Determining an optimal ion energy for plasma processing of a dielectric substrate

Citation for published version (APA):
Yu, Q., Lemmen, E., & Vermulst, B. J. D. (2021). Determining an optimal ion energy for plasma processing of a dielectric substrate. (Patent No. *WO2021064110*).
https://worldwide.espacenet.com/patent/search/family/068425237/publication/WO2021064110A1?q=pn%3DWO2021064110A1&queryLang=en%3Ade%3Afr

Document status and date:
Published: 08/04/2021

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

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Download date: 05. Oct. 2023

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property
Organization
International Bureau

(43) International Publication Date
08 April 2021 (08.04.2021)

WIPO | PCT

(10) International Publication Number
WO 2021/064110 A1

(51) International Patent Classification:
H01J 37/32 (2006.01) *G05F 3/20* (2006.01)
C23C 14/34 (2006.01)

(21) International Application Number:
PCT/EP2020/077536

(22) International Filing Date:
01 October 2020 (01.10.2020)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
2023935 02 October 2019 (02.10.2019) NL

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, IT, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:
— *of inventorship (Rule 4.17(iv))*

Published:
— *with international search report (Art. 21(3))*

(54) Title: DETERMINING AN OPTIMAL ION ENERGY FOR PLASMA PROCESSING OF A DIELECTRIC SUBSTRATE

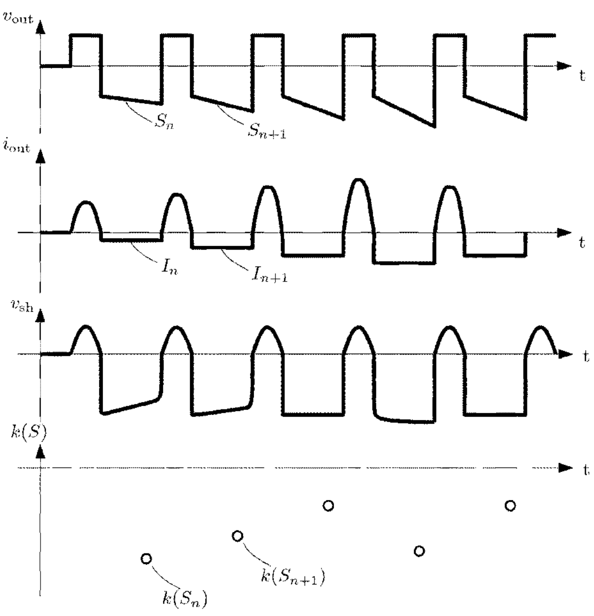

FIG 4

(57) Abstract: An ion energy for plasma processing of a dielectric substrate (109) is determined by exposing the dielectric substrate (109) to a plasma discharge and applying a pulsed voltage waveform to the dielectric substrate. The pulsed voltage waveform comprises a sequence of pulses, each pulse comprising a higher voltage interval and a lower voltage interval having a voltage slope. Further, first pulses of the sequence having differing voltage slopes between one another are generated and applied to the dielectric substrate. For each one of the first pulses, the voltage slope (S) and an output current (I_p) corresponding to the voltage slope are determined. For each one of the first pulses, at least one coefficient (*k*, *b*) of a mathematical relation between the voltage slope and the corresponding output current based solely on the voltage slope and the output current determined for one or more of the first pulses is determined. A test function is applied to the at least one coefficient and an optimal voltage slope value corresponding to the at least one coefficient making the test function true is selected. An apparatus for plasma processing of a dielectric substrate implements the above method.

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Determining an optimal ion energy for plasma processing of a dielectric substrate

Technical field

[0001] The present invention is related to methods and apparatuses for plasma processing of dielectric substrates, such as plasma-assisted etching and deposition. In particular, the present invention is related to methods of determining an optimal ion energy for plasma processing of dielectric substrates, and to corresponding apparatuses.

Background art

[0002] Plasma-assisted etching and deposition, such as reactive ion etching (RIE), atomic layer etching (ALD) and atomic layer deposition (ALD), are widely used in semiconductor manufacturing. Taking the reactive ion etching for example, plasma is used not only to increase the rate of removing or growing materials, but also to increase the quality of the process. The plasma consists of positive ions, negative electrons and neutral particles. During etching process, the ions are accelerated by the negative voltage potential on the material surface and bombard the material, so that supply additional energy to the surface and accelerate the chemical reactions. Besides, the normal direction of ion bombardment to the material surface also enhances the anisotropy of the etching.

[0003] The ion energy is controlled within a limited range. Ions with too low energy result in a slow reaction rate while ions with too high energy causes sputtering, which decreases the selectivity. With the increasing demands on the smaller semiconductor size, accurate control of ion energy becomes critical in both plasma-enhanced deposition and etching. In general, a narrow ion energy distribution (IED) falling into a certain range of energy value is desired, which requires a constant negative voltage potential on the substrate material surface.

[0004] The ion energy is determined by the voltage potential of the substrate surface. For a conductive substrate material, a negative dc bias voltage can be directly connected to the table in the reactor. By varying the dc value of the voltage, the energy of the ions can be controlled correspondingly. However, for a dielectric substrate material, there is an equivalent substrate capacitance. A simple dc bias does not work well because the ions are charging the substrate during etching, resulting in an increase to the substrate voltage potential.

[0005] To control the ion energy with a dielectric substrate, a radio-frequency (RF) sinusoidal bias voltage is usually used in the conventional reactor. In this case, a blocking capacitor is required for RF biasing in order to generate a self-biased negative dc potential on the sheath. The sinusoidal voltage waveform produces a variant voltage potential on the substrate surface, thus resulting in a wide and bimodal IED. Although increasing the frequency helps narrowing the IED, it is limited by the ion mass and it is much less effective for light ions such as hydrogen. Furthermore, a sufficiently large biasing frequency makes the RF wavelength comparable to the substrate dimension, causing severe nonuniformities. Finally, the RF biasing generates a lot of reactive power, leading to a low efficiency and high cost.

[0006] The pulse-shape biasing is also used in plasma-enhanced etching and deposition. It consists of a wide negative pulse in the deposition and etching phase and a short positive pulse during the discharge phase.

[0007] The positive pulse is applied to the substrate potential in order to attract electrons and discharge the accumulated ions periodically. However, the substrate potential is still charged by the ions during etching or deposition phase, thereby a narrow IED cannot be obtained with this simple waveform. Like the RF biasing, although increasing the frequency is effective in narrowing the IED under certain circumstances, it degrades the process quality.

[0008] It is known from US 2014/0061156, 6 March 2014 to apply a tailored pulsed-shape bias so as to compensate the ion accumulation effect on the dielectric substrate during etching or deposition phase. The bias voltage waveform consists of a decreasing negative voltage slope to compensate the substrate potential rise during deposition and etching phase, and a positive voltage pulse to attract electrons to keep charge balance during discharge phase. Such a voltage waveform can produce a narrow ion energy distribution. The repetition frequency is much less than the traditional RF biasing and pulse-shape biasing.

