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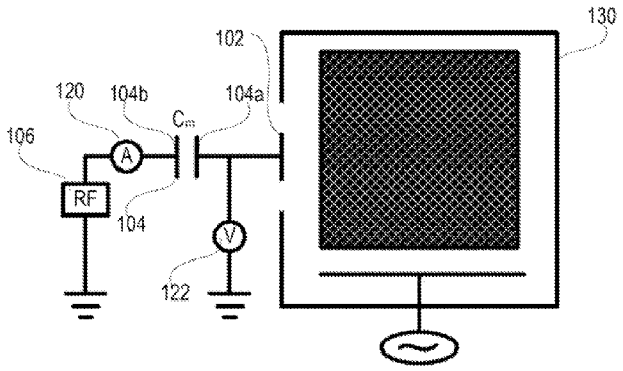

FIG. 1

(57) Abstract: A method for identifying a stabilized plasma within a processing chamber of a plasma processing system is provided. The method includes executing a strike step within the processing chamber to generate a plasma. The strike step includes applying a substantially high gas pressure within the processing chamber and maintaining a low radio frequency (RF) power within the processing chamber. The method also includes employing a probe head to collect a set of characteristic parameter measurements during the strike step, the probe head being on a surface of the processing chamber, wherein the surface is within close proximity to a substrate surface. The method further includes comparing the set of characteristic parameter measurements against a pre-defined range. If the set of characteristic parameter measurements is within the pre-defined range, the stabilized plasma exists.

WO 2010/005930 A2

CAPACITIVELY-COUPLED ELECTROSTATIC (CCE) PROBE ARRANGEMENT FOR DETECTING STRIKE STEP IN A PLASMA PROCESSING CHAMBER AND METHODS THEREOF

BACKGROUND OF THE INVENTION

[Para 1] During the processing of a substrate in the plasma processing chamber, satisfactory results often require tight control of the process parameters. This is particularly true for processes such as deposition, etching, cleaning, etc., that are employed to manufacture modern high density integrated circuits.

[Para 2] In the execution of certain etch processes, for example, the plasma needs to be stable and well-characterized before the actual etch step may be performed on the substrate. To initiate a stable and well-characterized plasma, a special recipe known as a strike-step recipe is often employed. During this strike step, a relatively high gas pressure is employed in the plasma processing chamber to ensure plasma ignition. Radio frequency (RF) power is often kept low to prevent inadvertent damage to the substrate and/or the chamber components. The strike step ensures that the plasma conditions in the chamber reaches some pre-defined acceptable level before actual etching (which typically employs a higher RF power) begins on the substrate in accordance with a pre-defined etch recipe. Thus, while the strike step may involve plasma conditions that are not suitable for the actual etching, the strike step is nevertheless a very important step in ensuring satisfactory etch results and high device yield per substrate.

[Para 3] In the prior art, the strike step is often executed for some arbitrary period of time in accordance with some pre-defined best known method, or BKM. The strike step duration is typically empirically determined beforehand based on feedback data obtained from test substrates and is executed before the execution of each etch recipe. For example, some BKMs may call for a five second strike step to ensure reliable ignition and stabilization of the plasma prior to etching. The entire five second strike step is typically performed irrespective whether the plasma has been ignited and stabilized in the first, second, third or fourth second of the five-second duration.

[Para 4] If the plasma is ignited and stabilized very early on in the predefined strike step duration, the remaining portion of the strike step duration represents, in essence, wasted time since the plasma has already been ignited and stabilized, and no useful etching occurs during that time. The wasted time reduces the overall throughput of the plasma processing

system, leading to a higher cost of ownership for the plasma tool (as a function of units of device produced). Furthermore, the presence of the strike plasma in the chamber during the wasted time contributes to the premature degradation of the chamber components (thereby necessitating more frequent cleaning and maintenance cycles) and/or contributes to the unwanted etching of the substrate without a corresponding benefit in terms of improved and/or increased substrate production.

[Para 5] On the other hand, if the plasma fails to ignite or stay sustained after the expiration of the strike step, the initiation of the main etch step in the absence of a well-characterized plasma often results in damage to the substrate.

[Para 6] In view of the foregoing, there are desired improved techniques for detecting whether the strike step is successful and/or for minimizing the time duration required to perform the strike step.

BRIEF SUMMARY OF THE INVENTION

[Para 7] The invention relates, in an embodiment, to a method for identifying a stabilized plasma within a processing chamber of a plasma processing system. The method includes executing a strike step within the processing chamber to generate a plasma. The strike step includes applying a substantially high gas pressure within the processing chamber and maintaining a low radio frequency (RF) power within the processing chamber. The method also includes employing a probe head to collect a set of characteristic parameter measurements during the strike step, the probe head being on a surface of the processing chamber, wherein the surface is within close proximity to a substrate surface. The method further includes comparing the set of characteristic parameter measurements against a pre-defined range. If the set of characteristic parameter measurements is within the pre-defined range, the stabilized plasma exists.

[Para 8] The above summary relates to only one of the many embodiments of the invention disclosed herein and is not intended to limit the scope of the invention, which is set forth in the claims herein. These and other features of the present invention will be described in more detail below in the detailed description of the invention and in conjunction with the following figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[Para 9] The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings and in which like reference numerals refer to similar elements and in which:

[Para 10] Fig. 1 shows an example CCE probe arrangement.

[Para 11] Fig. 2 shows a plot of the ion current (ion flux per unit area per unit of time) versus time as is done in the prior art.

[Para 12] Fig. 3 shows, in accordance with an embodiment of the invention, a plot of the ion current (ion flux per unit area per unit of time) versus time.

[Para 13] Fig. A of the DISCUSSION shows a simple schematic diagram of a portion of a plasma system with a radio frequency (RF) source capacitively-coupled to a reactor chamber to produce plasma.

[Para 14] Fig. B1 of the DISCUSSION shows a graph of voltage versus time after a RF charge.

[Para 15] Fig. B2 of the DISCUSSION shows a graph of current data collected after a RF charge.

[Para 16] Fig. C of the DISCUSSION shows a simple current versus voltage graph for a single time interval between a RF burst.

[Para 17] Fig. D of the DISCUSSION shows, in an embodiment of the invention, a simple flow chart illustrating the overall steps for automatically characterizing plasma during substrate processing.

[Para 18] Fig. E of the DISCUSSION shows, in an embodiment of the invention, a simple algorithm for determining the relevancy range and the seed values.

[Para 19] Fig. F1 of the DISCUSSION shows an example of current versus time after a RF burst.

[Para 20] Fig. F2 of the DISCUSSION shows an example of voltage versus time after a RF burst.

[Para 21] Fig. F3 of the DISCUSSION shows an example of an inflection point.

[Para 22] Fig. F4 of the DISCUSSION shows an example of a curve-fitting applied to a current versus voltage graph.

DETAILED DESCRIPTION OF EMBODIMENTS

[Para 23] The present invention will now be described in detail with reference to a few embodiments thereof as illustrated in the accompanying drawings. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art, that the present invention may be practiced without some or all of these specific details. In other instances, well known process steps and/or structures have not been described in detail in order to not unnecessarily obscure the present invention.

[Para 24] Embodiments of the invention relate to the use of capacitively-coupled electrostatic (CCE) probes to detect the successful completion of the strike step. CCE probes have long been employed to measure plasma processing parameters. CCE probes are known in the art and details may be obtained from publicly available literature, including for example US Patent No. 5,936,413 entitled "Method And Device For Measuring An Ion Flow In A Plasma" (August 10, 1999), which is incorporated herein by reference. CCE probes offer many advantages, including for example improved detection sensitivity, minimal perturbation to the plasma due to the small size of the sensor, ease of mounting on the chamber wall, insensitivity to polymer deposition on the sensor head. Furthermore, the plasma-facing surface of the sensor can often be made of the same material as that of the surrounding chamber wall, thereby further minimizing perturbation to the plasma. These advantages make CCE probes highly desirable for use in sensing process parameters.

[Para 25] Generally speaking, a CCE probe arrangement involves a plasma-facing sensor connected to one plate of a measuring capacitor. An example CCE probe arrangement is shown in Fig. 1 herein. In Fig. 1, plasma facing sensor 102 (which is disposed in a wall of chamber 130) is coupled to one plate 104a of measuring capacitor 104. The other plate 104b of the measuring capacitor 104 is coupled to an RF voltage source 106. The RF voltage source 106 periodically supplies RF oscillation trains, causing the probe to become negatively biased, and measurements are performed across the measuring capacitor to determine the rate of capacitor current discharge immediately following the end of each RF oscillation train. A current measurement device 120 is disposed in series between measuring

capacitor 104 and RF voltage source 106 to detect the capacitor current discharge rate. Alternatively or additionally, a voltage measurement device 122 is coupled between plate 104a and ground to measure the potential of the probe head. Details pertaining to the CCE probe arrangement and CCE probe operation are discussed in the aforementioned US Patent No. 5,936,413 and will not be further discussed herein.

[Para 26] As mentioned, a probe head made of a conductive material is installed in a surface of the chamber. A short RF train is applied to the probe, causing the capacitor (Cm) to charge up and the surface of the probe to acquire a negative potential (several tens of volts negative with respect to ground). Following the end of the RF pulse, the potential of the probe decays back to the floating potential as Cm discharges. The rate at which the potential changes is determined by the plasma characteristics. During this discharge, the potential of the probe Vf is measured with voltage measurement device 122, and the current following to the probe and through capacitor Cm is measured with the current measurement device 120. The curves V(t) and I(t) are used to construct a current-voltage characteristic, VI, which is then analyzed by a signal processor. A model function is fitted to these data points, producing estimates of the floating potential Vf, ion saturation current Isat and electron temperature Te. Further details may be found in a co-pending application entitled "Methods for Automatically Characterizing a Plasma", filed June 26, 2008 in the US Patent Office (Application No. 61/075,948) and filed June 2, 2009 in the US Patent Office (Application No. 12/477,007), which is included in the DISCUSSION herein.

[Para 27] In accordance with one or more embodiments of the present invention, innovative techniques are proposed to enable the detection of the successful completion of the strike step. It is realized by the inventors herein that by monitoring the ion flux, a signal step characteristic of plasma ignition in the ion flux data may be detected using appropriate signal processing system software and/or hardware. Once plasma ignition has occurred, the ion flux may be monitored for a period of time. The monitoring of the signal step characteristic of plasma ignition may be performed in the time frame where plasma ignition may be expected to occur. If the establishment of a stable ion flux is observed within this window of time, the plasma is said to be stabilized and the strike step is deemed successful. Thus the successful completion of the strike step requires both the detection of a plasma ignition event and the determination that subsequent plasma parameters fulfill certain conditions for a given period of time.

[Para 28] Alternatively or additionally, the electron temperature may be monitored. By monitoring the electron temperature, an additional verification data point may be available to verify the detected plasma ignition event.

