating voltage is selected preferably in dependence of the size and the material of the particles in such a way that the transported particles are entrained with the front edges of the travelling waves. Voltage sources are particularly preferred in this case which provide for sinus-shaped or pulse-shaped voltage characteristics.

[0014]According to an alternative variant, the collection alternating voltage has an asymmetrical voltage characteristic. This means that, within one period, the rising and falling edges have various slopes. With this embodiment of the invention, the travelling wave has advantageously the form of a ramp profile that moves over the strip electrodes and, under whose effect, the particles are transported to the collection area. Preferably the front edge has the lesser slope, so that there is relatively a lot of time for an effective force exertion on the particles, whereas the rear-side edge has a steeper drop. During the passage through the rear-side edge there is hardly any backward movement due to the particle inertia with larger particles. As a result, only larger particles are selectively transported in the plasma.

[0015]Advantageously, the collection alternating voltage within a period can have a trapezoidal form. This means that there is in each case a direct voltage section between the rising and falling edges. This embodiment of the invention has the advantage that the steepness of the edges is freely selectable without having to change the period (or frequency) of the collection alternating voltage.

[0016]The asymmetrical form of the travelling wave has the particular advantage that, with the setting of the wave form and in particular with the setting of the slope and/or the duration of the edges, a size selection of the transported particles according to the invention can take place. The larger the particles, the slower the requirement for the edge of the collection alternating voltage to change so that an effective particle transport is obtained. This enables that the wave form, at least by means of one of the measures which comprise an increase of the frequency of the collection alternating voltage, an increase of the slope and a shortening of the edges of the collection alternating voltage, only such particles are subjected to the transport according to the invention whose size does not exceed a pre-determined maximum size.

[0017]Due to the already-mentioned correlation between the frequency and/or the form of the travelling waves and the size of the transportable particles according to the invention, the collection alternating voltage with one embodiment of the invention, where the plasma is generated in the plasma device by means of a high-frequent operating alternating voltage, is provided preferably with a frequency which is less than the frequency of the operating alternating voltage. Particularly preferred is a frequency of the collection alternating voltage in the range of 0.01 Hz to 10 Hz, particularly from 0.1 Hz to 10 Hz where, however, the particle transport according to the invention can be adjustably set at higher frequencies also (e.g., 100 Hz or higher).

[0018]If, according to a preferred embodiment of the invention, the strip electrodes are loaded with the collection alternating voltage as well as with an operating voltage of the plasma device for the purpose of forming the plasma, there can be further advantages for the practical operation of the plasma device. Firstly, and as a result of the superimposition of the collection alternating voltage and the operating voltage, the particles are subjected to the electric travelling waves at that particular location where they primarily originate. Secondly, the structure of the plasma device is simplified because no separate electrode is required for the generation of the plasma. With this embodiment of the invention, all strip electrodes are impacted with the operating voltage of the plasma device which is superimposed with the collection alternating voltage. Depending on the operating mode of the plasma device, the operating voltage can be a direct voltage or a high-frequency voltage.

[0019]Alternatively, at least one separate power electrode can be provided in the plasma device in addition to the strip electrodes, which power electrode is charged with the operating voltage of the plasma device for the purpose of plasma formation. This embodiment of the invention has the advantage that, by the strip electrodes, only two functions are taken over, particularly the travelling wave generation and a homogenisation of the electric field (see below), whereas the power electrode is provided for the operation of the plasma process.

[0020]With the superimposition of the collection alternating voltage and the operating voltage of the plasma device, the electric travelling waves can be advantageously and continually generated during the generation of the plasma. Alternatively, a separate provision of the collection alternating voltage (superimposed with a direct voltage) is possible, with which the particle transport takes place only during pre-determined collecting times before or after the generation of the plasma.

[0021]According to a further preferred embodiment of the invention, the collection alternating voltage is superimposed with a higher frequent modulation voltage. This superimposition advantageously enables a timing-averaged homogenisation of the plasma. Under the effect of the modulation voltage, ions in the plasma are moved while the substantially larger particles remain unaffected. The ions can be distributed more evenly in this way, a fact that is advantageous in particular with the plasma-based material separation on substrates. The parameters of the, e.g., sinus-shaped modulation voltage are selected in dependence of the geometrical properties of the electrode strips (particularly the strip width) and the wave form of the travelling wave as well as in dependence of the concentration and energy of the ions in the plasma. The amplitude of the modulation voltage is preferably selected in such a way that, in the course of a half period of the modulation voltage, ions can be transported over a length corresponding to half the step width between the electrode strips.