[0009] The negative voltage slope in US 2014/0061156 can be obtained by incorporating an ion current compensation, such as a current source, to a switch-mode power supply coupled to the substrate. The negative voltage slope of the pulsed voltage waveform must be finely tuned in order to obtain the narrowest IED. US 2014/0061156 proposes to evaluate a function based on the voltage slope, the effective capacitance of the substrate and the ion current compensation, and to adjust the ion current compensation until the function is true which would correspond to the narrowest IED. The function is made to be true when the ion current compensation equals the ion current. To determine the ion current compensation that equals the ion current, in one embodiment, a first ion current compensation is applied for a first cycle and a first voltage slope of the pulsed voltage waveform is measured. A second ion current compensation for a second cycle is applied and a second voltage slope is measured. From this, a third ion current compensation can be determined at which the function is expected to be true and therefore would result in a narrow IED.

[0010] One drawback however of the above method, is that a very simplified equivalent electrical model is used to synthesize the function, in which some stray capacitances, such as the table capacitance, are neglected. Furthermore, the effective capacitance of the substrate must be determined in order to be able to evaluate the function, requiring additional measurement. Measuring this capacitance in real time is very difficult to perform. On the other hand, measuring the capacitance once and assuming it to be constant may lead to erroneous results as the effective capacitance might be variant and dependent on parasitic capacitances introduced by the table, other components in the plasma chamber, the voltage potential on the substrate, and the plasma sheath.

[0011] The plasma sheath (also simply referred to as sheath) is a layer in a plasma near the substrate surface and possibly the walls of the plasma processing chamber with a high density of positive ions and thus an overall excess of positive charge. The surface with which the sheath is in contact with typically has a preponderance of negative charge. The sheath arises by virtue of the faster velocity of electrons than positive ions thus causing a greater proportion of electrons to reach the substrate surface or walls, thus decreasing the density of electrons in the sheath.

[0012] As a result, the capacitances and ion currents are different under different etching or deposition conditions. In addition, the sheath capacitance is also voltage dependent. A slight difference of the plasma condition or a change to the etching reactor might require a recalculation. These non-ideal factors bring on an inaccuracy in practice.

Summary of the invention

[0013] It is an aim of the present invention to overcome the above drawbacks. It is an aim to find optimal operating conditions in plasma processing of dielectric substrates efficiently and in an automated way, without requiring manual intervention. It is also an aim to find optimal operating conditions in plasma processing of dielectric substrates more accurately, without relying on overly simplified equivalent electrical models.

[0014] According to a first aspect of the invention, there is provided a method of determining an ion energy for plasma processing of a dielectric substrate, as set out in the appended claims.

[0015] Methods according to the invention comprise exposing the dielectric substrate to a plasma discharge and applying a pulsed voltage waveform generated by a power supply to the dielectric substrate, particularly during the exposure. The pulsed voltage waveform comprises a sequence of pulses, each pulse comprising a higher, e.g. positive, voltage interval and a lower, e.g. negative, voltage interval, wherein the lower voltage interval comprises a voltage slope, in particular a negative voltage slope.

[0016] According to the invention, the sequence comprises first pulses having differing voltage slopes between one another. The first pulses are applied to the dielectric substrate, in particular during exposure to the plasma discharge. For each one of the first pulses, the voltage slope and an output current corresponding to the voltage slope at an output of the power supply are determined. Either one or both of the voltage slope and corresponding output current can be measured, and the other one can be set by a control unit coupled to the power supply.

[0017] For each one of the first pulses, at least one coefficient of a mathematical relation between the voltage slope and the corresponding output current is determined based solely on the voltage slope and the output current determined for one or more of the first pulses. The mathematical relation is a function expressing a relation between the voltage slope and the output current. Either one of the voltage slope and the output current can be a variable of the function, and evaluating the function for the variable yields the other one of the voltage slope and output current. The function comprises at least one coefficient, which can be variable with the voltage slope and/or the output current. According to the invention, the mathematical relation (function) is resolved for the at least one coefficient, such that the at least one coefficient is determined based on known (determined) values of voltage slope and output current.

[0018] Advantageously, a test function can be applied to the at least one coefficient in order to determine an optimal voltage slope. The test function is true when the at least one coefficient relates to an optimal voltage slope making the IED narrowest. The test function advantageously finds an extremum of the at least one coefficient.

[0019] Since the method relies only on voltage and current values, which can be determined automatically, methods of the invention allow to tune the operational parameters of the plasma processing apparatus in a fully automated way, without manual intervention, and without requiring time consuming or cumbersome measurements of other electrical quantities, such as capacitance, which reduces cost and throughput time.

Additionally, the automated tuning according to the invention allows to auto-tune every dielectric substrate that is processed, leading to higher accuracy. Typically, a sequence of between 10 and 50 first pulses would suffice in order to find an optimal voltage slope with satisfactory accuracy.

[0020] Furthermore, the at least one coefficient is advantageously related to the system capacitances. By evaluating the coefficient(s) based on the voltage and current values only, the voltage-dependent and/or current-dependent behaviour of the system capacitances are implicitly taken into account and there is no need to measure them separately. Methods according to the invention therefore can provide a more accurate tuning to a desired (e.g., narrowest) IED.

[0021] Advantageously, the mathematical relation is a polynomial function between the output current and the voltage slope. The polynomial function can be of any degree, e.g. zero, one, two, three, etc., depending on the equivalent electrical model of the plasma processing system. By way of example, the polynomial function is a first degree polynomial, in particular of the kind: $I_P = k\ S + b$, wherein I_P represents output current, S represents voltage slope and wherein the at least one coefficient is at least one of k and b.

[0022] The first pulses can form a sequence having monotonically increasing voltage slopes. By way of example, the method may start with very small, e.g. zero, voltage slope, and systematically increasing the (negative) voltage slope until an extremum (e.g. maximum value) of the at least one coefficient is found. The voltage slope steps between consecutive pulses can be constant, or variable, and the method may provide to automatically adapt the voltage slope step between the first pulses, e.g. based on a behaviour of the at least one coefficient that is determined. It will be convenient to note that any other suitable convergence algorithm can be used for selecting the voltage slopes in order to converge to an extremum of the at least one coefficient.

[0023] According to a second aspect of the invention, there is provided an apparatus for plasma processing of a dielectric substrate, as set out in the appended claims.

[0024] An apparatus according to the invention comprises means for generating a plasma, e.g. a plasma reactor coupled to an external power supply through a matching network, a processing platform for supporting the dielectric substrate and configured for exposure to the plasma, a power supply (power amplifier), a voltage measurement device and a current measurement device. The plasma is excited and sustained by the external power supply. The power amplifier is coupled to the processing platform and to a control unit. The power amplifier is configured to output a configurable tailored pulse-shape voltage waveform.

[0025] Advantageously, the apparatus is configured to carry out any of the methods according to the present invention. Methods of the invention can be implemented in the control unit.

[0026] Methods and apparatuses as described herein can also be used to calculate and dimension electrical parameters which are hard to measure directly in practice, including the substrate capacitance, the table capacitance and the ion current.