[Para 29] Alternatively or additionally, the floating potential of the probe head may be monitored. By monitoring the floating potential, a signal step characteristic of plasma ignition in the floating potential data may be detected using appropriate signal processing system software and/or hardware. Once plasma ignition has occurred, the floating potential may be monitored for a period of time. If certain conditions are met within this window of time, the plasma is said to be stabilized and the strike step is deemed successful. As in the case with ion flux monitoring, the successful completion of the strike step requires both the detection of a plasma ignition event and the determination that subsequent plasma parameters fulfill certain conditions for a given period of time.

[Para 30] Fig. 2 shows a plot of the ion current (ion flux per unit area per unit of time) versus time as is done in the prior art. In Fig. 2, point 200 represents the start of the strike step. The time period between point 200 and point 210 represents the strike step. Step 202 reflects the ignition of the plasma. In fact, as can be seen in Fig. 2, the plasma already is stabilized starting at point 204. Since the prior art BKM calls for a fixed amount of time after the start of the strike step 200, the strike step is allowed to run until the fixed time period expires at point 210. One in the art can readily appreciate that the time period between point 204 and point 210 represents essentially wasted time, which reduces system throughput and potentially damages the substrate and/or the chamber components due to the presence of the strike plasma over a lengthy post-stabilization point.

[Para 31] Fig. 3 shows, in accordance with an embodiment of the invention, a plot of the ion current (ion flux per unit area per unit of time) versus time. In Fig. 3, point 300 represents the start of the strike step. Step 302 reflects the ignition of the plasma. Following the ignition event, the plasma then begins to stabilize. At point 304, the plasma is stabilized. By monitoring the ion flux and/or the electron temperature and/or the floating potential, the ignition of the plasma may be detected. If plasma conditions in the time period between point 302 (plasma ignition) and point 304 are satisfactory, the etch process may start from point 304, thereby eliminating the lengthy wasted period (such as the time period between point 204 and 210 of prior art Fig. 2). Note that if plasma ignition is never detected (e.g., there is no step 302), the strike step is deemed to have failed. In this manner, the invention offers significant advantages over the prior art in which the etch step is started at the

expiration of the predefined strike step duration irrespective whether the plasma has been successfully ignited and/or has stabilized.

[Para 32] In one or more embodiments of the invention, characteristic parameter measurements (such as ion flux measurements, electron temperature measurements and/or floating potential measurements) may be empirically obtained for the plasma ignition, for the stabilization period, etc. in an example etch. Once these characteristic parameters are ascertained for some test substrates, the characteristic parameter patterns may be employed to compare against parameter readings from future process runs to determine whether the strike step has been successfully completed.

[Para 33] In contrast to prior art parameter measurement techniques, such as measuring the incident or reflected RF power or RF impedance probes, the inventive CCE probe-based strike step detection technique is highly sensitive. This is because embodiments of the invention uses a probe that directly measures the ion flux to a reactor wall, close to the substrate being processed. Thus, the ion flux measured by the probe is very closely related to the flux that arrives at the substrate surface, rendering this measurement an inherently absolute measurement. Therefore, a detection system may verify that the ion flux is stable (e.g., no undue oscillations or instabilities) and within set control limits before triggering the transition to the etch step.

[Para 34] This direct measurement approach is unlike prior art techniques (such as the aforementioned RF power measurement or impedance probe measurement) that tend to be more indirect measurements and are more likely to provide false positives and/or false negatives for the strike step detection and are more difficult to calibrate or make absolute.

[Para 35] Additionally, there is minimal perturbation to the plasma since the CCE probe head tends to be small, to be installed flushed with the surrounding plasma-facing structures of the plasma processing chamber, and may have a plasma-facing probe surface formed of the same material as that of the plasma-facing components of the chamber. Furthermore, the inventive CCE probe-based strike step detection technique is insensitive to polymer deposition on the plasma-facing probe head since the current is capacitively coupled through any deposition that may be formed on the plasma-facing surface of the probe head.

[Para 36] While this invention has been described in terms of several preferred embodiments, there are alterations, permutations, and equivalents, which fall within the scope of this invention. It should also be noted that there are many alternative ways of

implementing the methods and apparatuses of the present invention. Although various examples are provided herein, it is intended that these examples be illustrative and not limiting with respect to the invention.

[Para 37] Also, the title and summary are provided herein for convenience and should not be used to construe the scope of the claims herein. Further, the abstract is written in a highly abbreviated form and is provided herein for convenience and thus should not be employed to construe or limit the overall invention, which is expressed in the claims. If the term "set" is employed herein, such term is intended to have its commonly understood mathematical meaning to cover zero, one, or more than one member. Also, it is intended that the following appended claims be interpreted as including all such alterations, permutations, and equivalents as fall within the true spirit and scope of the present invention.

[Para 38] The DISCUSSION is also found in a co-pending application entitled "Methods for Automatically Characterizing a Plasma", filed June 26, 2008 in the US Patent Office (Application No. 61/075,948) and filed June 2, 2009 in the US Patent Office (Application No. 12/477,007) and are incorporated by reference herein.

[Para 39] DISCUSSION OF METHODS FOR AUTOMATICALLY CHARACTERIZING A PLASMA

[Para 40] Advances in plasma processing have provided for growth in the semiconductor industry. To supply chips for a typical electronic product, hundreds or thousands of substrates (such as semiconductor wafers) may be processed. In order for the manufacturing company to be competitive, the manufacturing company needs to be able to process the substrates into quality semiconductor devices with minimal processing time.

[Para 41] Typically, during plasma processing, problems may arise that may cause the substrates to be negatively impacted. One important factor that may alter the quality of the substrate being processed is the plasma itself. In order to have sufficient data to analyze the plasma, sensors may be employed to collect processing data about each substrate. The data collected may be analyzed in order to determine the cause of the problems.

[Para 42] To facilitate discussion, Fig. A shows a simple schematic diagram of a data collecting probe in a portion of a plasma system A-100. Plasma system A-100 may include a radio frequency (RF) source A-102, such as a pulsating RF frequency generator, capacitively-coupled to a reactor chamber A-104 to produce plasma A-106. When RF source A-102 is turn on, a bias voltage is developed across an external capacitor A-108, which may be about

26.2 nanofarads (nF). In an example, RF source A-102 may provide a small burst of power (e.g., 11.5 megahertz) every few milliseconds (e.g., about five milliseconds) causing external capacitor A-108 to be charged. When RF source A-102 is turned off, a bias voltage remains on external capacitor A-108 with a polarity such that probe A-110 is biased to collect ions. As the bias voltage decays, the curves as shown in Figs. B1, B2 and C may be traced.

[Para 43] Those skilled in the art are aware that probe A-110 is usually an electrical probe with a conducting planar surface that may be positioned against the wall of reactor chamber A-104. Probe A-110 is thus directly exposed to reactor chamber A-104 environment. Current and voltage data collected by probe A-110 may be analyzed. Since certain recipe may cause a non-conducting deposition layer A-116 to be deposited on probe A-110, not all probes may be able to collect reliable measurements. However, those skilled in the art are aware that a PIF (planar ion flux) probe enables data to be collected despite the non-conducting deposition layer since the PIF probe scheme is not required to draw a direct current (DC) to implement a measurement.

[Para 44] The current and voltage signal in plasma system A-100 is measured by other sensors. In example, when RF source A-102 is switched off, current sensor A-112 and a high impedance voltage sensor A-114, are employed to measure the current and the voltage, respectively. The measurement data collected from current sensor A-112 and voltage sensor A-114 may then be plotted to create a current graph and a voltage graph. The data may be manually plotted or the data may be entered into a software program to create the graphs.

[Para 45] Fig. B1 shows a graph of voltage versus time after a RF charge cycle. At data point B1-202, RF source A-102 has been switched off after an RF charge has been provided (i.e., RF burst). In this example, at data point B1-202, the voltage across probe A-110 is about negative 57 volts. As plasma system A-100 returns to a rest state (interval between data points B1-204 and B1-206), the voltage usually reaches a floating voltage potential. In this example, the floating voltage potential rises from about negative 57 volts to about zero volt. However, the floating voltage potential does not have to be zero and may be a negative or a positive bias voltage potential.

[Para 46] Similarly, Fig. B2 shows a graph of current data collected after a RF charge. At data point B2-252, RF source A-102 has been switched off after an RF charge has been provided. During a decay period B2-254, the return current at external capacitor A-108 may be discharged. In an example, at full charge (data point B2-252), the current is about 0.86

mA/cm^2. However, when the current is fully discharged (data point B2-256), the current has returned to zero. Based on the graph, the discharge takes about 75 milliseconds. From data point B2-256 to data point B2-258, the capacitor remains discharged.

[Para 47] Since both the current data and the voltage data are collected over a period of time, a current versus voltage graph may be generated by coordinating the time in order to eliminate the time variable. In other words, the current data collected may be matched against the voltage data collected. Fig. C shows a simple current versus voltage graph for a single time interval between a RF burst. At data point C-302, RF source A-102 has been switched off after an RF charge has been provided.

[Para 48] By applying a non-linear fit to the data collected during each RF burst, plasma A-106 may be characterized. In other words, parameters (e.g., ion saturation, ion saturation slope, electron temperature, floating voltage potential, and the like) that may characterize plasma A-106 may be determined. Although plasma A-106 may be characterized with the data collected, the process of calculating the parameters is a tedious manual process that requires human intervention. In an example, when the data has been collected after each RF burst (i.e., when the RF charge has been provided and then turned off), the data may be fed into a software analysis program. The software analysis program may perform a non-linear fit to determine the parameters that may characterize the plasma. By characterizing the plasma, the engineer may be able to determine how a recipe may be adjusted in order to minimize substandard processing of the substrates.

[Para 49] Unfortunately, the prior art method of analyzing the data for each RF burst may require several seconds or as much as several minutes to complete. Since there are typically thousands, if not millions of RF bursts to analyze, the total time for characterizing the plasma for a recipe may take hours to calculate. As a result, the prior art method is not an effective method in providing timely relevant data for process control purposes.

[Para 50] The present invention will now be described in detail with reference to a few embodiments thereof as illustrated in the accompanying drawings. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art, that the present invention may be practiced without some or all of these specific details. In other instances, well known process steps and/or structures have not been described in detail in order to not unnecessarily obscure the present invention.

[Para 51] Various embodiments are described hereinbelow, including methods and techniques. It should be kept in mind that the invention might also cover articles of manufacture that includes a computer readable medium on which computer-readable instructions for carrying out embodiments of the inventive technique are stored. The computer readable medium may include, for example, semiconductor, magnetic, opto-magnetic, optical, or other forms of computer readable medium for storing computer readable code. Further, the invention may also cover apparatuses for practicing embodiments of the invention. Such apparatus may include circuits, dedicated and/or programmable, to carry out tasks pertaining to embodiments of the invention. Examples of such apparatus include a general-purpose computer and/or a dedicated computing device when appropriately programmed and may include a combination of a computer/computing device and dedicated/programmable circuits adapted for the various tasks pertaining to embodiments of the invention.