[0022]The frequency of the modulation voltage is selected in dependence of the practical operating conditions of the plasma device. If the strip electrodes according to the above-mentioned embodiment of the invention are impacted with the collection alternating voltage as well as with the operating voltage, the frequency of the modulation voltage is selected preferably in the kHz-range, particularly in the range from 0.1 kHz to 100 kHz. With the modified embodiment with separate strip and power electrodes, however, the frequency of the modulation voltage is selected in the kHz range to the MHz range, particularly in the range between 10 kHz to 1 MHz.

[0023]It can be advantageous for a reliable collection of the transported particles in the collection area if, according to a further modification of the invention, the at least one collection area has a hollow cathode in each case. The hollow cathode as such is known (refer to: Y. Kurimoto et al. in "Film Solid Film", Vl. 457, 2004, Page 285-291, and WO 01/01467). Their use has the advantage that the particles in the collection area are retained under the effect of electric fields. The particles can be collected and used again.

[0024]Alternatively or additionally, the collection area can be formed by an accumulation zone in which the particles are accumulated in the suspended condition in the plasma. The formation of an accumulation zone in the plasma chamber can be advantageous for the examination of particle clouds or for the deposition of large particle quantities on substrates.

[0025]According to a further variant of the invention the electric travelling waves can be generated with various directions, particularly with directions opposing one another, so that the particles perform aligned movements to at least two pre-determined collection areas. A material-specific or size-specific collection of the particles can advantageously and subsequently take place in various collection areas. The movements in the various directions can be realised simultaneously or time-separated, for example in successive order.

[0026]A further significant advantage of the invention lies in the variability during the configuration of the movement direction of the particles. The travelling waves can move linearly in a pre-specified direction which runs essentially vertical to the expansion of planar-arranged strip electrodes. Alternatively, a circular movement can be induced with strip electrodes which are arranged in a circular shape on the outer periphery of a plasma chamber.

[0027]The above-mentioned object is solved related to the device by the general technical teaching of equipping a plasma device, which is provided for the formation of a plasma, with at least one electrode for generating electric travelling waves for the directed transport of particles in the plasma device and at least one collection area for accommodating the particles. The combination, according to the invention, of at least one electrode for the generation of travelling waves (in the following: travelling wave electrode) and at least one collection area enables advantageously the specific removal of particles from the plasma and particularly from a layer-shaped zone above a substrate in the plasma device.

[0028]The travelling wave electrode preferably comprises a plurality of strip electrodes, each of which is connected to a voltage source for generating the collection alternating voltage. The strip electrodes are arranged preferably in one plane, so that the travelling wave electrode can be advantageously arranged immediately adjacent to a substrate on its opposing side relative to the plasma.

[0029]The strip electrodes of the travelling wave electrode preferably form a line lattice. They all have the same size and form, for example a straight form or a curved line form, and a constant step width (constant mutual distances from centre-to-centre of adjacent strip electrodes). The use of straight electrode strips has advantages for the homogeneity of the travelling waves for the particle transport.

[0030]Generally, each of the strip electrodes can be integrally formed. Alternatively, the formation of an electrode strip is possible by means of a series of electrode segments joined electrically to one another, for example square-type electrode segments as known from conventional adaptive electrodes.

[0031]According to a preferred embodiment of the plasma device according to the invention the travelling wave electrode has a plate-shaped electrode carrier, wherein the strip electrodes are arranged on at least one surface of the electrode carrier. The provision of the electrode carrier has the advantage that a compact structural component is created with a defined arrangement of the strip electrodes.

[0032]It can be advantageous particularly for applications related to plasma-based material deposition if strip electrodes are arranged on both surfaces of the electrode carrier. This enables a coating arrangement with two vertically arranged substrates, between which the travelling wave electrode is located for transporting away the particles over both electrode surfaces.

[0033]According to a preferred embodiment of the invention, the strip electrodes comprise wire electrodes which are insulated from one another and inserted into the electrode carrier or arranged on its surface. Wire electrodes have the advantage that they can be arranged with a particularly narrow spacing distance. This has a positive effect on the setting of an essentially smooth and stepless wave form of the travelling waves. Furthermore, wire electrodes have advantages with reference to the freedom of the configuration of the electrode arrangement. Alternatively, the electrode strips are formed in a layer-type manner on the surface of the electrode carrier. The layer-type configuration is advantageous because of the reduced capacitive coupling in this case between adjacent electrode strips.

