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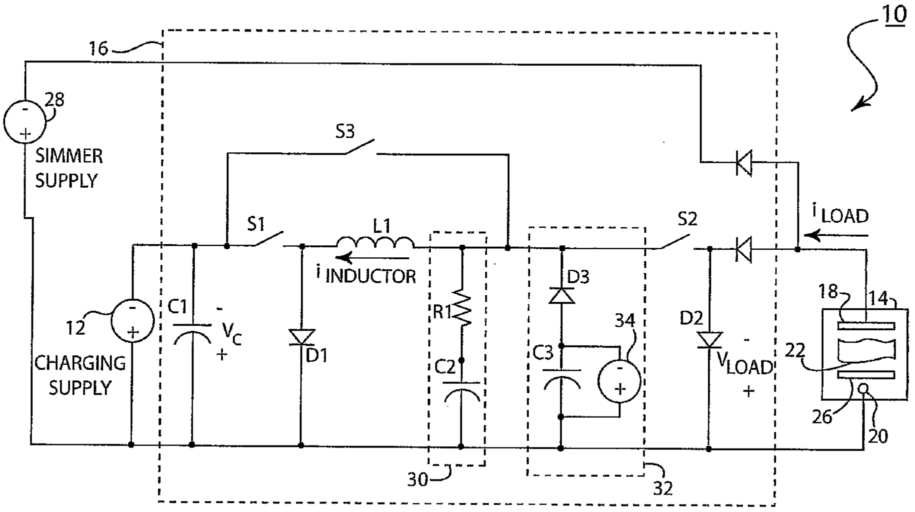
(54) Title: HIGH PEAK POWER PLASMA PULSED SUPPLY WITH ARC HANDLING



(57) Abstract: A magnetron sputtering system is provided comprising a pulsed DC power supply capable of delivering peak powers of 0.1 mega Watts to several megaWatts with a peak power density greater than 1kW/cm^2. A sputtering plasma in a highly ionized state is created without first adopting an arc discharge state. The power supply has a pulsing circuit comprising an energy storage capacitor and serially connected inductor with a switching means for disconnecting the pulsing circuit from the plasma and recycling the inductor energy back to the energy storage capacitor at the detection of an arc condition. The energy storage capacitor and the serially connected inductor provide an impedance match to the plasma, limits the current rate of rise and peak magnitude in the event of an arc, and shapes the voltage pulses to the plasma.

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HIGH PEAK POWER PLASMA PULSED SUPPLY WITH ARC HANDLING

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates generally to apparatus and methods for magnetron sputtering, and more particularly to magnetron sputtering apparatus that delivers high peak powers to a sputtering magnetron plasma load with arc handling capability.

Brief Description of the Prior Art

It is desirable to coat some substrates by generating metal ions and attracting the ions to the work piece by means of an electrical bias. The utility of this approach includes application of coatings to surfaces with irregularities that would prevent uniform deposition by normal sputtering, which essentially requires line of sight from the sputtering source to the workpiece feature. Coating and even filling high aspect ratio trenches in semiconductor devices is possible by biasing the wafer to attract the ions, as reported by Monteiro in JVST B 17(3), 1999 pg. 1094 and Lu and Kushner in JVST A 19(5), 2001 pg. 2652.

Sputtering deposition may be enhanced by making use of plasmas in a highly ionized state. A technique for generating highly ionized, high density metal plasma by driving conventional sputtering magnetrons with electrical pulses having high peak power and low duty factor has been reported by Kouznetsov, et al. in Surface and Coatings Technology 122 (1999) pg. 290. Additional teachings can be found by Macak, et al, JVST A 18(4), 2000 pg. 1533; Gudmundsson, et al., APL, Vol. 78, No. 22, 28 May 2001, pg. 3427; and Ehiasarian, et al., Vacuum 65 (2002) p. 147.

U.S. Patent No. 6,296,742 B1 describes a method of producing a fully ionized plasma for use in magnetron sputtering applications. A pulse generator delivers pulses of up to 10 MW to a sputtering target, thereby completely ionizing a sputtering gas. In this method, the sputtering gas is described as first adopting a glow discharge state, then continuing to an arc discharge state, and finally adopting a fully ionized state. As shown in Figure 1 of that patent, the arc discharge state is described as a break-down condition occurring at current densities beyond those of the abnormal glow discharge region, and is characterized by a sudden drop in plasma impedance, as shown by an abrupt drop in plasma voltage as the current density further increases. In practical systems, this is usually represented by a drop in the voltage across the plasma to at most a few tens of volts and may be accompanied by a discharge between some part of the sputtering target and the chamber. The '742 patent indicates that, under that patent's teachings, the plasma, after passing through this arc region, develops into a fully ionized state.