[Para 52] As aforementioned, the PIF probe method may be employed to collect data about the plasma that may be positioned within the reactor chamber environment. Data collected from a sensor (e.g., PIF probe) may be employed to characterize the plasma in the reactor chamber. Additionally, since the sensor employs a collection surface as shown in Fig. A, data about the chamber surface may also be determined. In the prior art, the data collected by the PSD probe provides a ready source of data that is available for analysis. Unfortunately, the sheer volume of data that may be collected has made analyzing the data in a timely manner a challenge. Since thousands or even millions of data points may be collected, the task of identifying the relevant interval in order to accurately characterize a plasma may be a daunting task, especially since the data is usually being analyzed manually. As a result, the data collected has not been useful in providing the plasma processing system with a timely characterization of the plasma.

[Para 53] However, if relevant data points that are needed in order to characterize a plasma are identified from the thousands/millions of data points that may be collected, then the time required to characterize a plasma may be significantly reduced. In accordance with embodiments of the invention, a method is provided for automatically characterizing plasma in a relatively short time period. Embodiments of the invention described herein provide for an algorithm for identifying the relevancy range in order to reduce the data points that may need to be analyzed in order to characterize a plasma. As discussed herein, the relevancy

range refers to a smaller set of data points from the thousands or millions of data points that may be gathered between each RF burst. Embodiments of the invention further provide for estimating seed values that may be applied to a mathematical model that calculates the values for characterizing a plasma. By performing curve-fitting to the relevancy range, parameters that may be employed to characterize a plasma may be calculated.

[Para 54] The features and advantages of the present invention may be better understood with reference to the figures and discussions that follow.

[Para 55] Fig. D shows, in an embodiment of the invention, a simple flow chart illustrating the steps for automatically characterizing plasma during substrate processing. Consider the situation wherein, an RF charge has been provided during substrate processing.

[Para 56] At a first step D-402, current and voltage data are collected. In an example, after the RF source has been turned on, an RF charge (pulse) is provided. After the RF charge has been turn off, a current sensor and a voltage sensor may be employed to collect data at a probe, such as a planar ion flux probe, which may be mounted to a chamber wall of the reactor chamber. As aforementioned, the number of data points that may be collected by the sensors may range in the thousands or millions. In some cases, thousands to ten of thousands of data points may be collected between each RF burst making near-realtime analysis in the prior art nearly impossible.

[Para 57] In the prior art, several hours may be allotted for analyzing the measurement data that is collected during semiconductor substrate processing. In one aspect of the invention, the inventors herein realized that the measurement data between each RF burst does not have to be analyzed in order to characterize a plasma. Instead, if curve-fitting is applied to a relevancy range of the data set, parameters that may be employed to characterize the plasma may be determined.

[Para 58] At a next step D-404, a relevancy range is determined. As aforementioned, the relevancy range refers to a subset of the data set that has been collected between each RF burst. In the prior art, since the data is being manually analyzed, the sheer volume of the data collected make calculating the relevancy range a challenging task. In many instances, the relevancy range may be visually estimated. In identifying the relevancy range, noises that may exist may be substantially eliminated from the subset of data set. In an example, during complex substrate processing, a polymer buildup may occur on the probe, causing a portion

of the data collected to be skewed. For example, the portion of the data that may be impacted tends to be the data that may be collected once the capacitor has been fully discharged. In identifying the relevancy range, data associated with the polymer buildup may be removed from the analysis. In other words, the determination of the relevancy range may enable plasma characterization to occur without being subject to random noises. Discussion about how a relevancy range may be determined, for an example, is provided later in the discussion of Fig. E.

[Para 59] In addition to identifying the relevancy range, the seed values may also be determined, at a next step D-406. As discussed herein, the seed values refer to the estimated value of the slope, the electron temperature, the ion saturation value, the floating voltage potential, and the like. Discussion about how the seed values may be estimated, for example, is provided in the discussion of Fig. E.

[Para 60] The relevance range and the seed values are utilized to perform curve-fitting. Since curve-fitting has to be performed before the next RF burst, the methods employed to determine the relevancy range and/or seed values have to utilize minimum overhead and produce values that are close to the final fit values, thereby reducing number of curve-fitting iterations that may be required in order to achieve a rapid convergence.

[Para 61] With the relevancy range and the seed values, at a next step D-408, a non-linear fit (e.g., curve-fitting) may be performed, thereby enabling the plasma to be characterized within a shorter time period without requiring an expensive high-end computer. Unlike the prior art, the method allows for results from a decay interval due to a single RF burst to be characterized in approximately 20 milliseconds instead of requiring a few minutes or even a few hours to process. With near-realtime analysis capability, the method may be applied as part of an automatic control system to provide the engineer with relevant data during plasma processing.

[Para 62] Fig. E shows, in an embodiment of the invention, a simple algorithm for determining the relevancy range and the seed values. Fig. E will be discussed in relation to Figs. F1, F2, F3, and F4.

[Para 63] At a first step E-502, the data collected during each RF burst is automatically plotted. In an example, the current data that may be collected by the current sensor is plotted into a current versus time graph F1-600, such as the one shown in Fig. F1. In another

example, the voltage data collected may be plotted into a voltage versus time graph F2-650, as shown in Fig. F2. Although the data may produce similar graphs as the prior art, unlike the prior art, the data collected is automatically fed into the analysis program without requiring human intervention. Alternatively, the measurement data collected does not have to be plotted. Instead, the data may be fed directly into the analysis program. Instead, the graphs are provided as visual examples to explain the algorithm.

[Para 64] Unlike the prior art, the entire data set is not analyzed in order to characterize a plasma. Instead, a relevancy range is determined. To determine the relevancy range, a percentage decay point may first be determined, at a next step E-504. As discussed herein, the percentage decay point refers to the data point at which the original value has decayed to a certain percentage of the original value. In an embodiment, the percentage decay point may represent the end of the data interval to be analyzed. In an example, when the RF source is switched off, the current value is about 0.86 mA/cm^2. The value is represented by a data point F1-602 on graph F1-600 of Fig. F1. If the percentage decay point is set to ten percent of the original value, the percent decay point is at data point F1-604, which is about 0.086 mA/cm^2. In other words, the percentage decay point may be determined by applying a pre-defined percentage to the original value, which is value of the electrical charge when the RF source is switched off and the system is returning to an equilibrium state. In an embodiment, the percentage is empirically determined. In an embodiment, instead of employing a percentage decay point to determine the end of the data interval, the peak of a first derivative of the data collected for each RF burst may be calculated.

[Para 65] At a next step E-506, the algorithm may determine the ion saturation interval, which is the data subset between the original value and a second decay point. As discussed herein, the ion saturation interval refers to the region of the current-voltage (IV) curve at which the probe potential is sufficiently negative with respect to the floating potential such that the electron flux to the probe is negligible. In this region the current to the probe increases slowly and linearly with increasingly negative potential. In addition, the ion saturation interval is the regime at which the bias voltage is sufficiently negative with respect to the floating potential such that the probe will collect all the available ions in the system. In other words, the collected current "saturates" as the bias voltage is raised sufficiently high. Also, as discussed herein, the "available ions" refers to the flux of ions impinging upon the sheath boundary, which may enlarge as the bias voltage is further increased.

[Para 66] In other words, the ion saturation interval is the interval from data points F1-602 and F1-606 of Fig. F1. In an embodiment, the second decay point may be determined by taking a percentage of the original value (i.e., data point F1-602). In an example, if the second decay point is about 95 percent of the original value, the second decay point is about 0.81 mA/cm^2 (i.e., data point F1-606). Hence, the ion saturation interval is from the original value (data point F1-602) to the second decay point (data point F1-606). Note that the second decay point is between the original value (data point F1-602) and the percentage decay point (data point F1-604). Similar to the percentage decay point, the second decay point may also be based on a pre-defined threshold, in an embodiment. In an embodiment, the percentage is empirically determined.

[Para 67] Once the ion saturation interval has been determined, at a next step E-508, the slope (s) and the ion saturation (i_0) may be estimated. As aforementioned, the slope (s) and the ion saturation (i_0) are two of the four seed values that may be applied to a mathematical model (Equation 2 below) to determine the parameters that characterize a plasma. In an example, the slope (s) may be determined by performing linear regression. In another embodiment, the algorithm may also determine the ion saturation (i_0) by taking the average of the data values between data points F1-602 and F1-606.

[Para 68] At a next step E-510, the algorithm may determine the inflection point, which is the point at which the first derivative changes sign. In an embodiment, the inflection point may be calculated by identifying the minimal value of the first derivative of the current values between the percentage decay point and the second decay point. To illustrate, Fig. F3 shows the first derivative of the values between a percentage decay point (F3-664) and an original point (F3-662) of a current signal F3-660. The inflection point is the minimal data point of the first derivative (F3-670), which has a value of -0.012 mA/cm^2 and an index value of 226 (as shown by data point F3-666). To determine the inflection value, the index value is mapped to current signal plot F3-660. In this example, when the index value of the first derivative is mapped to current signal F3-660, the inflection value is 0.4714 mA/cm^2, as shown by data point F3-668.

[Para 69] In an embodiment, the relevancy range is defined as the range between the original value and the inflection point. Additionally or alternatively, a percent decay threshold may be set (e.g., at 35 percent) instead of calculating the inflection point. In an

example, using the percent decay point of 35 percent, which may be empirically determined, the relevancy range may fall between points F1-602 and F1-604 of Fig. F1.

$$T_e = abs\left(\frac{I_{meas}(t)}{\left(\frac{dI_{meas}}{dV_{meas}}\right)}\right) = abs\left(\frac{I_{meas}(t)}{\left(\frac{dI_{meas}}{dt}\right)\left(\frac{dt}{dV_{meas}(t)}\right)}\right) \quad \textit{[Equation 1]}$$

Table 1: Parameters defined

Parameters	Variable name
I_{meas}	Current measured
V_{meas}	Voltage measured
t	Current time
T_e	Electron temperature

[Para 70] With the inflection point identified, the electron temperature may be estimated, at a next step E-512. The electron temperature may be estimated by employing Equation 1 above. The current and voltage data utilized to calculate the electron temperature is within the transition interval, which is usually when a probe is drawing less current than the ion saturation current. In an embodiment, the time at which the current and voltage data is measured may correspond with the inflection point. Alternatively, the inflection point of the current-voltage (I-V) curve may also be employed. Since the electron temperature is a ratio of a first derivative (as determined in calculating the percentage decay point) of the data collected for an RF burst at a time corresponding to the inflection point on the current-voltage curve, the computational overhead that may be required to generate the number is minimal.

[Para 71] At a next step E-514, the algorithm may determine the floating voltage potential. Since the floating voltage potential is determined based on the voltage data collected, the floating voltage potential may be determined without first having to determine the values as calculated in steps E-504 – E-512. Those skilled in the art are aware that floating voltage potential is the electrical potential at which the probe floats after the external capacitor has fully discharged. Typically, the floating voltage potential may be determined by looking at the signal that occurs right before the next RF burst. However, due to the possibility of polymer buildup causing distortion, erroneous data (i.e., noise) may be

collected; thus, the floating voltage potential may be calculated by averaging the voltage values collected toward the end of the collection period. In an embodiment, the floating voltage potential may be calculated from data point F2-652 (the data point at which the voltage first reaches its floating potential) to data point F2-654 (the data point just right before the next RF burst), as shown in Fig. F2. In another embodiment, the floating voltage potential may be based on the voltage values within a window F2-656, which is located between data points F2-652 and F2-654, as shown in Fig. F2. In an embodiment, window F2-656 may be of any size as long as the window begins before the prior pulse has decayed more than 99 percent and ends when the next pulse begins. In one embodiment, the floating voltage potential may be determined from a window that provides an average value with a low standard deviation (error).