Brief description of the figures

[0027] Aspects of the invention will now be described in more detail with reference to the appended drawings, wherein same reference numerals illustrate same features and wherein:

[0028] Fig. 1 illustrates the block diagram of an apparatus for plasma processing according to the invention;

[0029] Fig. 2 represents a simplified electric model of the system of Fig. 1;

[0030] Fig. 3 depicts a typical waveform of the output voltage, the output current and the substrate voltage potential;

[0031] Fig. 4 illustrates a possible implementation of the auto-tuning method according to the invention, comprising applying a sequence of first pulses having different voltage slopes;

[0032] Fig. 5 represents a possible realization of the power supply for use in the apparatus of FIG. 1;

[0033] Fig. 6 shows graphs of output voltage output current and calculated coefficient values for an experimental setup of the method of the present invention;

[0034] Fig. 7 shows the measured ion energy distribution corresponding to different voltage slopes of Fig. 6.

Description of embodiments

[0035] An apparatus for plasma processing a dielectric substrate, such as a semiconductor substrate, is shown in FIG. 1. Gas is infused to the reactor 110. The plasma is ignited in the reactor 110 with an external power supply 101, which is coupled with the gas by a matching network 105 and a coil 108 outside the chamber. The power supply is connected to the matching network 105 and the matching network is connected to the coil 108. The power supply 101 can be any suitable power source including radio-frequency (RF), microwave-frequency (MF) and pulsed dc power sources. Although the plasma source as shown in FIG. 1 is inductively coupled, it can be of any other variety, such as capacitively coupled plasma source and helicon type plasma source.

[0036] The apparatus of Fig. 1 can be used for plasma etching or deposition. Therefore, a dielectric substrate material 109 is placed on the table 111 inside the reactor 110. The pressure in the reactor is kept low (i.e. below atmospheric pressure) by a (vacuum) pump depicted in FIG. 1. A power amplifier 114 is connected to the table 111 through electrical connection 113.

[0037] A voltage measurement unit 116 can be connected to the power amplifier 114, measuring the output voltage of the amplifier. The voltage measurement unit 116 is coupled to controller 115 through (data) connection 117 for sending measured results to the controller 115.

[0038] A current measurement unit 119 can be provided to measure the output current of the power amplifier 114, e.g. through an interface 112 connected to electrical connection 113 and/or table 111. The current measurement unit 119 is coupled to controller 115 through (data) connection 120 for sending measured results to the controller 115.

[0039] The controller 115 implements an automatic control algorithm according to the present invention, which is based on the measured voltage and/or current values. The controller 115 is coupled to the power amplifier 114 through (data) connection 118 for sending control signals to the power amplifier 114 to adjust the output (voltage) waveform. The automatic control algorithm is configured to control ion energy in order to obtain a narrowest IED. Advantageously, the control algorithm is implemented as a real-time control system with a voltage and/or current feedback.

[0040] A basic equivalent electric model of the system of Fig. 1 is depicted in FIG. 2. During etching or deposition phase, the plasma can be assumed to be a constant voltage source V_p. An ion sheath is formed between the plasma and the surface of the material. The ion sheath is equivalent to a dc current source I_I in parallel with a sheath capacitance C_sh and a diode D_1. The substrate is equivalent to a capacitor C_sub. For a conductive substrate, C_sub is infinitely large, which can be treated as an ideal wire. For a dielectric substrate, C_sub has a finite value. There are parasitic capacitances between the table and other components, including the plasma and the reactor wall, which is defined by the table capacitance C_t. The table is conductive and connected to the output of the power amplifier.

[0041] For a conductive substrate, the output voltage V_out is a constant dc value. The sheath voltage V_sh is then defined by $V_\mathrm{sh} = V_\mathrm{out}$. The voltage and current measurement unit are used to monitor the dc value. V_out is regulated by the feedback controller.

[0042] As depicted in FIG. 3, for a dielectric substrate, the waveform of V_{out} is of a tailored pulse-shape, which can be divided into 2 phases, including a discharge phase and an etching or deposition phase. The discharge phase consists of a positive pulse V_0 lasting for T_1, used to attract electrons and discharge the substrate periodically. T_1 should be as short as possible only if the substrate surface gets fully discharged. The etching or deposition phase consists of a negative slope defined by V_1, V_2 and T_2. A negative voltage V_1 is applied to the table after the substrate is fully discharged. The voltage potential V_{e} on the substrate surface during etching or deposition is approximated by

$$V_{\mathrm{e}} \approx V_1 - V_0.$$

To compensate the ion accumulation on the substrate surface, a negative voltage slope should be applied to the table. The voltage slope is defined by 3 portions V_1, V_2 and T_2. The slope rate S is defined by

$$S = \frac{V_2 - V_1}{T_2}.$$

In order to obtain a constant negative voltage on the substrate during etching or deposition phase, the voltage slope rate should be tuned to an exact value, which is equivalent to

$$S = -\frac{I_{\mathrm{i}}}{C_{\mathrm{sub}}}.$$

However, in practice, I_{I} and C_{sub} are unknown. In the prior arts, it is tuned either by hand or by theoretical calculation. Both tuning methods result in a deviation with the optimal voltage slope. In addition, the hand-tuning method requires a lot of time and an additional retarding field energy analyzer or equivalent. Furthermore, the above theoretical calculation method is based on an over-simplified model and relies on the pre-measured substrate capacitance, which might vary in the process.

[0043] Referring to FIG. 4, an algorithm to auto-tune the output voltage slope according to the invention, works based only on output voltage and output current. Either one can be set, e.g. by controller 115 and the other one can be measured, e.g. by voltage measurement unit 116 and/or current measurement unit 119. The tuning algorithm according to the invention can be implemented by the controller 115 in a fully automatic way and discards the need for any manual intervention or additional measurement (e.g. measurement of capacitance values).

[0044] During the etching or deposition phase, the output current is a negative dc value and equal to $-I_{\mathrm{P}}$. The value of I_{P} is given by

$$I_{\mathrm{P}} = -\left(\frac{C_{\mathrm{sh}} C_{\mathrm{sub}}}{C_{\mathrm{sh}} + C_{\mathrm{sub}}} + C_{\mathrm{t}}\right) S + \frac{C_{\mathrm{sub}}}{C_{\mathrm{sh}} + C_{\mathrm{sub}}} I_{\mathrm{i}}.$$

If all the capacitances and the ion current are constant and independent of the sheath voltage, I_P has a linear relation with the voltage slope rate S. However, in practice, the sheath capacitance C_sh is dependent on the sheath voltage thus changing with the voltage slope rate S. I_P can then be described as

$$I_\mathrm{P} = k(S)S + b(S),$$

Where $k(S)$ and $b(S)$ are a function of the voltage slope rate S and given by

$$k(S) = -\left(\frac{C_\mathrm{sh}C_\mathrm{sub}}{C_\mathrm{sh} + C_\mathrm{sub}} + C_\mathrm{t}\right)$$

and

$$b(S) = \frac{C_\mathrm{sub}}{C_\mathrm{sh} + C_\mathrm{sub}} I_\mathrm{i}.$$

respectively. When the voltage slope rate S is tuned to the optimal value, with which the narrowest IED is obtained, V_sh turns to be constant. I_P is then given by

$$I_\mathrm{P} = -C_\mathrm{t}S + I_\mathrm{i}.$$

Since the capacitance C_sh, C_sub, C_t are all positive, function $k(S)$ and $b(S)$ both reach their maximum values when the narrowest IED is achieved. When varying the voltage slope S, by finding the maximum value of $k(S)$ or $b(S)$, the IED can be tuned to be the narrowest.