Part of the appeal of these techniques is the ability to generate a large population of ionized species that can in turn be attracted to the work piece by the application of a bias voltage. The above references on the high peak power techniques appear to use a simple capacitor discharge through an inductor. However, the technique taught by these references does not disclose any arc handling capability, and in fact suggests that it is possible, once the fully ionized state is attained, to achieve thereafter arc-free operation. Unavoidable imperfections in hardware, however, make the physical realization of a completely arc free region of operation (after the initial passing through of the arc state) essentially impossible, even if its existence is suggested by theory. Use of the technique, therefore, without arc handling capability, may make commercial utilization impractical. It may also, at the least, make processing time excessive because of the long time which may be needed to condition the target to operate in near arc-free conditions, and may at the very least prevent operation at the highest power levels due to an inability to condition the target adequately. Thus, it would be desirable to provide apparatus that enables commercial processes using high peak power pulses to magnetrons to produce high density, highly ionized plasmas by minimizing arc energy that in turn keeps product and target damage due to arcing within acceptable limits. In view of the possible damage created by passing through the arc state at the outset of the pulsing, it would also be very desirable to prevent the occurrence of the arc state in the initial establishment of the highly ionized condition.

Typically arc control and arc diverting apparatus have been comprised of circuits that either detect the arc and disconnect the power supply from the load or are comprised of a switching circuit that effectively short circuits the power supply to extinguish the arc. These types of arc handling methods are very costly because they may result in a complete shut down of the process, wasting expensive stock material, or require complete dissipation of all of the energy stored in the power supply circuits. In high power applications, short circuits to the power supply may result in extremely high currents – even enough to cause destruction of the power supply itself – and repetitive dissipation of stored energy in any case requires expensive resistive elements capable of high peak power and high average power, as well as the means for cooling them.

It would also be desirable, then, if there were provided a magnetron sputtering apparatus and method that could deliver peak powers of 1 Megawatt or greater, with arc handling capability for high yield commercial applications. It is an object of this invention to provide a magnetron sputtering plasma system that has the capability both to detect arcs and to take action to limit the energy delivered to the arc. It is a further object of this invention to provide a magnetron sputtering system that creates sputtering plasmas in a highly ionized state without first adopting an arc discharge state, which may cause damage to the chamber, substrate, or target, even if only as a transient condition on each pulse.

SUMMARY OF THE INVENTION

There is provided by this invention an apparatus and method for producing high current pulses suited for delivering high peak power to high-density magnetron plasmas with efficient arc handling capability. In one embodiment of the invention, a pulsing circuit comprised of an energy storage capacitor is repetitively charged and then discharged through an inductor in series with the plasma. The combination of the inductor and capacitor serve to shape the pulse, which accomplishes three functions. First, it has been found that it is possible to avoid the initial arc condition by properly shaping the pulse. This is done by controlling the beginning of the voltage pulse. In one embodiment, a network is added for the purpose of controlling the voltage rate of rise, the unclamped peak amplitude of the voltage pulse in the event that the plasma does not ignite, and the frequency at which the voltage waveform rings, particularly in the case that the plasma does not ignite. This circuit in this embodiment amounts to a resistor in series with a capacitor shunt connected at the output of the pulser, or its equivalent implemented as a distributed circuit with a number of discrete capacitors and resistors, possibly also utilizing parasitic capacitors and resistors in devices and circuit conductors. In addition, a circuit is provided to clamp or limit the voltage pulse to a maximum level, implemented with a diode, normally reverse biased in series with a capacitor held at the clamp voltage, connected to the output of the pulser. This circuit is activated when the amplitude of the voltage pulse exceeds a preset adjustable value and acts to prevent the voltage from exceeding a preset level. This has the benefit of preventing undesirable arcs both inside and outside the vacuum chamber. All of this makes it possible to reach a highly ionized plasma state without first passing through the arc state.