[Para 72] As can be appreciated from the foregoing, the methods for determining the relevancy range and the seed values account for anomalies that may occur in the current, voltage and/or current-voltage (I-V) curves. In an example, polymer buildup may occur at the end of an RF burst. However, by applying the aforementioned algorithms, the relevancy range and the seed values are impervious to unexpected artifacts that may occur during processing.

[Para 73] Once the relevancy range has been determined and the seed values have been calculated, at a next step E-516, the current values may be plotted against the voltage values and curve-fitting may be applied to generate graph F4-680 of Fig. F4. In an example, a non-linear curve fit, such as Levenberg-Marquardt algorithm, may be applied to perform the curve-fitting. By generating a curve-fitting graph and applying the seed values to the mathematical model, such as Equation 2 below, the four parameters that may be employed to characterize the plasma may be determined.

$$I = I_0\left\{1 - s*\left(V - V_f\right) - \exp\left[\frac{\left(V - V_f\right)}{T_e}\right]\right\} \qquad \textit{[Equation 2]}$$

Table 2: Parameters defined

Parameters	Variable name
I	Current
I_0	Ion saturation
S	Slope

V	Voltage
V_f	Floating voltage potential
T_e	Electron temperature

[Para 74] As can be appreciated from one or more embodiments of the present invention, an automated method for characterizing plasma during plasma processing is provided. By determining a relevancy range and a set of seed values, plasma characterization may occur without having to process thousands or millions of data points that are usually collected after a single RF burst. The automated method transforms a previously tedious and manual process into an automatic task that may be performed quickly and efficiently. With data analysis significantly shortened from a few minutes (or even a few hours) to a few milliseconds, plasma characterization may be performed during plasma processing instead of being a post- production process. Thus, relevant data may provide insights into the current plasma environment, thereby enabling recipe and/or tool adjustment to occur and waste to be minimized.

[Para 75] While this invention has been described in terms of several preferred embodiments, there are alterations, permutations, and equivalents, which fall within the scope of this invention. It should also be noted that there are many alternative ways of implementing the methods and apparatuses of the present invention. Although various examples are provided herein, it is intended that these examples be illustrative and not limiting with respect to the invention.

[Para 76] Also, the title and summary are provided herein for convenience and should not be used to construe the scope of the claims herein. Further, the abstract is written in a highly abbreviated form and is provided herein for convenience and thus should not be employed to construe or limit the overall invention, which is expressed in the claims. If the term "set" is employed herein, such term is intended to have its commonly understood mathematical meaning to cover zero, one, or more than one member. Also, it is intended that the following appended claims be interpreted as including all such alterations, permutations, and equivalents as fall within the true spirit and scope of the present invention.

CLAIMS

What is claimed is:

1. A method for identifying a stabilized plasma within a processing chamber of a plasma processing system, comprising:

executing a strike step within said processing chamber to generate a plasma, wherein said strike step includes

applying a substantially high gas pressure within said processing chamber, and

maintaining a low radio frequency (RF) power within said processing chamber;

employing a probe head to collect a set of characteristic parameter measurements during said strike step, said probe head being on a surface of said processing chamber, wherein said surface is within close proximity to a substrate surface; and

comparing said set of characteristic parameter measurements against a pre-defined range, if said set of characteristic parameter measurements is within said pre-defined range, said stabilized plasma exists.

2. The method of claim 1 wherein said probe head is a capacitively-coupled electrostatic (CCE) probe.

3. The method of claim 2 wherein said probe head is a small device, wherein a plasma-facing surface of said probe head is made from a material similar to other plasma-facing components of said processing chamber.

4. The method of claim 1 wherein said set of characteristic parameter measurements is a set of ion flux measurement.

5. The method of claim 1 wherein said set of characteristic parameter measurements is a set of electron temperature measurements.

6. The method of claim 1 wherein said set of characteristic parameter measurements is a set of floating potential measurements.

7. The method of claim 1 wherein if said set of characteristic parameter measurements is not within said pre-defined range, said plasma is not stabilized and corrective actions is applied.

8. An arrangement for identifying a stabilized plasma within a processing chamber of a plasma processing system, comprising:

a substrate, wherein said substrate is positioned on a lower electrode within said processing chamber;

a radio frequency (RF) power source, wherein said RF power source is being applied at a low RF power within said processing chamber;

a gas delivery system, wherein a gas is delivered into said processing chamber to interact with said RF power to create a plasma;

a pressure module, wherein said pressure module is applied at a substantially high force within said processing chamber;

a probe arrangement, wherein said probe arrangement includes a plasma-facing sensor and is disposed on a surface of said processing chamber, said surface is within close proximity to a surface of said substrate, wherein said probe arrangement is configured at least to collect a set of characteristic parameter measurements during a strike step; and

a detection module, wherein said detection module is configured to compare said set of characteristic parameter measurements against a pre-defined range, if said set of characteristic parameter measurements is within said pre-defined range, said stabilized plasma exists.

9. The arrangement of claim 8 wherein said plasma-facing sensor is a capacitively-coupled electrostatic (CCE) probe head.

10. The arrangement of claim 9 wherein said plasma-facing sensor is a small device, wherein a plasma-facing surface of said plasma-facing sensor is made from a material similar to other plasma-facing components of said processing chamber.

11. The arrangement of claim 8 wherein said set of characteristic parameter measurements is a set of ion flux measurement.

12. The arrangement of claim 8 wherein said set of characteristic parameter measurements is a set of electron temperature measurements.

13. The arrangement of claim 8 wherein said set of characteristic parameter measurements is a set of floating potential measurements.

14. The arrangement of claim 8 wherein said detection module is a software algorithm.

15. The arrangement of claim 8 wherein if said detection module is unable to determine said stabilized plasma, corrective actions is applied.

16. An article of manufacture comprising a program storage medium having computer readable code embodied therein, said computer readable code being configured for identifying a stabilized plasma within a processing chamber of a plasma processing system, comprising:

code for executing a strike step within said processing chamber to generate a plasma, wherein said strike step includes

code for applying a substantially high gas pressure within said processing chamber, and

code for maintaining a low radio frequency (RF) power within said processing chamber;

code for collecting a set of characteristic parameter measurements during said strike step by using a probe head, said probe head being on a surface of said processing chamber, wherein said surface is within close proximity to a substrate surface; and

code for comparing said set of characteristic parameter measurements against a pre-defined range, if said set of characteristic parameter measurements is within said pre-defined range, said stabilized plasma exists.

17. The article of manufacture of claim 16 wherein said probe head is a capacitively-coupled electrostatic (CCE) probe.

18. The article of manufacture of claim 16 wherein said set of characteristic parameter measurements is one of a set of ion flux measurement, a set of electron temperature measurements, and a set of floating potential measurements.

19. The article of manufacture of claim 16 wherein if said set of characteristic parameter measurements is not within said pre-defined range, said plasma is not stabilized and corrective actions is applied.

20. The article of manufacture of claim 16 wherein said code for comparing of said set of characteristic parameter measurement against said pre-defined range is performed by a detection module.