[0034]For the purpose of realisation of the above-mentioned circular shaped movement of the particles, the travelling wave electrode has a ring-shaped electrode carrier on whose surface the strip electrodes are arranged. The ring-shaped strip electrode advantageously enables a further use of the particle transport, according to the invention, by means of travelling waves, a particle acceleration taking place in the plasma, e.g. by means of an increase of the migration velocity of travelling waves in one or several adjacently arranged rings of strip electrodes.

[0035]According to a further variant of the invention, the travelling wave electrode comprises strip electrode groups each with a plurality of strip electrodes. The strip electrodes belonging to a strip electrode group are electrically connected to one another. The strip electrodes are arranged in such a way that each one of the strip electrodes in successive order belongs to another strip electrode group. With the arrangement of the strip electrodes, a periodic pattern is provided wherein the periods respectively contain in the same order strip electrodes of each strip electrode group. The compilation of strip electrodes to groups advantageously enables that all strip electrodes belonging to a strip electrode group are impacted with the same phase position of the collection alternating voltage. By means of the above-mentioned periods, particularly the extension of a period of the electric travelling waves is defined.

[0036]If the travelling wave electrode is equipped with a heating device according to a further modification of the invention, this can have advantages for the manufacture of polymorphic layers, e.g., for Si-based solar cells and/or for the protection of the strip electrodes against deposition. The smaller particles can be transported away from the plasma according to the invention, whereas the larger particles are deposited on the substrate. These larger particles can be excitated to a further crystallographic growth by heating the substrate with the heating device, or can be subjected to a curing process.

[0037]Further details and advantages are described as follows with reference to the attached drawings. The drawings show the following:

[0038]FIG. 1: a schematic illustration of a first embodiment of a plasma device according to the invention,

[0039]FIG. 2: curve illustrations with examples of collection alternating voltages used according to the invention,

[0040]FIG. 3: embodiments of strip electrodes used according to the invention,

[0041]FIG. 4: an illustration of the formation of strip electrode groups,

[0042]FIGS. 5 and 6: details of further embodiments of plasma devices, according to the invention, with vertically aligned main electrodes,

[0043]FIG. 7: a schematic top view of a further embodiment of a plasma device, according to the invention, with strip electrodes in ring-shaped arrangement, and

[0044]FIG. 8: a perspective cross-sectional illustration of the arrangement of strip electrodes with the embodiment according to FIG. 7.

[0045]Details of the method according to the invention are explained as follows with reference to the plasma device 100 as shown in FIG. 1. Known details of the plasma device and its operation, particularly the operating conditions for the generation of plasma, are not described here.

[0046]FIG. 1 shows schematically the plasma device 100 with a travelling wave electrode 10, a collection area 20, a counter electrode 30, a substrate 40 and a control apparatus 50. The mentioned components 10 to 40 are arranged in a plasma chamber 101 which can be evacuated (illustrated with dashed lines). In the plasma chamber 101 a plasma condition can be ignited in an operating gas. Particles can form in the plasma, or particles can be fed from the outside into the plasma. The particles have sizes in the range, for example, between 10 nm to 20 .mu.m.

[0047]The travelling wave electrode 10 comprises a plurality of electrode strips 11 which are arranged on a plate-shaped electrode carrier 12 and are each connected with the control apparatus 50 by way of an electrode connection 14. In FIG. 1, the strip electrodes 11 are entered in the drawing for illustration purposes and are not to scale. In order to obtain best possible stageless travelling waves and a best possible small capacitive coupling between adjacent strip electrodes, these are arranged with a small thickness and a narrow spacing clearance as best as possible in each case. The straight strip electrodes 11 shown in cross-sectional arrangement and extending vertically to the drawing plane have, for example, a width of 4 mm and a vertical centre-centre-clearance of 10 mm.

[0048]The electrode connections 14 are connected, for example, at the periphery of the electrode carrier 12 to the individual electrode strips 11. Across the electrode strips 11 there is an electrically insulating protective layer 13, e.g. consisting of SiO.sub.2 (glass), over which the substrate 40 is located. The substrate 40 can lie immediately on the protective layer 13 or (as shown) can be arranged with spacers having a clearance spacing from the electrode carrier 12.