Second, the pulsing network, or mesh, serves to provide an impedance match to the plasma. Third, the network serves to limit the current rate of rise and peak magnitude in the event of a later occurrence of an arc. An arc may be detected by either the fall of the discharge voltage below a preset voltage threshold during a pulse, or an increase in discharge current above a preset current threshold. Note that the arc condition represents a lowering of the impedance of the plasma, which is represented by the ratio of the voltage to the current, so either or both detection methods will serve. When an arc is detected, the energy storage capacitor is disconnected from the series inductor to stop the current rise. The pulsing circuit is then disconnected from the plasma load and the inductor energy is recycled to the energy storage capacitor.

For a typical sputtering plasma in a glow or abnormal glow state, the proportion of ionized species is relatively low, on the order of a few percent at most. Using the present invention, sputtering plasmas in a highly ionized state may be achieved, having ionization fractions of ten percent or more. In sputtering systems wherein only very small ionization fractions are normally present, such as systems for sputtering carbon, a highly ionized plasma may be achieved using the present invention by raising the proportion of ionized species in the plasma by a factor of five or more.

Using the apparatus and method of this invention, a sputtering plasma in a highly ionized state may be created without first adopting an arc discharge state. The arc handling features of the invention serve to mitigate and extinguish any arcs that develop while the sputtering plasma is present.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic representation of a magnetron plasma processing system incorporating the principles of this invention.

Figure 2 illustrates the waveforms for normal operation of the magnetron plasma processing system shown in Figure 1.

Figure 3 illustrates the waveforms for arc handling operation.

Figure 4 illustrates the current, voltage, and impedance characteristics of the sputtering plasma during operation of the magnetron plasma processing system.

DETAILED DESCRIPTION

Referring to Figure 1 there is shown one embodiment of a magnetron plasma processing system 10. A DC power supply 12 is connected to a magnetron plasma-processing chamber 14 via a pulsing circuit 16. The magnetron plasma-processing chamber may be a conventional magnetron chamber well known to those skilled in the art having a magnetron cathode 18 and an anode 20. In sputtering applications, a material target serves as the cathode 18. The pulsed DC supply 16 may be of the type such as a MegaPulser™ model manufactured by Advanced Energy Industries, Inc. which supplies a high voltage pulse across the cathode 18 and anode 20 to ignite a plasma 22 between the electrodes. The plasma acts upon the material of the cathode 18 so as to result in a coating on a substrate 26 located within the chamber. This is accomplished by bombarding the material target or cathode 18 with ions from the plasma 22, which results in the atoms sputtered from the target being then deposited on the surface of the substrate 26. The embodiment of Figure 1 also comprises a smaller optional dc power supply 28 that maintains a minimum voltage to the magnetron to keep the plasma ignited between the high voltage pulses from the pulse circuit 16. This power supply may also be used to initially ignite the plasma before the high pulse operation begins.

For application of high voltage pulses to the magnetron processing chamber the pulsing circuit 16 is comprised of energy storage capacitor C_1 serially connected to an inductor L_1 via switch S_1. The inductor L_1 is connected to the cathode of the magnetron via switch S_2.

Figure 2 illustrates the waveforms for normal operation of the circuit. S_2 is closed and S_3 are open for the whole sequence. The capacitor C_1 is charged to its initial voltage by the dc power supply 12. The discharge is initiated by S_1, and capacitor C_1 is discharged through inductor L_1 into the plasma load. A control circuit initiates the timing of the switches to control the charge time of the capacitor C_1 and its pulse discharge to the load. The shapes of the V_C, $I_{inductor}$, V_{LOAD}, and I_{load} waveforms are determined solely by the initial value of V_C, the values of C_1 and L_1 and the characteristics of the plasma load and the output cable.

Figure 3 shows waveforms representative of an arc occurring during a pulse from the pulsing circuit 16. The sequence begins as shown in Figure 2 and described above, but when an arc occurs the current rises and the voltage falls until the arc is detected. Arcs are detected by one of two means. Specific circuit techniques required to implement the arc detection means are well known to those skilled in the art. First, an arc may be detected as the load current exceeding a preset threshold. This threshold can actually be updated on a pulse by pulse basis by predicting the output current, based on plasma load characteristics and the initial value of V_C and the values of C_1 and L_1 and adding a margin to prevent false detections. Prediction of the output current based on these parameters is well known to those skilled in the art. Alternately, the current threshold may be based on the average peak current, with some margin added to prevent false arc detections. In this case, it may be desirable to leave pulses with high arc currents out of the average calculation. Second, an arc may be detected as the load voltage being below a preset threshold when the load current is above a second current threshold, used only for this second method. When the arc is detected, S_1 is opened immediately and S_3 is closed after a short delay, and then S_2 is opened after another short delay. This disconnects the load from the pulse circuit 16 and initiates the resonant transfer of energy from inductor L_1 to capacitor C_1. The result is that the energy present in inductor L_1 when the arc occurred is recycled to capacitor C_1. This arc handling sequence minimizes the energy delivered to the load in the event of an arc. Without the arc handling provisions, the energy stored in C_1 and the energy stored in L_1 would be delivered to the arc, almost certainly causing damage to the target and the work piece. Arc handling provisions enable commercial use of this process.