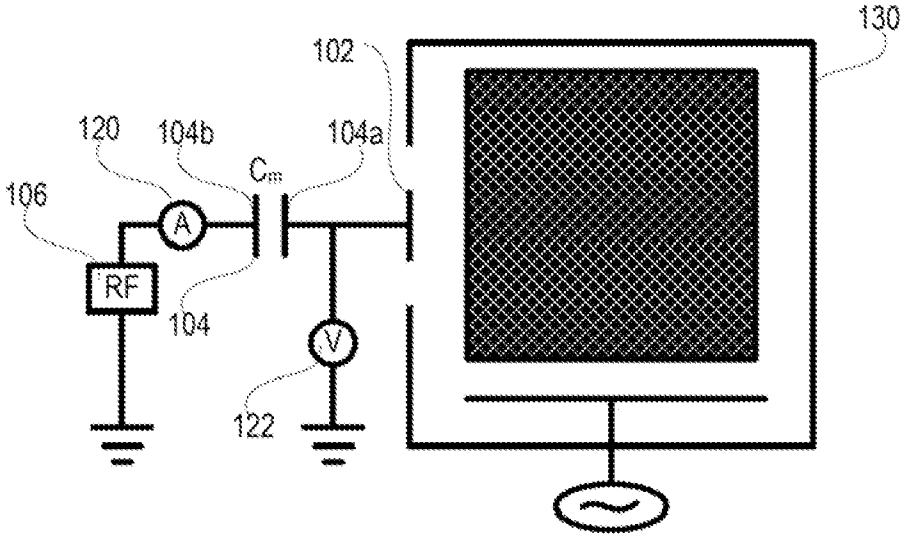

FIG. 1

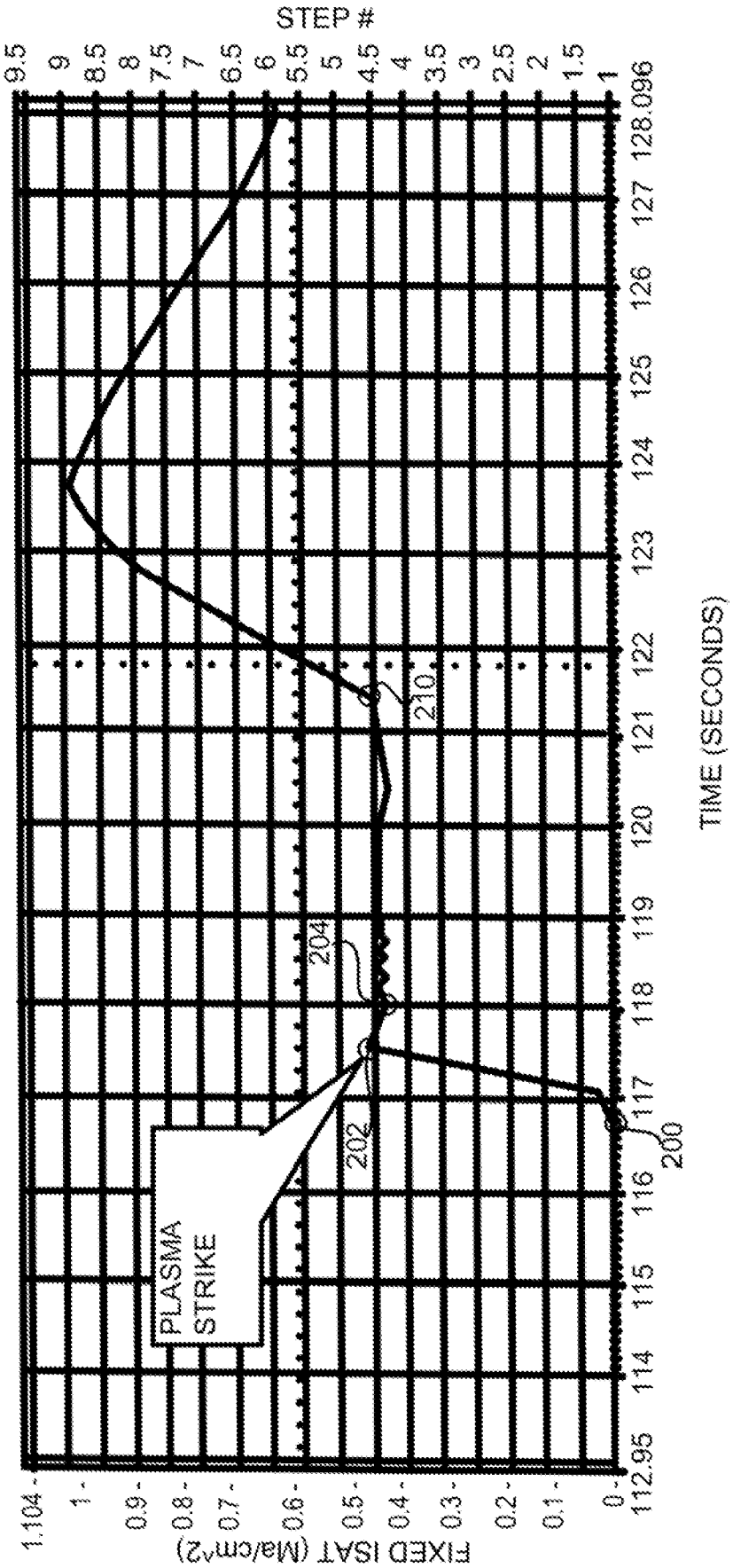

FIG. 2
(PRIOR ART)

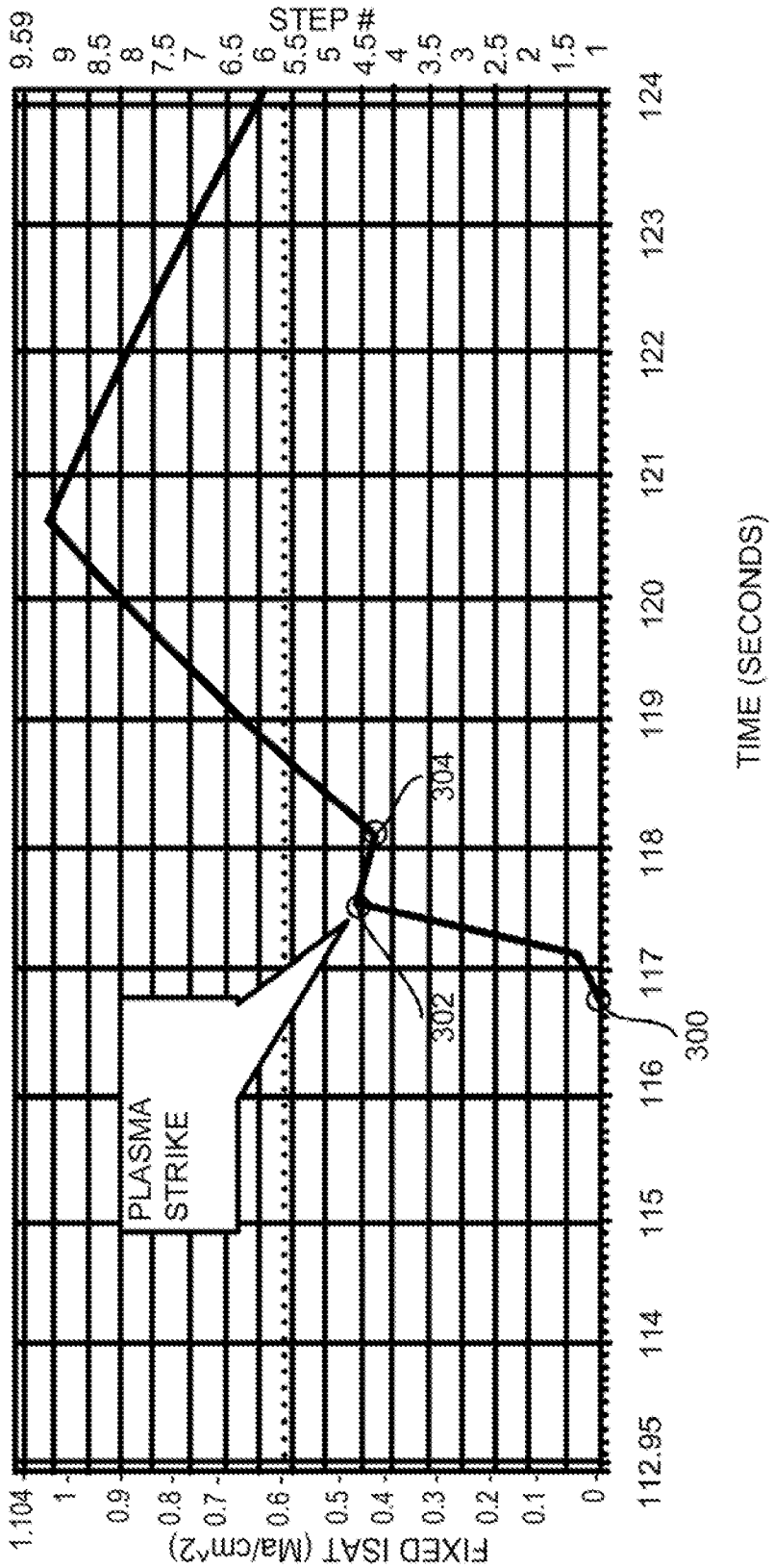
STEP #
9.59
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
124
123
122
121
120
119
118
117
116
115
114
112.95
TIME (SECONDS)
1.104
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
FIXED ISAT (Ma/cm^2)
PLASMA
STRIKE
300
302
304

FIG. 3

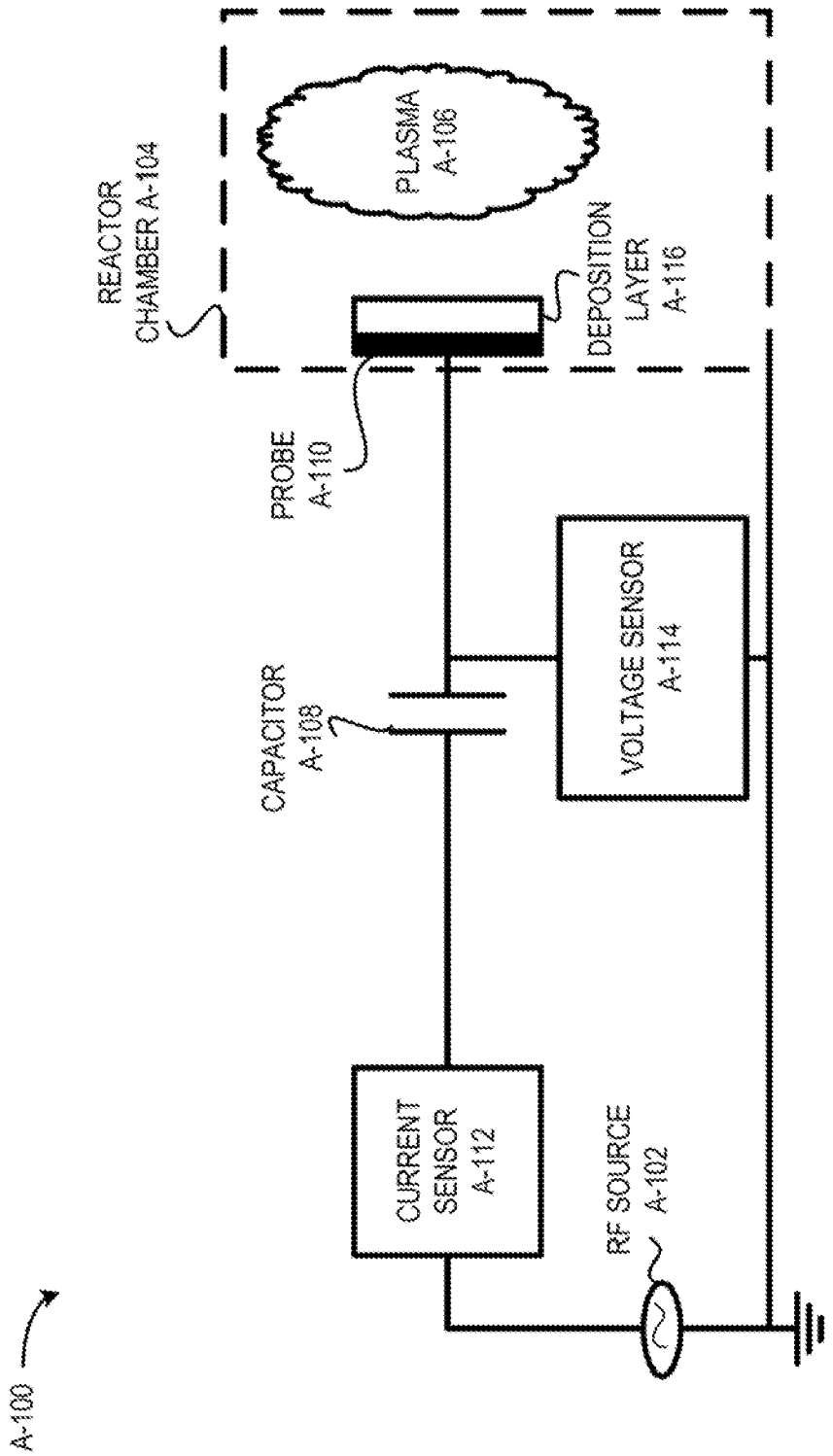

FIG. A
(PRIOR ART)