[0045] In order to find the optimal voltage slope S, a series of voltage slopes $S_n (n = 1,2,3 \ldots)$ are applied to the table in different switching cycles. The current measurement unit 119 then records the corresponding dc current values $I_n (n = 1,2,3 \ldots)$ during etching or deposition phase. Alternatively, a series of output current values $I_n (n = 1,2,3 \ldots)$ are set by the power amplifier 114, and the corresponding voltage slopes $S_n (n = 1,2,3 \ldots)$ can be measured by voltage measurement unit 116.

[0046] The value of $k(S)$ or $b(S)$ can be calculated based on the real-time measurement results of the output voltage and current. $k(S)$ is approximated by

$$k(S_n) = \frac{I_n - I_{n-1}}{S_n - S_{n-1}}.$$

$b(S)$ is approximated by

$$b(S_n) = \frac{S_n I_{n-1} - S_{n-1} I_n}{S_n - S_{n-1}}.$$

The approximation is accurate if the step value of $S_n - S_{n-1}$ is sufficiently small. As depicted by FIG. 4, when $k(S_n)$ reaches its maximum value at $S_n = S_m$, the optimal output voltage slope is found to be S_m. The corresponding output current is equivalent to be I_m. The maximum value of $b(S_n)$ can also be used to find the optimal voltage slope.

[0047] The above method can be also used to calculate the unknown parameters. The table capacitance is found to be

$$C_{\mathrm{t}} = k(S_m).$$

The ion current is found to be

$$I_{\mathrm{i}} = b(S_m).$$

The substrate capacitance is found to be

$$C_{\mathrm{sub}} = -\frac{b(S_m)}{S_m}.$$

[0048] It should be noted that the power amplifier 114 can be any variety of suitable power amplifiers. In one embodiment, it can be a voltage-source amplifier, including a switched-mode voltage amplifier, a linear amplifier or any combination of them. In another embodiment, the power amplifier can be realized by a hybrid converter.

[0049] As depicted in FIG. 5, the hybrid converter comprises two adjustable dc voltage-source amplifiers V_0 and V_1, two switches S_1 and S_2 and an adjustable dc current-source amplifier I_P. The positive pulse V_0 can be obtained by turning on S_1. After the discharge phase, by turning off S_1 and turning on S_2 synchronously the output voltage v_{out} turns to be V_1. By turning off S_2, a negative voltage slope is obtained since the current source is sinking current from the capacitive load. The output voltage slope rate is determined by the magnitude of the I_{P}. Such a hybrid converter is suitable for carrying out the tuning methods described herein. By varying the magnitude of the I_{P}, the maximum value of $k(S)$ or $b(S)$ can be found as described above, allowing to obtain the narrowest IED.

[0050] Methods of the present invention are not limited to find the maximum value of $k(S)$ or $b(S)$. In other embodiments, the structure of a reactor might be different, resulting in a different equivalent electric model. Since the sheath capacitance is virtually removed from the electric model when the narrowest IED is obtained, an exceptional behaviour is introduced to the mathematic relations, such as an extremum, a singularity, etc. Such a behaviour can be found by applying a dedicated test function, e.g. finding the maximum of coefficients $k(S)$ or $b(S)$, by varying the output voltage slope.

[0051] Referring to FIG. 6, the above auto-tuning method was implemented in an experiment. By varying the voltage slope S_{m-1}, S_m, S_{m+1} of consecutive pulses and measuring corresponding output current I_{m-1}, I_m, I_{m+1}, the coefficient $k(S_{m-1})$, $k(S_m)$, $k(S_{m+1})$ could be determined and a maximum $k(S)$ was found to be $k(S_m)$. In FIG. 6, the dc current was changed in small steps and therefore the voltage slope difference between consecutive pulses is very small and hard to recognize from the figure. Therefore, the optimum voltage slope is S_m. The ion energy distribution was measured for the different voltage slopes, as depicted in FIG. 7. The IED corresponding to S_m

effectively yielded the narrowest width, thereby proving the reliability of the method of the present invention.

CLAIMS

1. Method of determining an ion energy for plasma processing of a dielectric substrate (109), comprising:

exposing the dielectric substrate (109) to a plasma discharge,

applying a pulsed voltage waveform generated by a power supply (114) to the dielectric substrate,

wherein the pulsed voltage waveform comprises a sequence of pulses, each pulse comprising a higher voltage interval and a lower voltage interval, wherein the lower voltage interval comprises a voltage slope,

characterised in that the method comprises:

generating first pulses of the sequence having differing voltage slopes between one another and applying the first pulses to the dielectric substrate,

for each one of the first pulses, determining the voltage slope (S) and an output current (I_P) corresponding to the voltage slope at an output of the power supply,

for each one of the first pulses, determining at least one coefficient (k, b) of a mathematical relation between the voltage slope and the corresponding output current based solely on the voltage slope and the output current determined for one or more of the first pulses,

applying a test function to the at least one coefficient and selecting an optimal voltage slope value corresponding to the at least one coefficient making the test function true.

2. Method of claim 1, wherein the at least one coefficient is an expression consisting of: one or more mathematical operators, one or more values of the voltage slopes and one or more values of the output current.

3. Method of claim 1 or 2, wherein the mathematical relation is a polynomial function between the output current and the voltage slope.

4. Method of claim 3, wherein the polynomial function is a first degree polynomial $I_P = k S + b$, wherein I_P represents output current, S represents voltage slope and wherein the at least one coefficient is at least one of k and b.

5. Method of any one of the preceding claims, wherein the at least one coefficient is representative of one or more capacitances of an interaction between the plasma discharge and the dielectric substrate, the at least one coefficient being resolved based solely on the voltage slope and output current determined for one or more of the first pulses.

6. Method of any one of the preceding claims, wherein the first pulses have monotonically increasing voltage slopes.

7. Method of any one of the preceding claims, comprising measuring, for each of the first pulses, at least one of: the respective voltage slope and the output current corresponding to the voltage slope.

8. Method of any one of the preceding claims, wherein the test function is configured to determine an extremum of the at least one coefficient.

9. Method of any one of the preceding claims, further comprising generating second pulses of the sequence, the second pulses having a voltage slope corresponding to the optimal voltage slope value and applying the second pulses to the dielectric substrate to perform plasma processing.

10. Method of any one of the preceding claims, wherein plasma processing is selected from one or a combination of: plasma-assisted etching and plasma-assisted deposition.

11. Apparatus for plasma processing of a dielectric substrate (109), comprising:

means for generating a plasma (101, 105, 108),

a processing platform (111) for supporting the dielectric substrate,

a power supply (114) comprising an output (113) coupled to the processing platform,

at least one of: a voltage measurement unit (116) and a current measurement unit (119) coupled to the output, and

a control unit (115) coupled to the power supply (114), wherein the control unit and the power supply are jointly configured to generate a pulsed voltage waveform, wherein the pulsed voltage waveform comprises a sequence of pulses, each pulse comprising a higher voltage interval and a lower voltage interval, wherein the lower voltage interval comprises a voltage slope (S),

characterised in that:

the control unit (115) and the power supply (114) are jointly configured to generate first pulses of the sequence having differing voltage slopes between one another,

for each one of the first pulses, the control unit is configured to determine the voltage slope and the corresponding output current at the output, and to evaluate at least one coefficient (k, b) of a mathematical relation between the voltage slope (S) and the output current (I_P) based solely on the voltage slope and the output current determined for one or more of the first pulses, wherein the control unit is further configured to apply a test function to the at least one coefficient.