The embodiment depicted in Figure 1 also comprises circuitry for shaping the voltage pulse delivered to the magnetron plasma. A ring-up circuit 30 is provided for the purpose of controlling the voltage rate of rise of the pulse, the magnitude of the voltage pulse, and the frequency at which the voltage waveform rings. The ring-up circuit 30 comprises a resistor R_1 in series with a capacitor C_2 shunt connected at the power supply output. The ring-up circuit may also be implemented as distributed networks of discrete capacitors or resistors, and may make use of parasitic capacitance or resistance found in other circuit elements or components of the device. By shaping the voltage pulse delivered to the plasma through use of the ring-up circuit, the occurrence of arcing on initiation of the pulse may be eliminated, so that the arc state is not entered during the initiation of the pulse.

The voltage pulse generated by the embodiment of Figure 1 is also shaped and controlled by a clamp circuit 32. The clamp circuit comprises a diode D_3, reverse biased in series with a combination of a capacitor C_3 in parallel with a clamp voltage supply 34. The clamp circuit 32 acts to prevent the voltage level of a pulse from exceeding a predetermined maximum level. By limiting the pulse voltage, the clamp circuit prevents arcing conditions from developing due to voltage excursions, as when for example the pulse voltage increases due to parasitic capacitance at the power supply output. Thus, the clamp voltage may be set to a value that is high enough to allow the plasma to reach a highly ionized state, but not so high as to lead to arcing conditions due to overvoltage.

Figure 4 demonstrates operation of the magnetron plasma processing system to create a sputtering plasma in a highly ionized state without first adopting an arc discharge state. Illustrated in Figure 4 are the voltage, current, and impedance characteristics of the sputtering plasma as a function of time during one pulse in the operation of the device. The pulsed DC power supply first applies a high negative voltage, exceeding minus 1800 volts, to the material target (cathode) of the sputtering system. As the plasma is established, current develops through the plasma, rising to a level approaching minus 400 amps. At this point, the plasma is in a highly ionized state. At no time during the pulse lasting approximately 150 microseconds does the voltage suddenly drop to levels of a few tens of volts, which would be characteristic of an arc discharge state. The plasma state can also be understood with reference to the plasma impedance. As the plasma is established, the plasma impedance is high at first, and then settles to a nearly constant value of approximately 3.5 ohms. The impedance rises again sharply at the end of the pulse as the current drops to zero. At no time does the plasma impedance drop suddenly to arc levels, i.e., to values significantly below the steady state level of approximately 3.5 ohms.

The present invention therefore provides a novel high peak power plasma pulsed supply for magnetron sputtering with arc handling that minimizes damage due to arcs. It accomplishes this by tailoring the initiation of the pulse to prevent entering the arc state before entering the highly ionized state, and further by disconnecting the pulsing circuit from the plasma load and recycling the inductor energy stored for the high peak power pulse back to the energy storage capacitor at the detection of an arc condition, should such a condition occur once the highly ionized state is established.

Although there is illustrated and described specific structure and details of operation, it is to be understood that these descriptions are exemplary and that alternative embodiments and equivalents may be readily made therein by those skilled in the art without departing from the spirit and the scope of this invention. Accordingly, the invention is intended to embrace all such alternatives and equivalents that fall within the spirit and scope of the appended claims.

I claim:

1. A method of sputter deposition, comprising:
   a) providing a plasma chamber with a sputtering gas disposed therein;
   b) providing a material target disposed in the plasma chamber;
   c) providing a pulsed DC power supply that periodically applies a voltage pulse to the material target, the voltage pulse ionizing the sputtering gas to create a plasma, the plasma adopting a highly ionized state without first adopting an arc discharge state; and
   d) sputtering atoms from the target by bombarding the material target with ions from the plasma, the atoms being then deposited on the surface of a substrate in proximity to the plasma.