[0049]The collection area 20 comprises a hollow cathode 21 extending parallel to the periphery of the substrate 40, which cathode is also connected to the control apparatus 50. The hollow cathode 21 has, for example, the design type as described in WO 01/01467.

[0050]The travelling wave electrode 10 in the embodiment according to FIG. 1 simultaneously serves as a power electrode which acts together with the counter electrode 30 for the purpose of formation of the plasma in the plasma device 100. The counter electrode 30 can be arranged in the plasma chamber 101 as a ring-shaped, disk-shaped or rod-shaped electrode, or alternatively formed by the wall of the plasma chamber 101. The substrate 40 is selected in dependence on the application of the plasma device 100 and consists of, for example, a semiconductor wafer or glass.

[0051]In the control apparatus 50 a voltage source is provided for the establishment of the collection alternating voltage with a pre-determined voltage characteristic which is loaded on the strip electrodes 11 with defined phase shifts. The voltage source also serves to provide the operating voltage for generating the plasma in the plasma chamber 101. For example, all strip electrodes are impacted together with a high-frequent operating voltage with the use of suitable frequency filters.

[0052]In FIG. 1, a ramp-shaped voltage characteristic 1 at two different times is shown schematically as an example. As the collection alternating voltage at the strip electrodes 11 is provided in successive order with an increasing delay or phase shift, there is the resulting image of a ramp-shaped field distribution that moves in the time sequence in waveform towards the collection area 20 (see upper arrow). There results a field gradient extending parallel to the surface of the electrode carrier. Particles which, for example, are formed and grown above the substrate 40 as a result of nucleus formation in the plasma undergo a force action by the travelling wave towards the periphery of the substrate 40 where they are taken up or "suctioned up" with the hollow cathode 21.

[0053]FIG. 2 illustrates different variants of symmetrical or asymmetrical voltage characteristics of the collection alternating voltage. In each case the amplitudes of the alternating voltage portions are shown, with which the strip electrodes 11 are charged. FIG. 2a shows a sinus-shaped sequence of the collection alternating voltage which results in a travelling wave with even rising and falling edges. The other sequences in the FIGS. 2b-2e show asymmetrical shapes with a slowly rising front edge 1A, if required with a direct voltage zone 1B and a rapidly falling rear edge 1C. The edges 1A, 1C in FIG. 2b have, for example, a time ratio of 10:1. This can be varied by the insertion of the direct voltage zones 1B at constant period of the collection alternating voltage (FIGS. 2c, d). FIG. 2e illustrates that the voltage characteristic 1 does not have to be compellingly composed from linear curved pieces, but rather can have also any other time dependency factor.

[0054]The amplitude, frequency, curve form (particularly the steepness of the edges) and phase of the collection alternating voltage and, with this, particularly the propagation velocity of the travelling wave are pre-determined with the voltage source in the control apparatus 50. At least one of these variables is selectable with the voltage source. For example, by the selection of the steepness of the falling edge 1C, the particle size can be defined above which there is essentially no particle transport. The concrete quantitative variables are selected by those skilled in the art, particularly in dependence on the particle material, the particle sizes and the field strengths.

[0055]FIG. 3 illustrates different variants of a travelling wave electrode 10 with the strip electrodes 11 in or on the electrode carrier 12, in each case as an example with further features of the invention. According to FIG. 3a, wire electrodes are embedded in the surface of the electrode carrier 12. FIG. 3a also illustrates the combination of the travelling wave electrode 10, according to the invention, with a heating device 60 which is thermally connected with the electrode carrier 12 and is, for example, arranged on its underneath side. FIG. 3b shows a variant with strip electrodes 11 in the form of straight electrode bands (cross-sectional illustration). In the left part of FIG. 3b the effect of a high-frequent modulation voltage is shown which is superimposed on the collection alternating voltage. During the course of the travelling wave and subject to the effect of the modulation voltage, ions in the plasma are distributed over an area which extends over two adjacent strip electrodes. The coating of a substrate 40 is homogenised in this way. According to FIG. 3c the strip electrodes 11 are formed in each case by insulated wires or wires embedded in a non-conductive material such as a resin, for example, where said wires are arranged on the surface of the electrode carrier 12. The coating of the strip electrodes 11, shown as an example in FIG. 3c, can also be advantageous for the protection of the strip electrodes against undesirable deposition. Furthermore, FIG. 3c illustrates as an example the arrangement of two collection areas 20, 20A on different sides of the electrode carrier.