12. Apparatus of claim 11, wherein the control unit and the power supply are jointly configured to generate second pulses of the sequence, the second pulses having a voltage slope representative of the at least one coefficient making the test function true.

13. Apparatus of claim 11 or 12, wherein the control unit is configured to carry out the method of any one of the claims 1 to 8.

14. Apparatus of claims 13, wherein the control unit is configured to carry out the method of any one of the claims 1 to 8 for each dielectric substrate treated.

15. Apparatus of any one of the claims 11 to 14, wherein the power supply is a hybrid converter comprising a switch mode power supply and an adjustable current source.

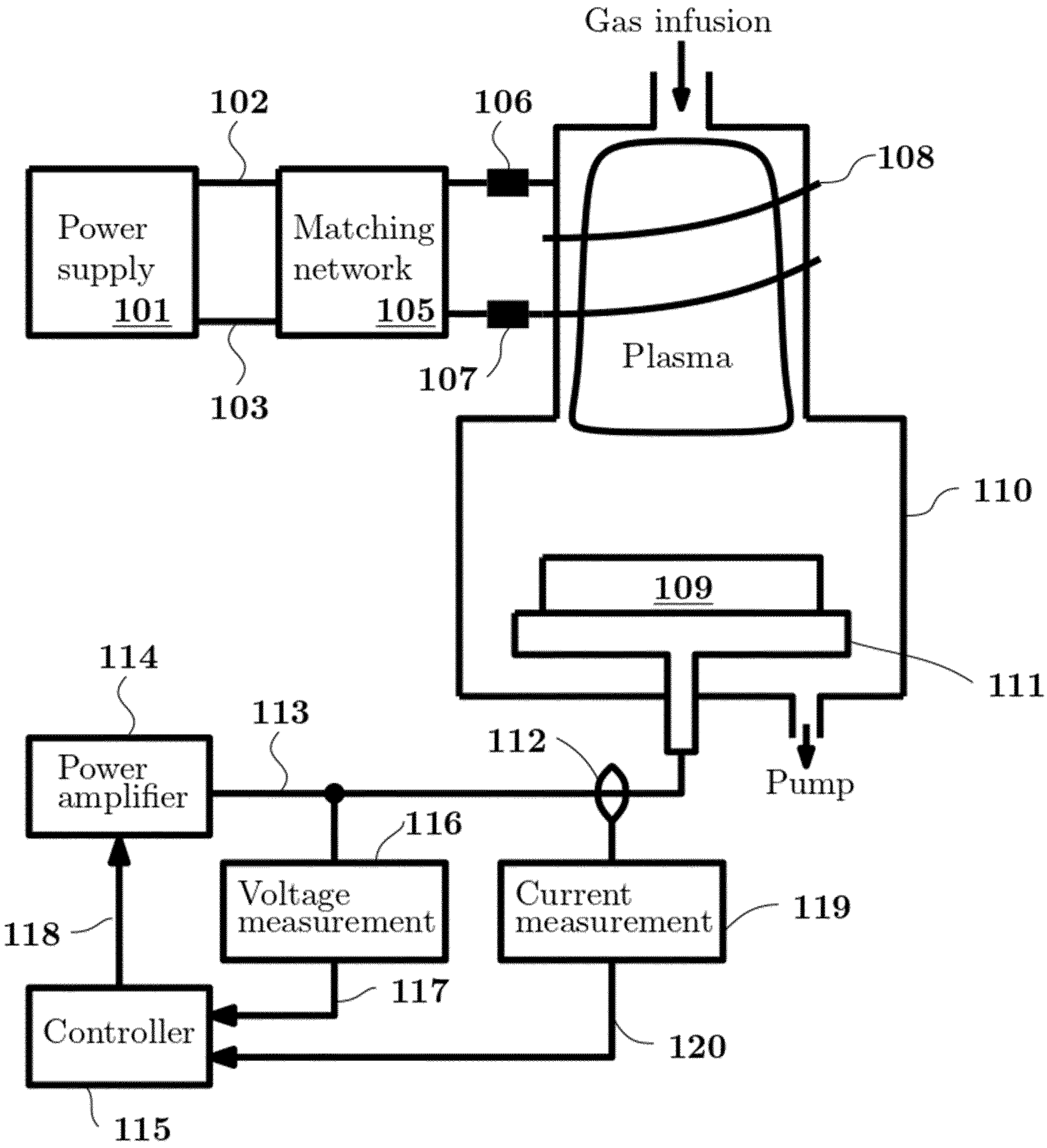
Gas infusion
102
106
108
Power supply 101
Matching network 105
Plasma
103
107
110
109
111
114
113
112
Pump
Power amplifier
116
Voltage measurement
Current measurement
119
118
117
Controller
120
115