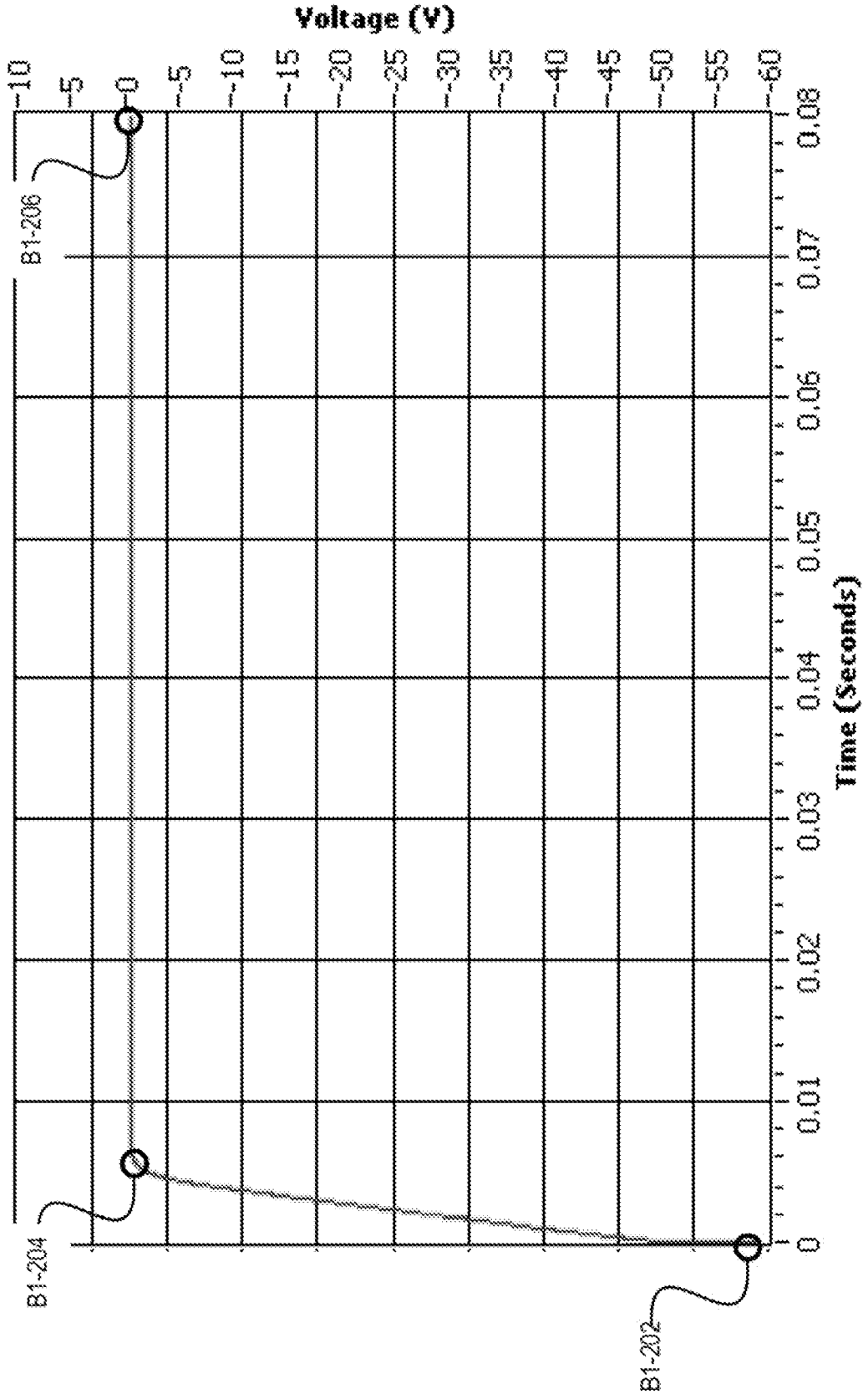

FIG. B1
(PRIOR ART)

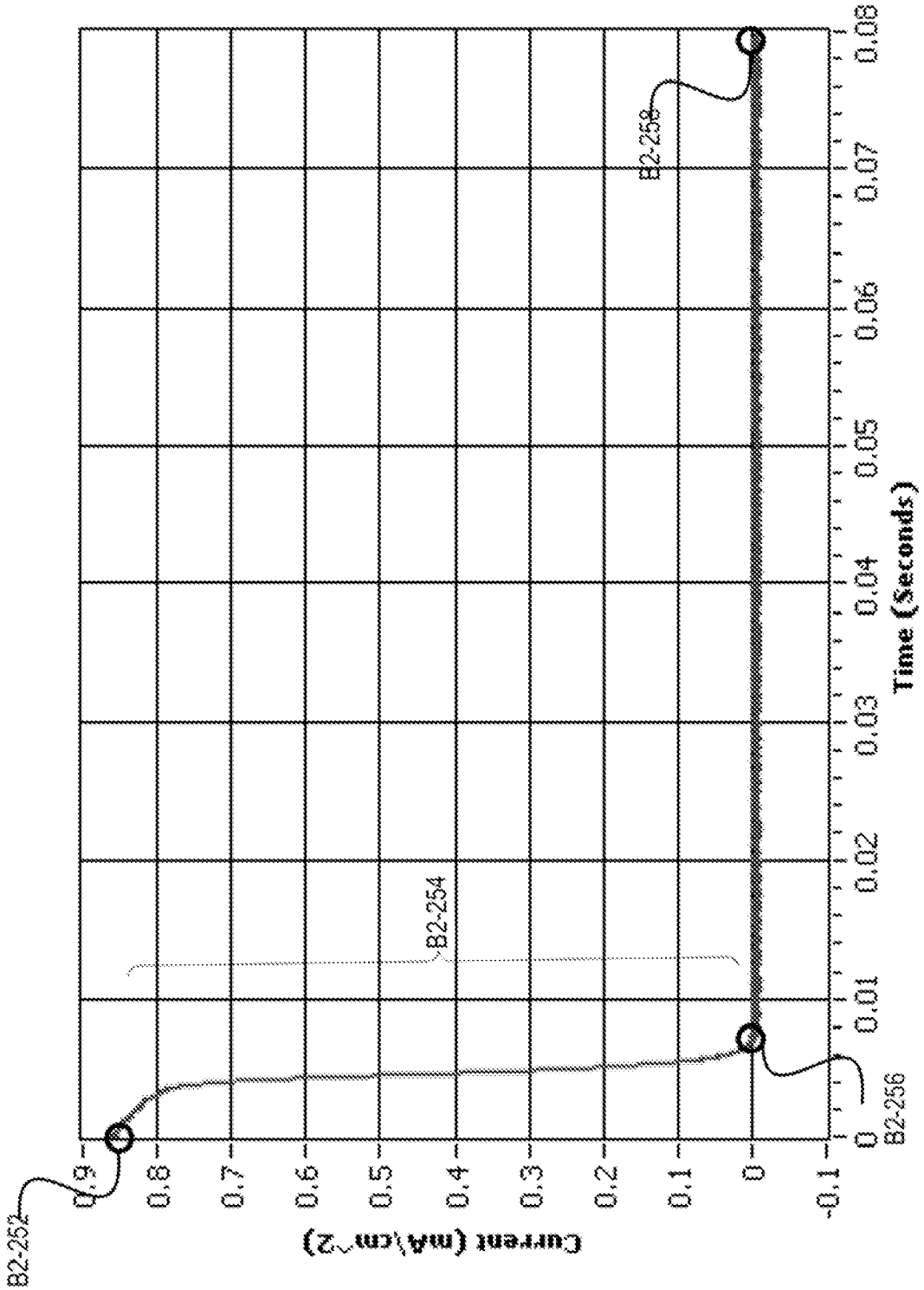

FIG. B2
(PRIOR ART)

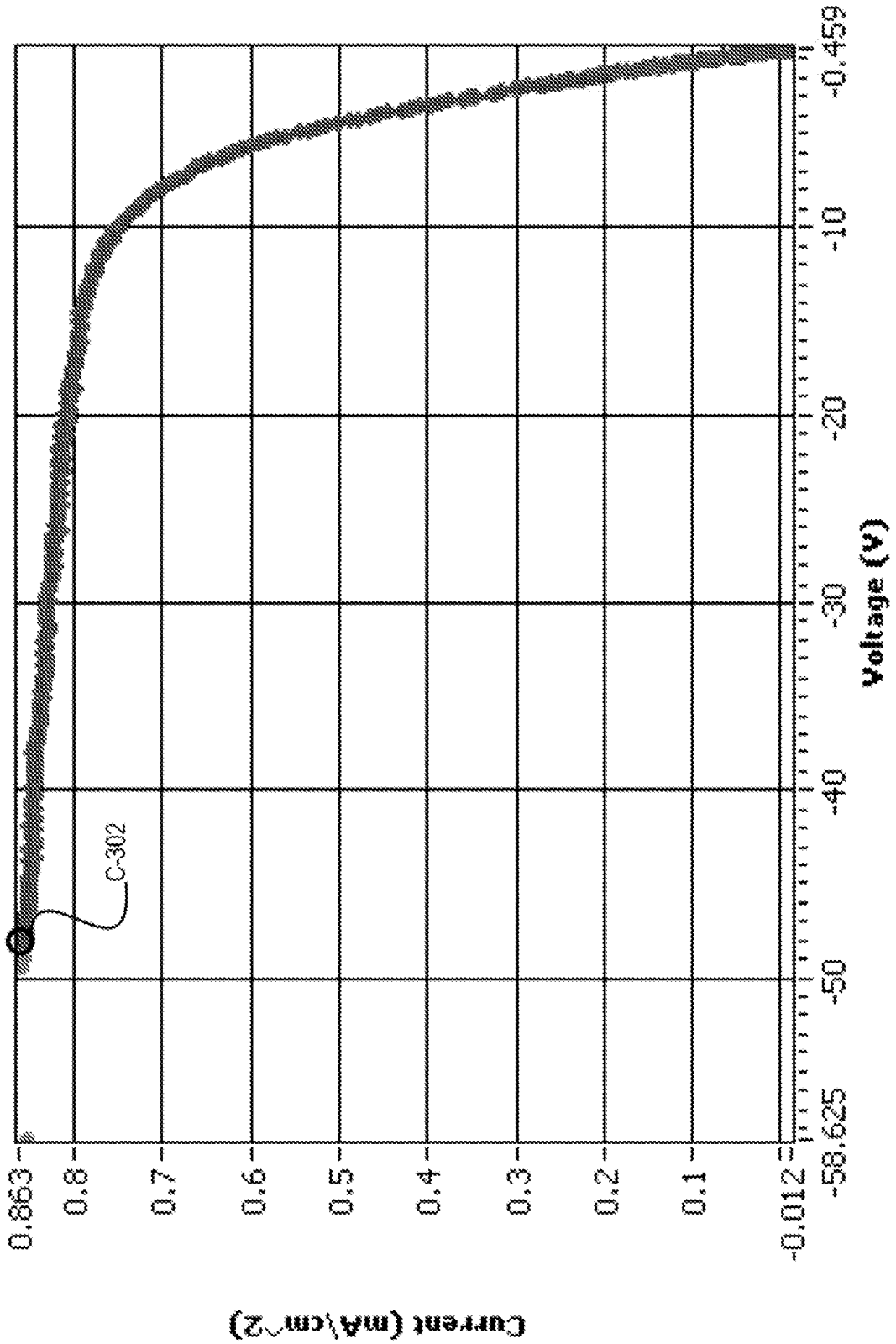

FIG. C
(PRIOR ART)