2. The method of claim 1, wherein the pulsed DC power supply delivers power greater than 0.1 MW with a peak power density greater than 1kW/cm^2.

3. The method of claim 1, wherein the plasma adopts the highly ionized state without first adopting an arc discharge state by controlling the voltage rate of rise of the voltage pulse applied to the material target.

4. The method of claim 3, wherein the voltage rate of rise of the voltage pulse is controlled using a circuit comprising a resistor in series with a capacitor.

5. The method of claim 1, wherein the plasma adopts the highly ionized state without first adopting an arc discharge state by limiting the magnitude of the voltage pulse to a maximum level.

6. The method of claim 5, wherein the magnitude of the voltage pulse is limited using a circuit comprising a resistor in series with a capacitor.

7. The method of claim 5, wherein the magnitude of the voltage pulse is limited using a circuit comprising a reverse biased diode, a capacitor, and a clamp voltage supply.

8. A sputter deposition system, comprising:
   - a) a plasma chamber with a sputtering gas disposed therein;
   - b) a material target disposed in the plasma chamber;
   - c) a pulsed DC power supply that periodically applies a voltage pulse to the material target, the voltage pulse ionizing the sputtering gas to create a highly ionized plasma; and
   - d) pulse shaping circuitry that shapes the voltage pulse so as to allow the plasma to adopt a highly ionized state without first adopting an arc discharge state.

9. The sputter deposition system of claim 8, wherein the pulse shaping circuitry controls the voltage rate of rise of the voltage pulse.

10. The sputter deposition system of claim 9, wherein the pulse shaping circuitry comprises a resistor in series with a capacitor.

11. The sputter deposition system of claim 8, wherein the pulse shaping circuitry limits the magnitude of the voltage pulse to a maximum level.

12. The sputter deposition system of claim 11, wherein the pulse shaping circuitry comprises a reverse biased diode, a capacitor, and a clamp voltage supply.

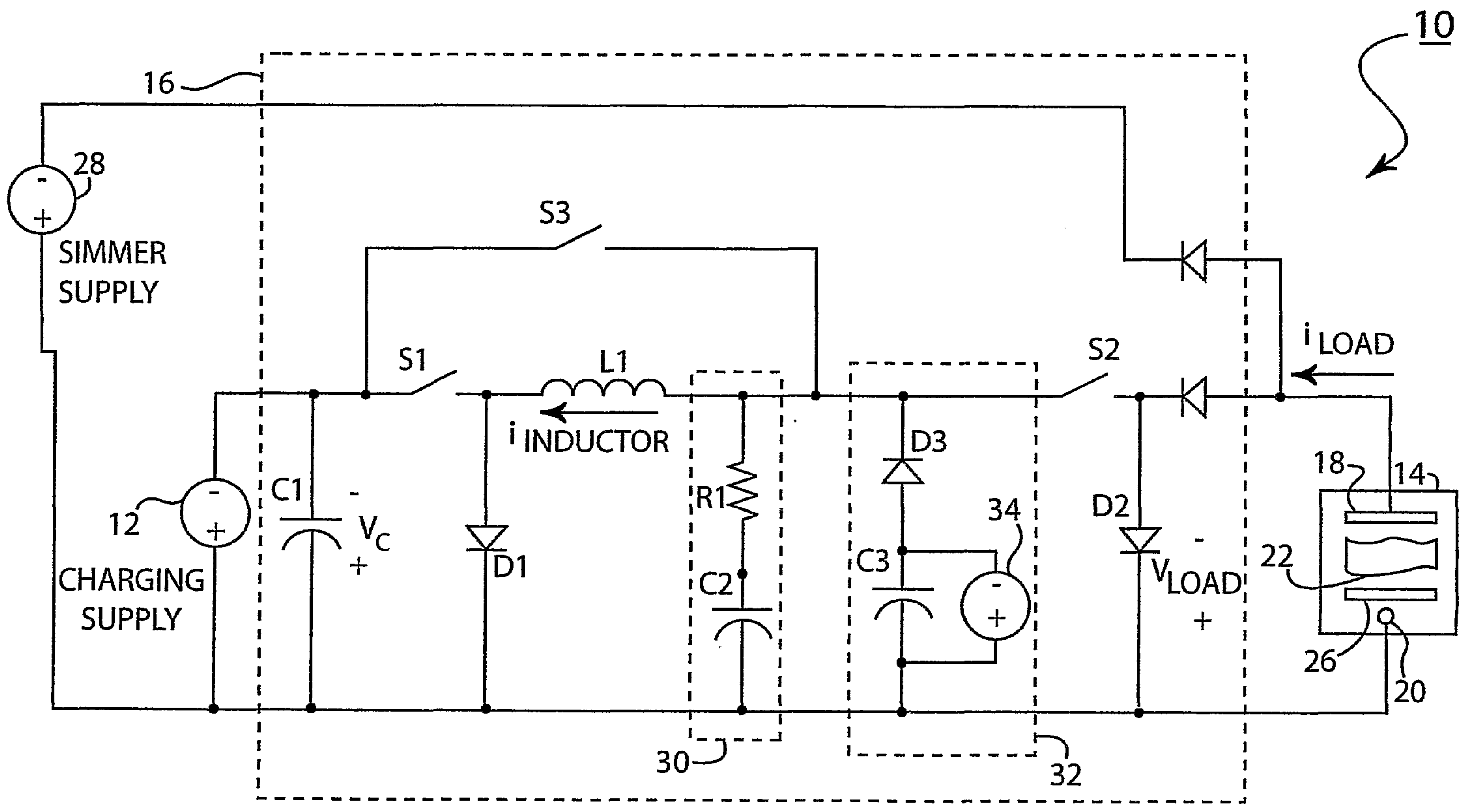
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FIGURE 1