FIG 1

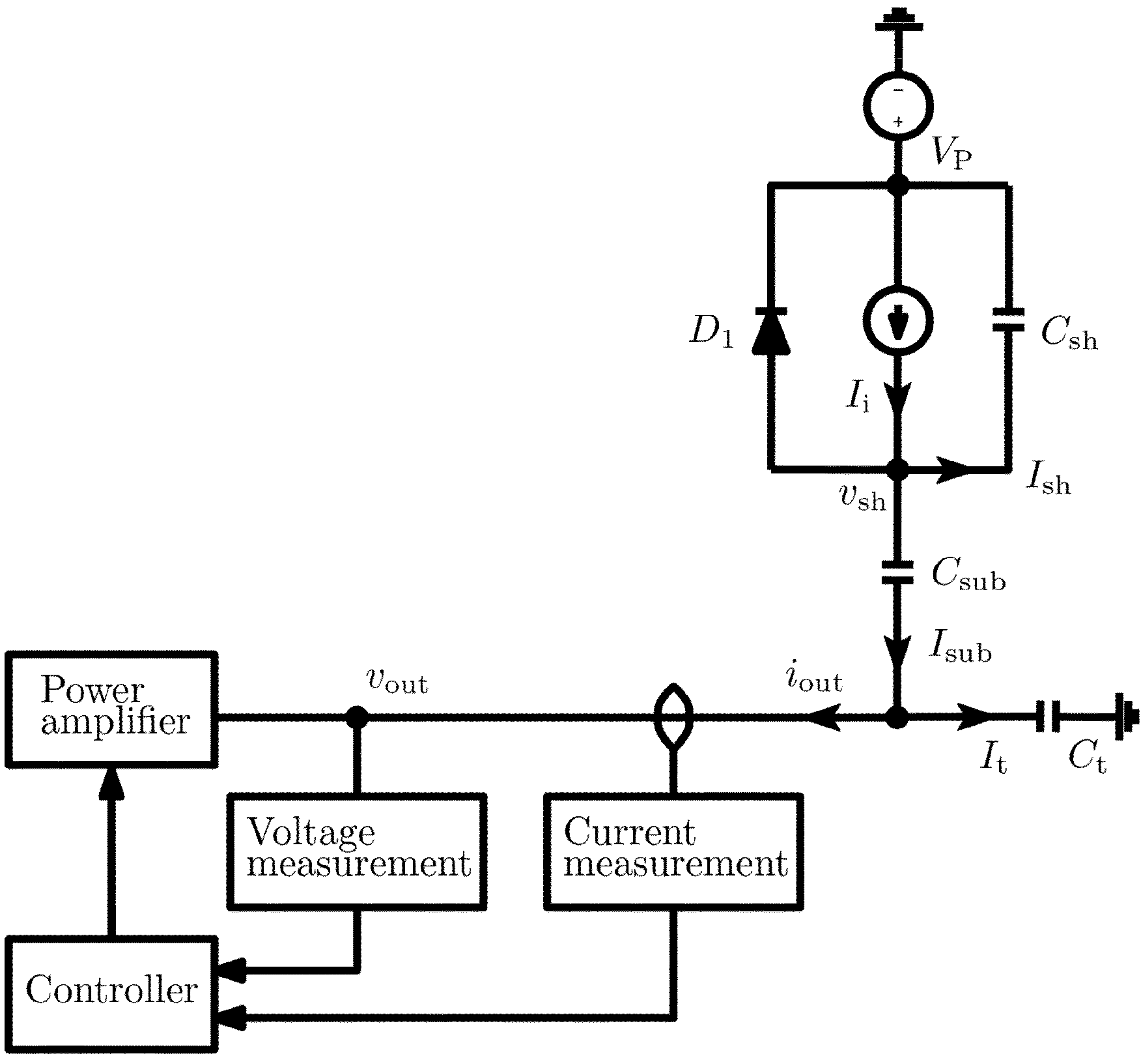
−
+
V_P
D_1
C_{sh}
I_i
I_{sh}
v_{sh}
C_{sub}
I_{sub}
Power amplifier
v_{out}
i_{out}
I_t
C_t
Voltage measurement
Current measurement
Controller

FIG 2

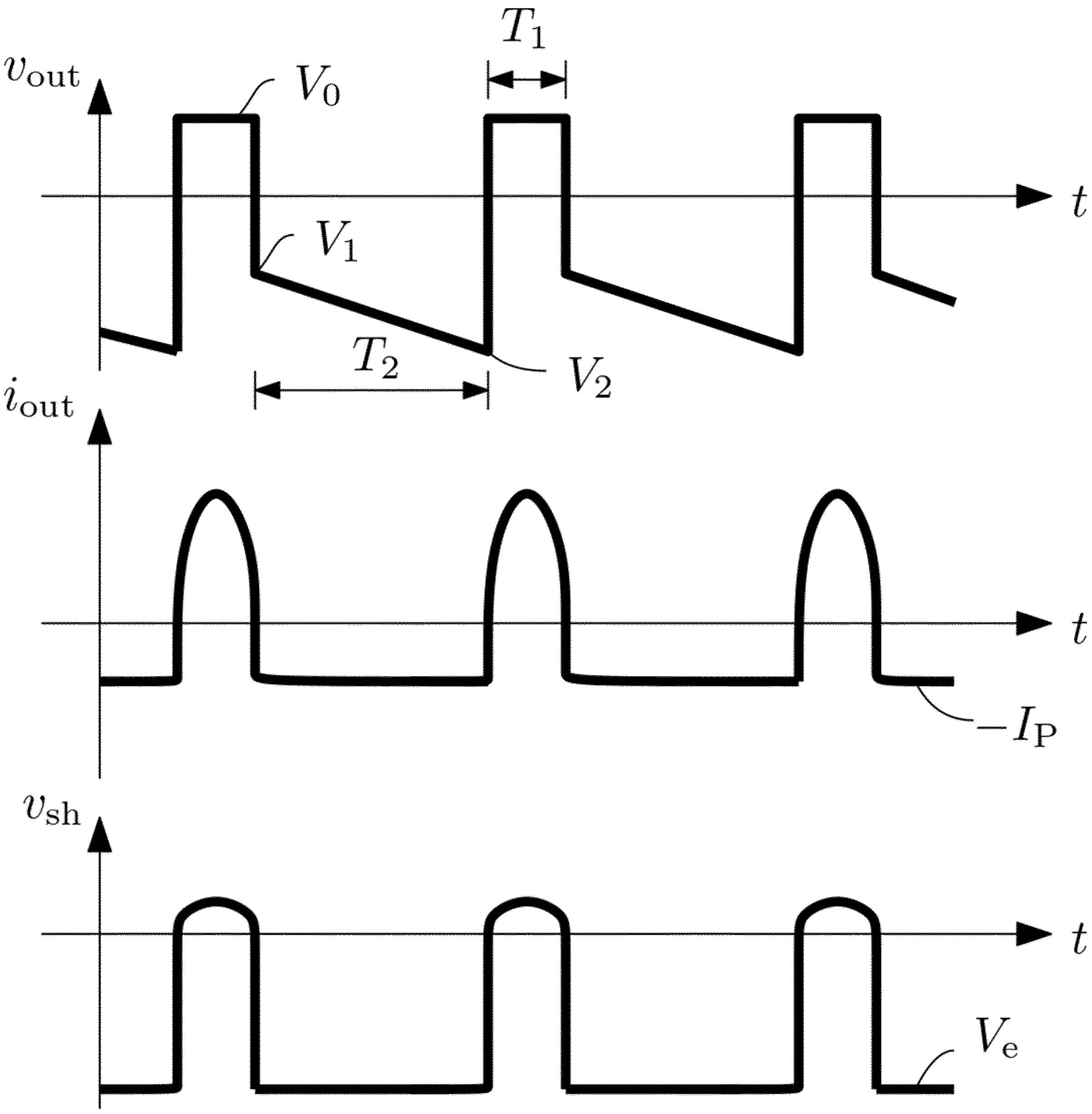
v_{out}
V_0
T_1
t
V_1
T_2
V_2
i_{out}
t
$-I_{\mathrm{P}}$
v_{sh}
t
V_{e}