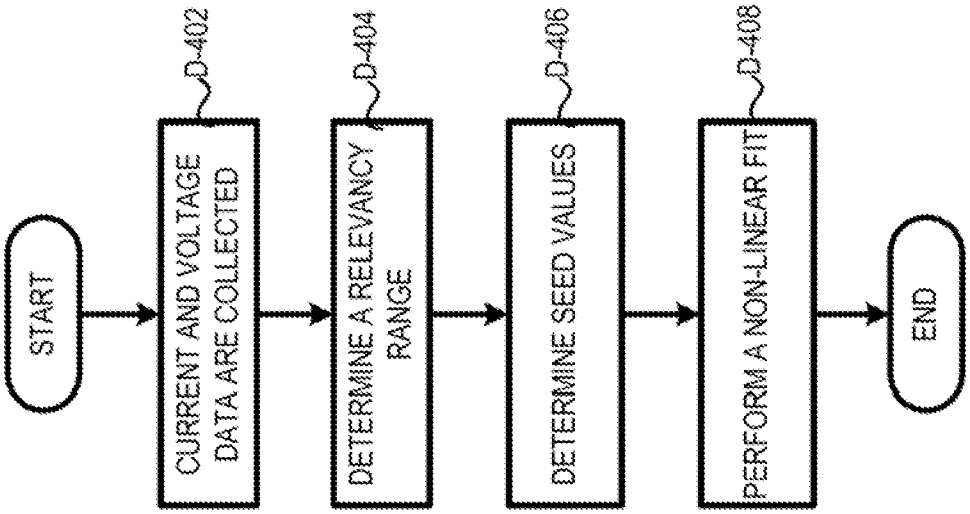
START
CURRENT AND VOLTAGE DATA ARE COLLECTED
D-402
DETERMINE A RELEVANCY RANGE
D-404
DETERMINE SEED VALUES
D-406
PERFORM A NON-LINEAR FIT
D-408
END

FIG. D

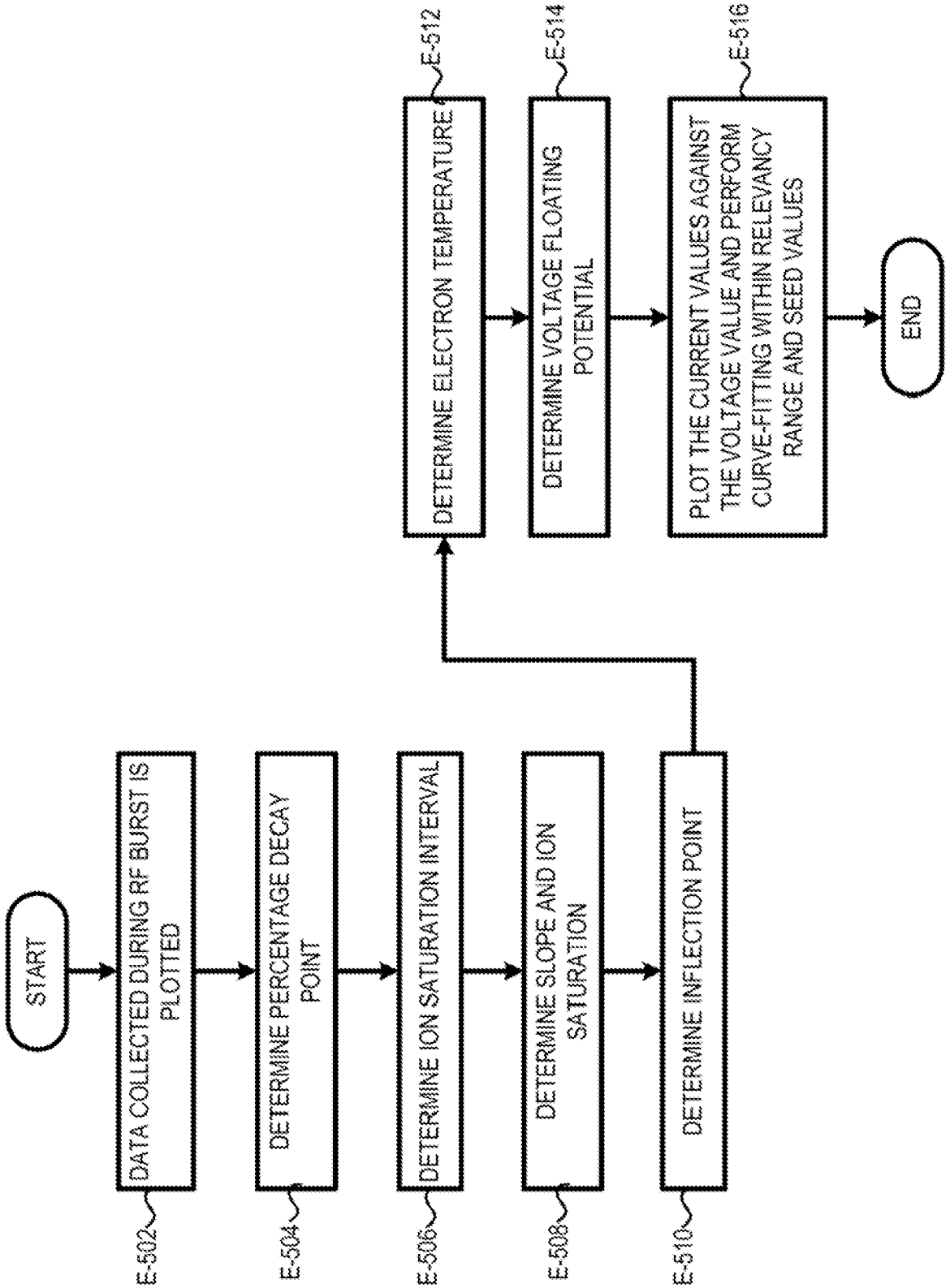
START
DATA COLLECTED DURING RF BURST IS PLOTTED
E-502
DETERMINE PERCENTAGE DECAY POINT
E-504
DETERMINE ION SATURATION INTERVAL
E-506
DETERMINE SLOPE AND ION SATURATION
E-508
DETERMINE INFLECTION POINT
E-510
DETERMINE ELECTRON TEMPERATURE
E-512
DETERMINE VOLTAGE FLOATING POTENTIAL
E-514
PLOT THE CURRENT VALUES AGAINST THE VOLTAGE VALUE AND PERFORM CURVE-FITTING WITHIN RELEVANCY RANGE AND SEED VALUES
E-516
END

FIG. E

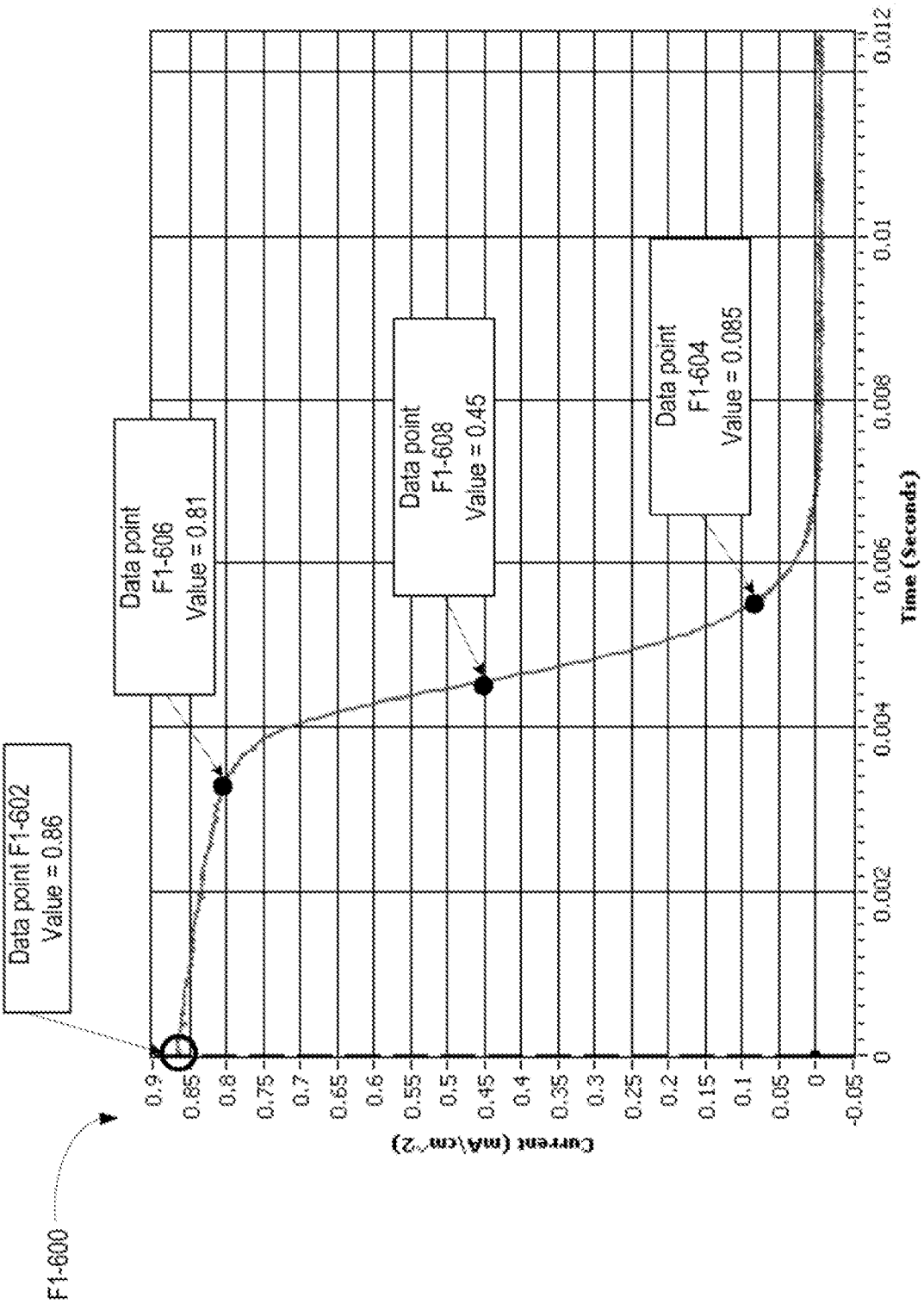
F1-600
Data point F1-602
Value = 0.86
Data point
F1-606
Value = 0.81
Data point
F1-608
Value = 0.45
Data point
F1-604
Value = 0.085
Current (mA\cm^2)
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Time (Seconds)
0
0.002
0.004
0.006
0.008
0.01
0.012