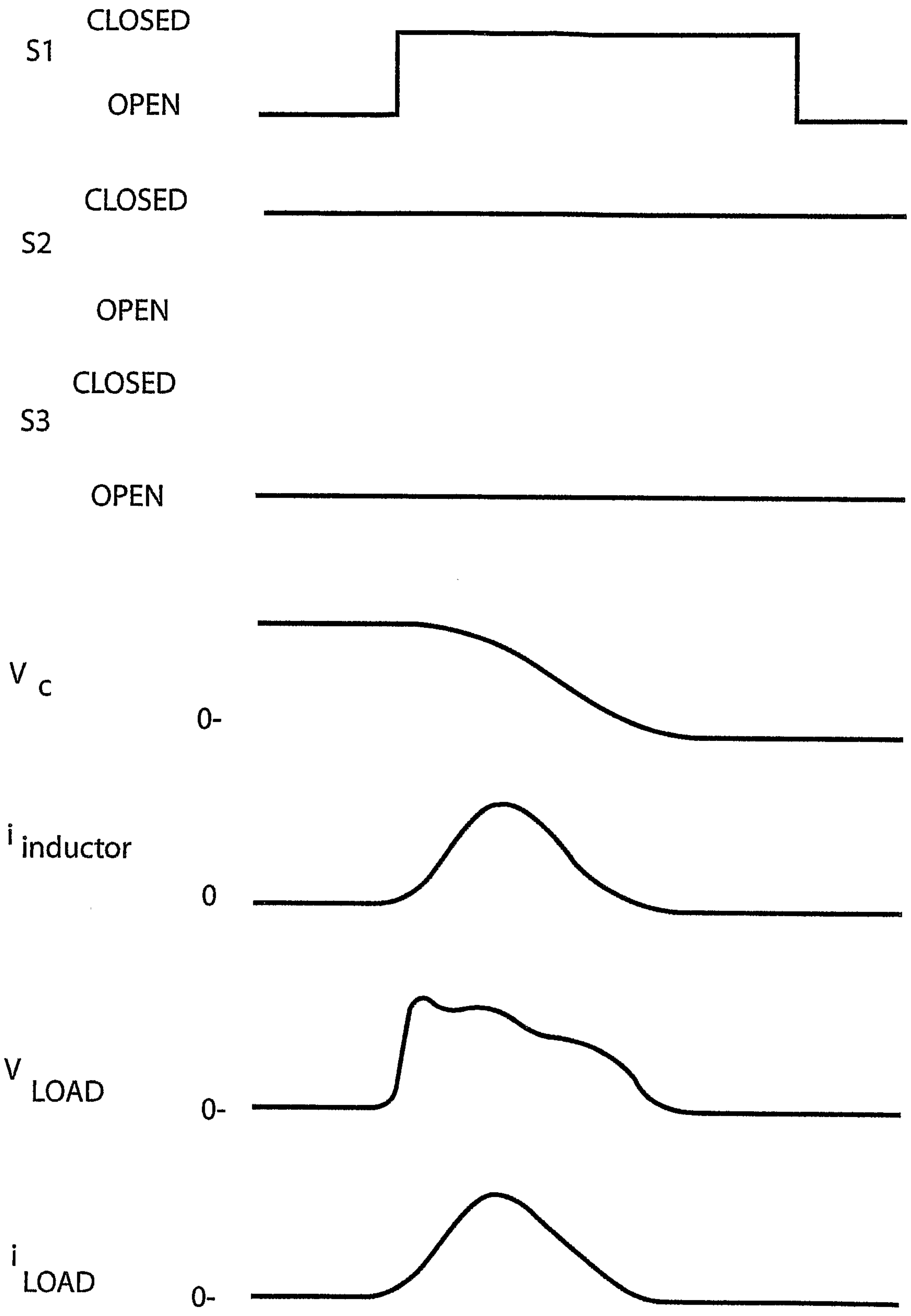
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FIGURE 2