FIG 3

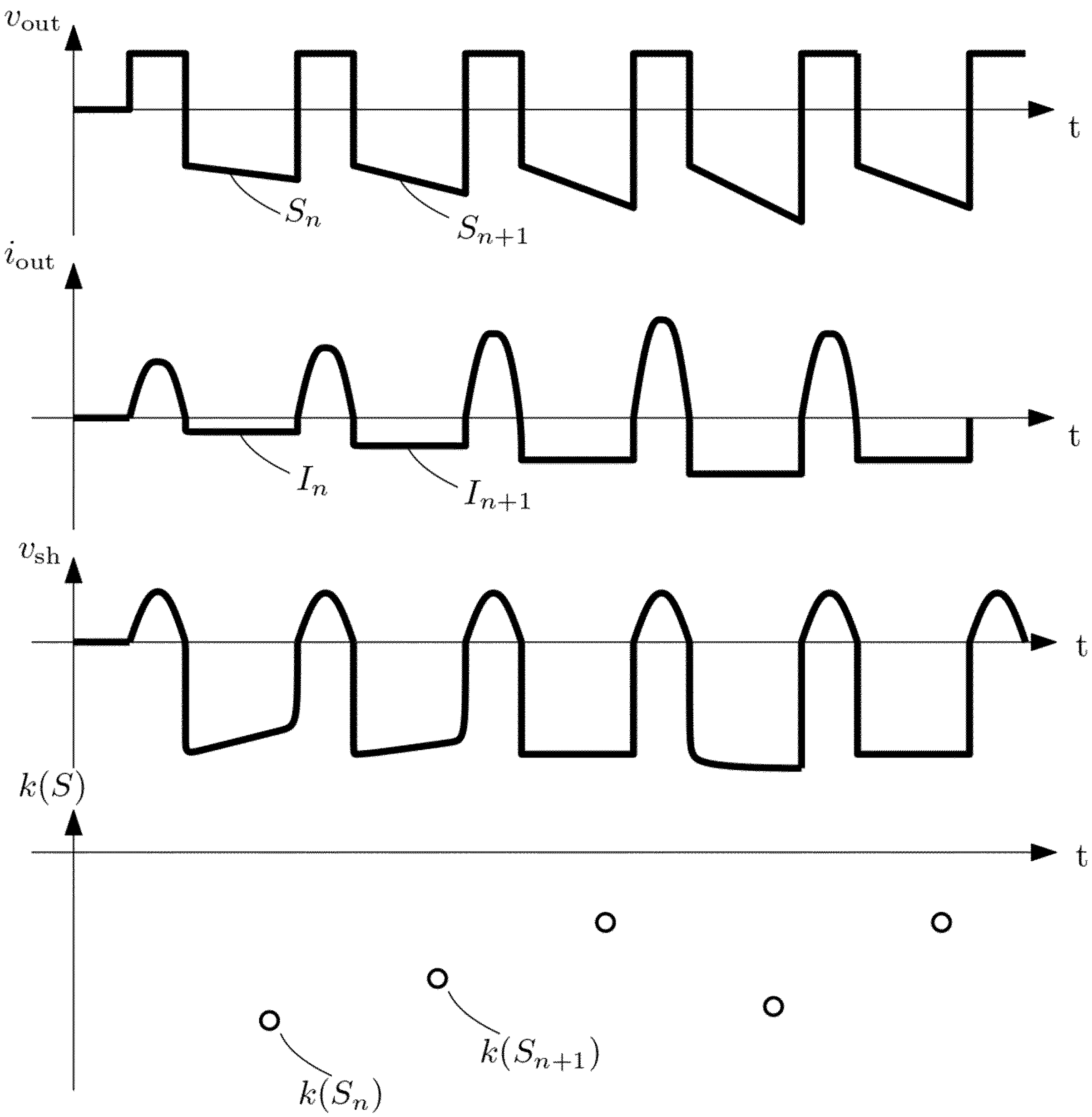
v_{out}
t
S_n
S_{n+1}
i_{out}
t
I_n
I_{n+1}
v_{sh}
t
$k(S)$
t
$k(S_{n+1})$
$k(S_n)$

FIG 4

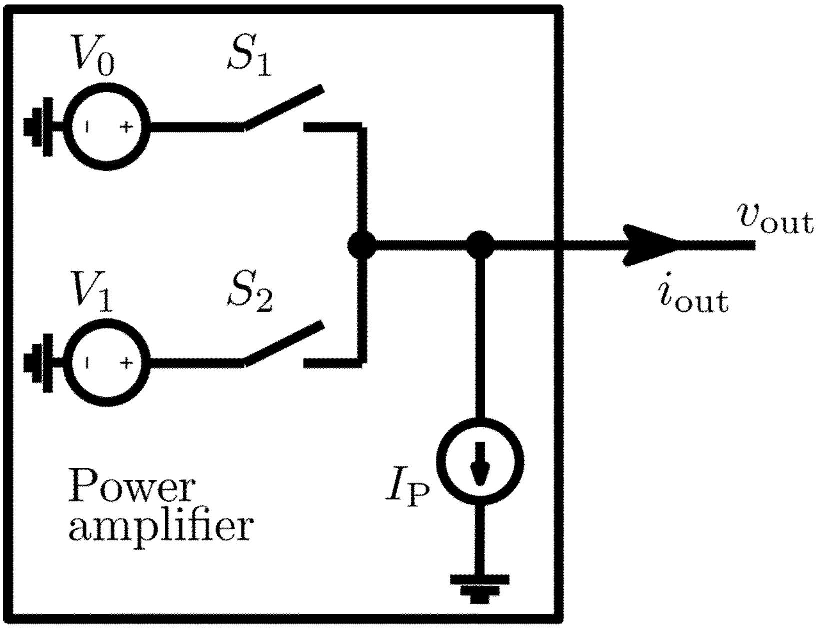

FIG 5

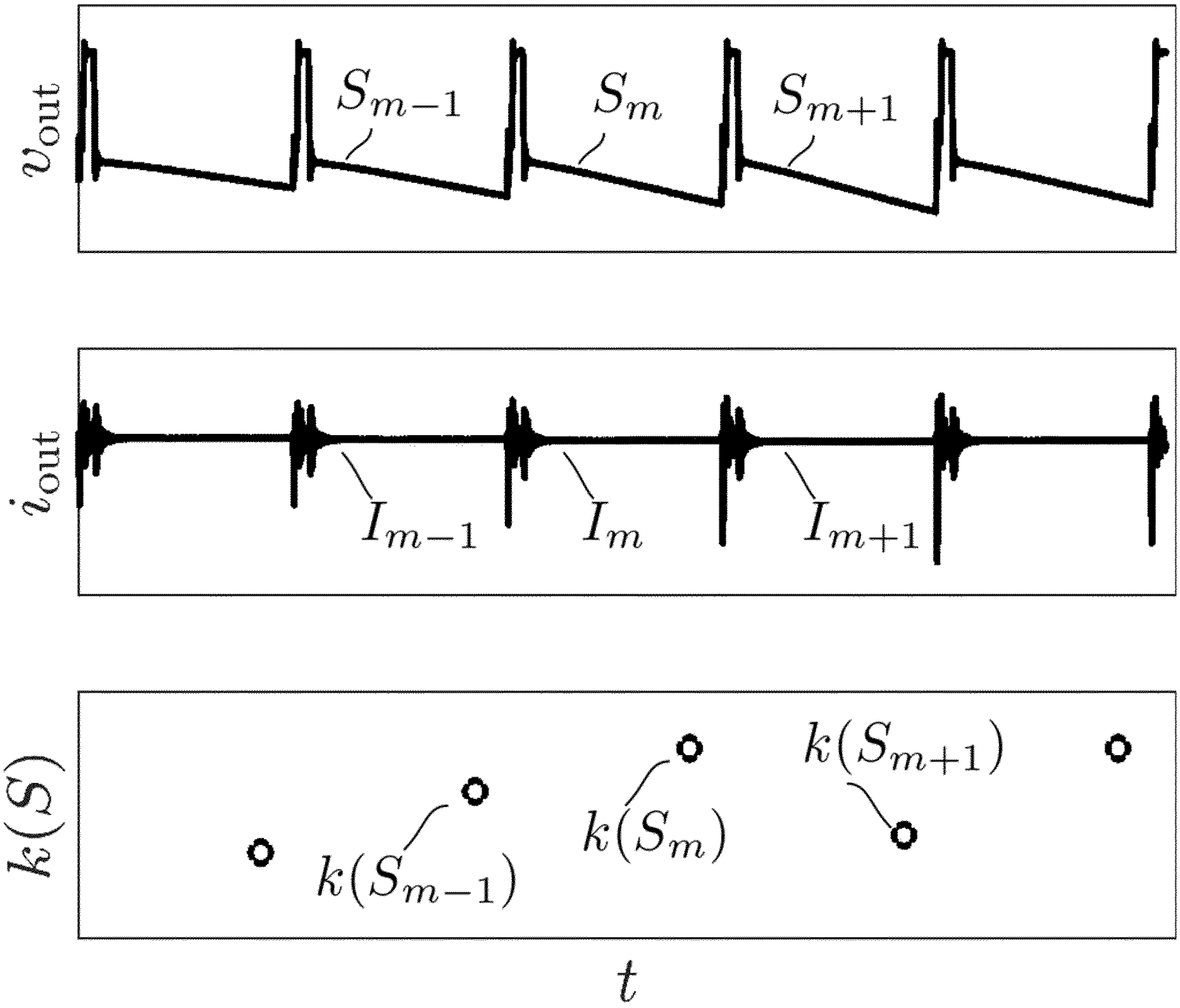
v_{out}
S_{m-1}
S_m
S_{m+1}
i_{out}
I_{m-1}
I_m
I_{m+1}
$k(S)$
$k(S_{m-1})$
$k(S_m)$
$k(S_{m+1})$
t