[0056]FIG. 3d shows a structural arrangement with a substrate 40 to be coated, similar to FIG. 3b, where in this case, however, a separate power electrode 31 is provided in addition to the travelling wave electrode 10, which power electrode is loaded with the operating voltage for the formation of the plasma condition in the plasma device. For this purpose, the strip electrodes 11 and the power electrode 31 have separate connecting lines (not shown) for connection to the control apparatus 50.

[0057]FIG. 4 illustrates schematically the formation of electrode strip groups 15 where successively arranged electrode strips 11 are periodically connected with one another. In the illustrated example, the 1st, 16th, 32nd etc. electrode strips 11 are electrically connected with one another and are loaded with the same phase position of the collection alternating voltage, while the following 2nd, 17th and 33rd strip electrode, in each case, are loaded with a common phase which is, however, delayed relative to the first phase position. Accordingly, and with the control apparatus 50, the voltage characteristic of the desired collection alternating voltage must only be established with 15 different phase positions in order to generate the travelling wave moving over the entire substrate.

[0058]FIGS. 5a and 5b show the application of the invention with the plasma-based material deposition on the substrate 40. According to FIG. 5a the travelling wave electrode 10 is located on the side of the vertically aligned substrate 40 facing away from the plasma 2. The travelling waves are generated parallel to the substrate surface, running vertically downwards, to the lower periphery of the substrate. FIG. 5 shows the two-sided usage of the travelling wave electrode 10 which is arranged here between two substrates 41, 42 and which is significant for practical applications.

[0059]FIG. 6 illustrates the combination, according to the invention, of the travelling wave electrode 10 and the collection area 20 in a schematic perspective view with further details. The strip electrodes 11 are embedded in the electrode carrier 12. The electric connection is effected by way of the electrode connections 14 at the periphery of the electrode carrier 12. The hollow cathode 21 of the collection area 20 extends over the entire length of the strip electrodes 11 at the periphery of the electrode carrier 12.

[0060]A further modified embodiment of the invention, in which circular shaped particle movements are generated, is schematically illustrated in the FIGS. 7 and 8. According to FIG. 7, in the plasma device 100 with the plasma chamber 101 which can be evacuated, a power electrode 31 is provided and shown schematically in top view, on whose peripheral rim the travelling wave electrode 10 extends with a plurality of electrode strips 11 on a ring-shaped electrode carrier 16. The power electrode 31 contains a cut-out 32, at which the collection area 20 is formed. FIG. 8 shows a corresponding structural configuration in cross-sectioned perspective view. Each of the strip electrodes 11 is connected to the control apparatus 50 which contains the voltage source for generating the collection alternating voltage and the modulation voltage. For reasons of clarity, not all electrode connections 14 of the individual strip electrodes 11 are shown in FIG. 7 and not all strip electrodes in FIG. 8.

[0061]With the embodiment shown in FIGS. 7 and 8, circularly running travelling waves are generated with which the particles 3 in the plasma are moved over the power electrode 31 on circular paths. The movement is effected up to section 32 where, for example, the particles are suctioned out of the plasma chamber with a hollow cathode (not shown).

[0062]FIG. 7 also schematically shows an accumulation zone 22 which comprises a zone area in the plasma chamber, in which and by means of a corresponding activation of the adjacent electrodes or as a result of the non-existence of electrodes, conditions are present in such a way that the particles 3 accumulate in this zone area.

[0063]The particle transport takes place with a higher degree of effectiveness at the radial outer rim of the power electrode 31. For this reason, the circular movement of the particles is superimposed with a radial and outwardly directed diffusion movement of particles.

[0064]A significant advantage of the embodiment of the invention as shown in FIGS. 7 and 8 lies in the fact that, with the ring-shaped electrode carrier 16, existing plasma reactors can be backfitted in an uncomplicated manner. In order to protect the strip electrodes 11 against deposition during the operation of the plasma device, a heating device can be provided for heating the strip electrodes 11 and/or a coating of the strip electrodes 11, e.g. with glass, can be provided.

[0065]A further advantage of the illustrated embodiment lies in the option of generating a continual particle flow with a constant or with a variable speed in the plasma device in order to examine the interactions between the particles which form the so-called fluid or crystalline conditions.

[0066]The features of the invention as disclosed in this description, in the claims and in the drawings can be of significance both individually as well as in combination for the realisation of the invention in its various embodiments.