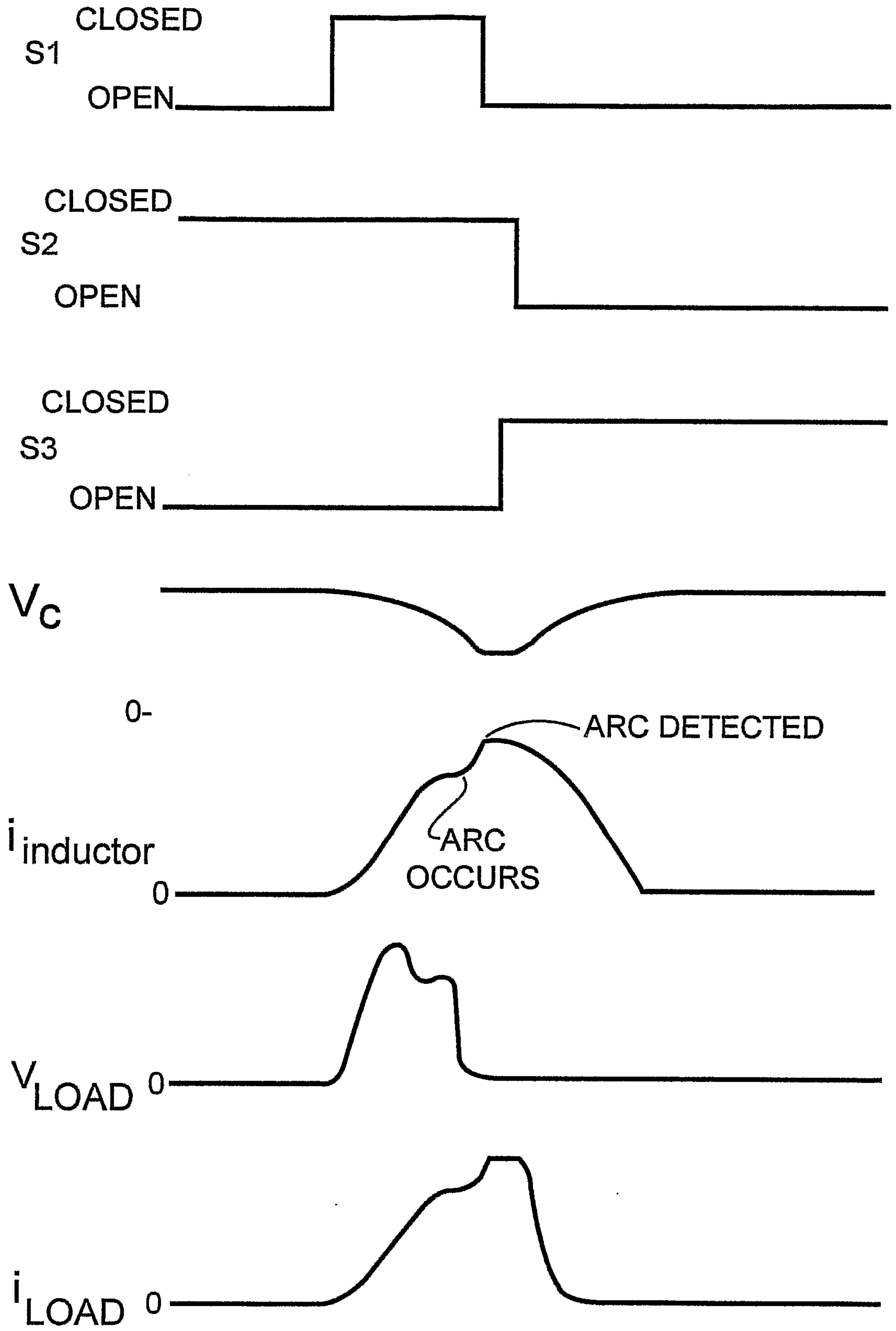
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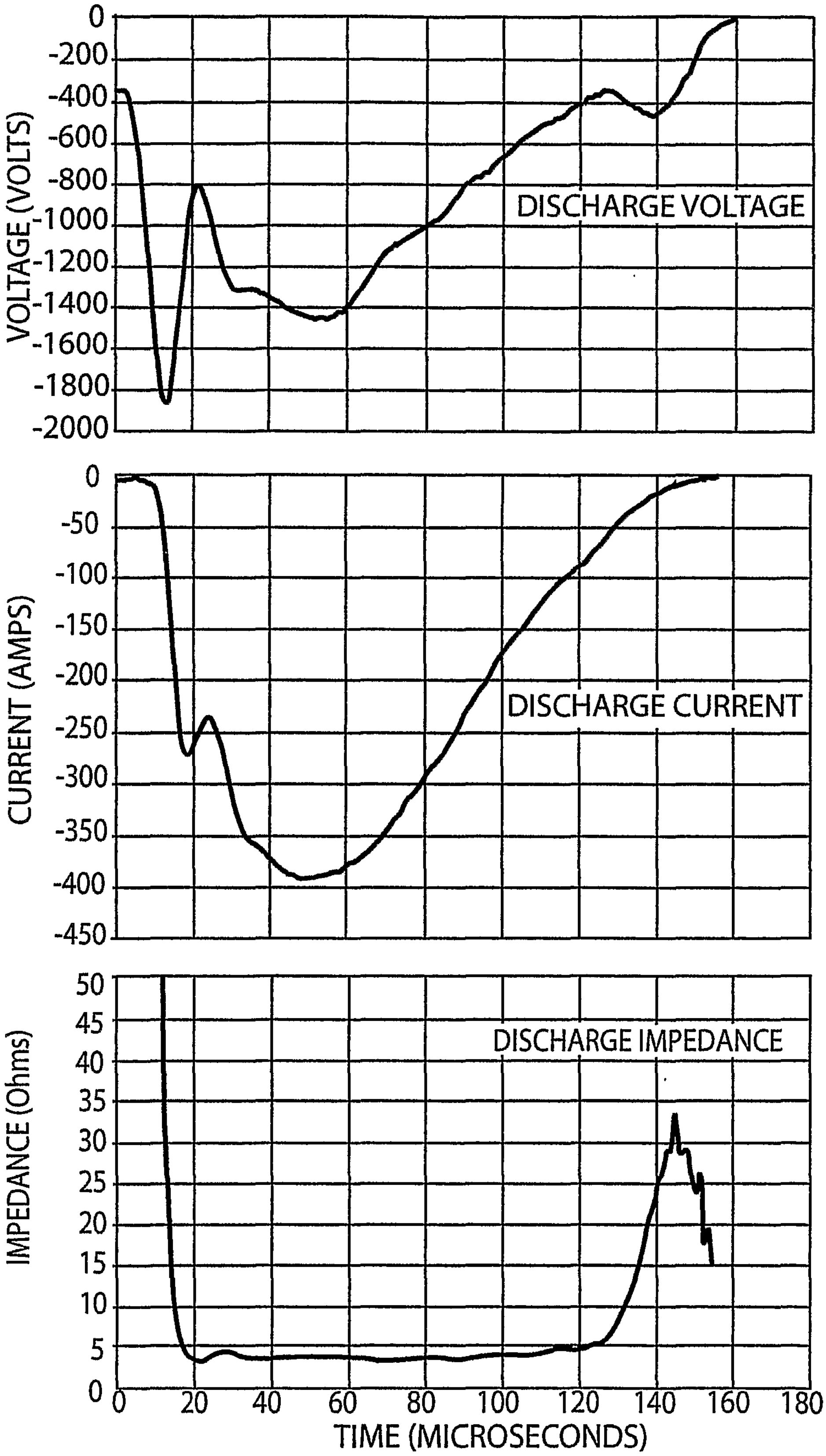
FIGURE 3

FIGURE 4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25
20
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10
5
0
DISCHARGE IMPEDANCE
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20
40
60
80
100
120
140
160
180
TIME (MICROSECONDS)