FIG 6

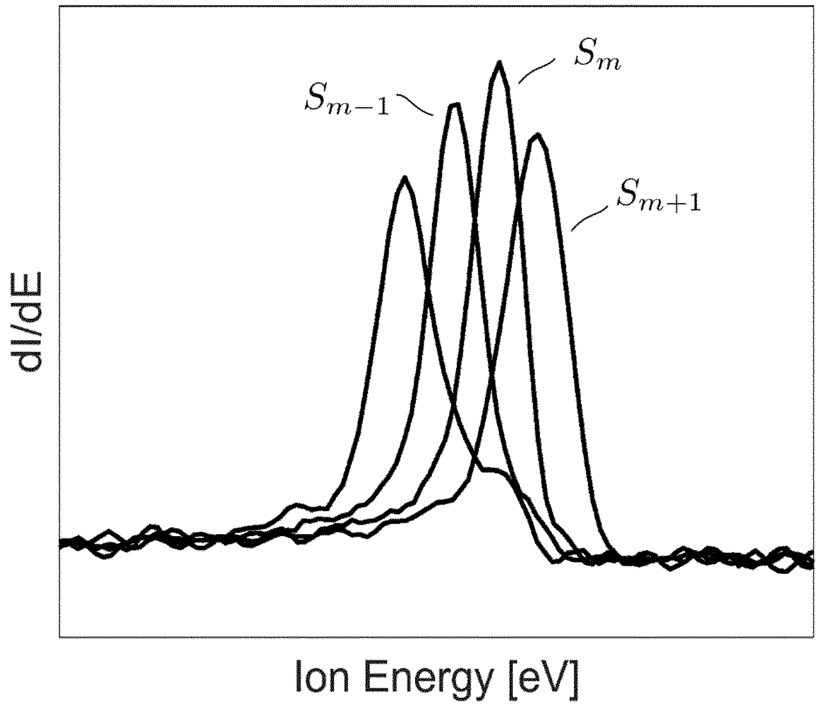
S_{m-1}
S_m
S_{m+1}
dI/dE
Ion Energy [eV]

FIG 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2020/077536

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01J37/32 C23C14/34 G05F3/20
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01J C23C G05F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, COMPENDEX, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2017/358431 A1 (DORF LEONID [US] ET AL) 14 December 2017 (2017-12-14) abstract; figures 2-4,6,7 paragraphs [0002] - [0006], [0033] - [0046], [0053] - [0056] -----	1-7,9-15
A	KUDLACEK P ET AL: "Accurate control of ion bombardment in remote plasmas using pulse-shaped biasing", JOURNAL OF APPLIED PHYSICS, AMERICAN INSTITUTE OF PHYSICS, US, vol. 106, no. 7, 7 October 2009 (2009-10-07), pages 73303-73303, XP012127493, ISSN: 0021-8979, DOI: 10.1063/1.3225690 abstract; figures 1-3,5,9,10 the whole document ----- -/--	1-15

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
26 November 2020

Date of mailing of the international search report
04/12/2020

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Remy, Jérôme

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2018/032100 A1 (KIM HYUN-BAE [KR] ET AL) 1 February 2018 (2018-02-01) abstract; figures 1,10,13,14,16,17,19,23,24 paragraphs [0002], [0036] - [0040], [0042] - [0045], [0051], [0093] - [0122], [0131] - [0139] -----	1,6,9-15
A	US 2014/061156 A1 (BROUK VICTOR [US] ET AL) 6 March 2014 (2014-03-06) cited in the application abstract; figures 1,6-9,18,21 paragraphs [0002], [0003], [0064] - [0079], [0090] - [0096], [0103] - [0124], [0146] - [0147] -----	1-15
A	US 2018/166249 A1 (DORF LEONID [US] ET AL) 14 June 2018 (2018-06-14) abstract; figures 1,2,5,6,7,9,10 paragraphs [0002] - [0005], [0009], [0025], [0028], [0033] - [0046] -----	1,6,9-15

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2020/077536

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2017358431 A1	14-12-2017	CN 109417013 A	01-03-2019
		JP 2019523993 A	29-08-2019
		KR 20190006610 A	18-01-2019
		TW 201801224 A	01-01-2018
		US 2017358431 A1	14-12-2017
		WO 2017218394 A1	21-12-2017
US 2018032100 A1	01-02-2018	KR 20180012060 A	05-02-2018
		US 2018032100 A1	01-02-2018
US 2014061156 A1	06-03-2014	JP 6377060 B2	22-08-2018
		JP 6776303 B2	28-10-2020
		JP 2016500132 A	07-01-2016
		JP 2018195588 A	06-12-2018
		KR 20150047522 A	04-05-2015
		KR 20180115349 A	22-10-2018
		KR 20190109601 A	25-09-2019
		TW 201419371 A	16-05-2014
		US 2014061156 A1	06-03-2014
		US 2016020072 A1	21-01-2016
		US 2020090905 A1	19-03-2020
		WO 2014036000 A1	06-03-2014
US 2018166249 A1	14-06-2018	CN 109997214 A	09-07-2019
		JP 2020501351 A	16-01-2020
		KR 20190083007 A	10-07-2019
		TW 201833965 A	16-09-2018
		US 2018166249 A1	14-06-2018
		US 2019259562 A1	22-08-2019
		US 2020266022 A1	20-08-2020
		WO 2018111751 A1	21-06-2018