FIG. F1

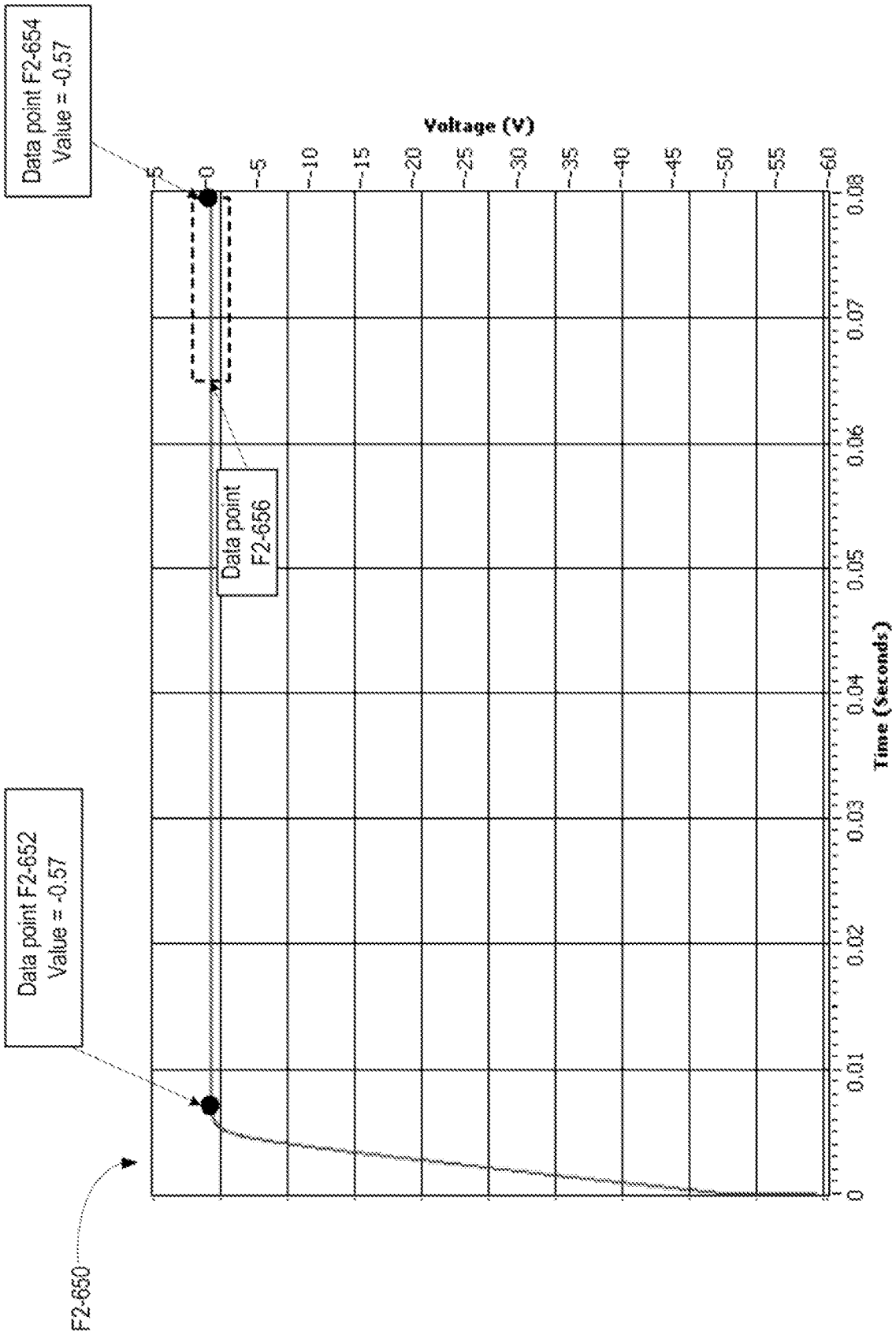
Data point F2-654
Value = -0.57
Data point F2-652
Value = -0.57
Data point
F2-656
F2-650
Voltage (V)
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
Time (Seconds)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08

FIG. F2

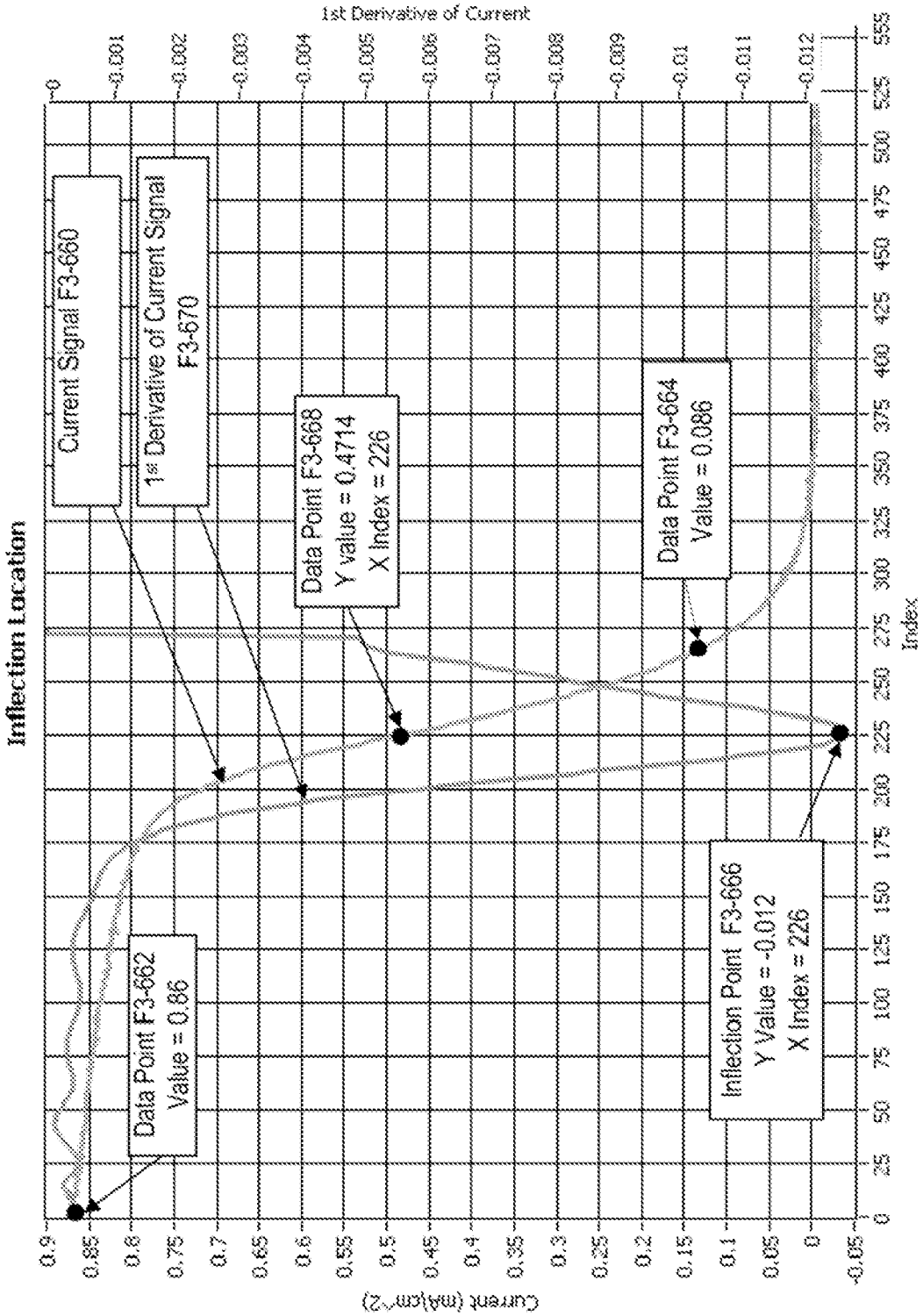
Inflection Location
1st Derivative of Current
Current Signal F3-660
1st Derivative of Current Signal F3-670
Data Point F3-668
Y value = 0.4714
X Index = 226
Data Point F3-664
Value = 0.086
Data Point F3-662
Value = 0.86
Inflection Point F3-666
Y Value = -0.012
X Index = 226
Current (mA/cm^2)
Index

FIG. F3

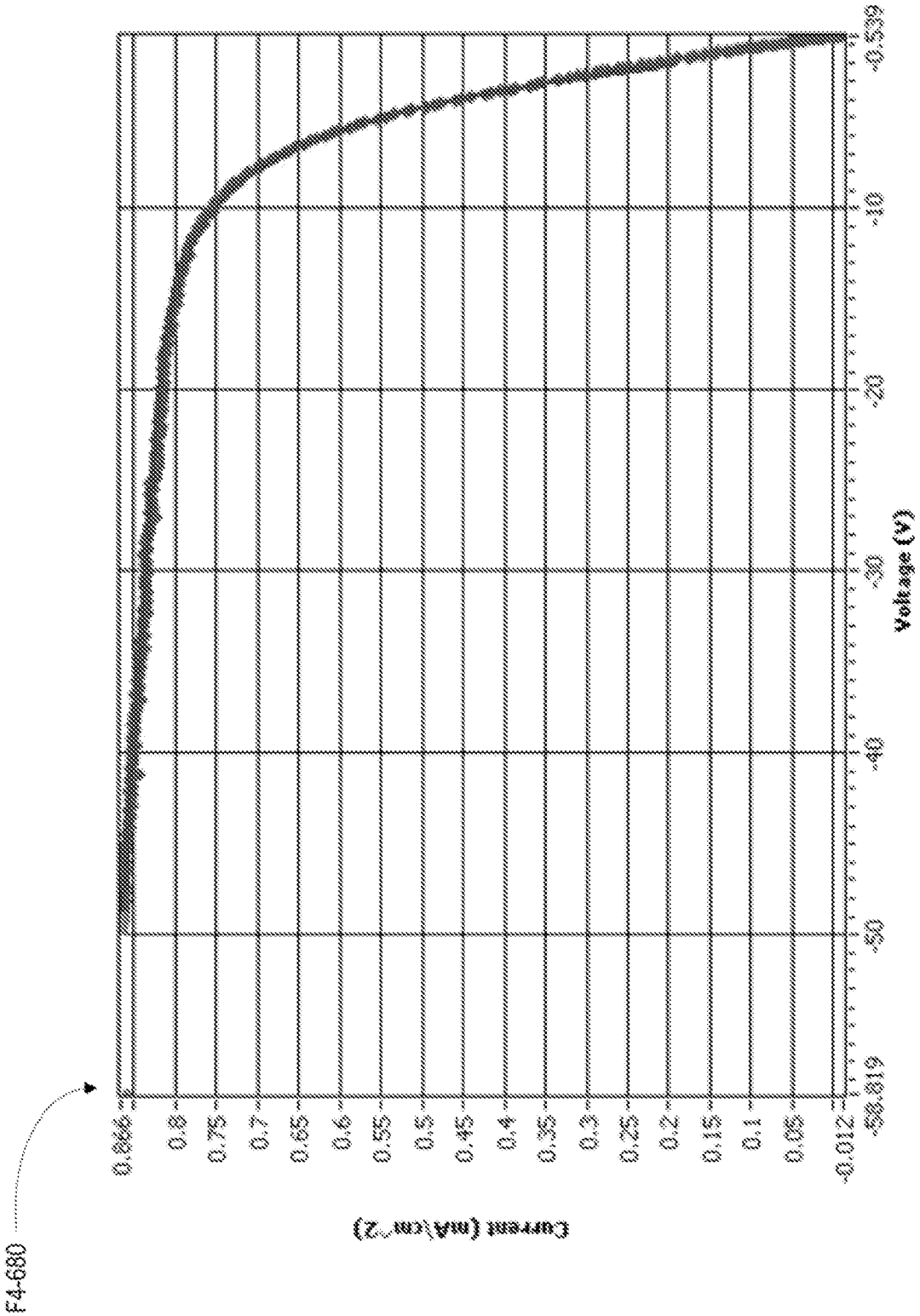
F4-680
Current (mA\cm^2)
0.866
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
-0.012
-50.819
-50
-40
-30
-20
-10
-0.539
Voltage (V)

FIG. F4