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(57) Abstract: Some embodiments include a high voltage waveform generator comprising: a generator inductor; a high voltage nanosecond pulser having one or more solid state switches electrically and/or inductively coupled with the generator inductor, the high voltage nanosecond pulser configured to produce a pulse burst having a burst period, the pulse burst comprising a plurality of pulses having different pulse widths; and a load electrically and/or inductively coupled with the high voltage nanosecond pulser, the generator inductor, and the generator capacitor, the voltage across the load having an output pulse with a pulse width substantially equal to the burst period and the voltage across the load varying in a manner that is substantially proportional with the pulse widths of the plurality of pulses.

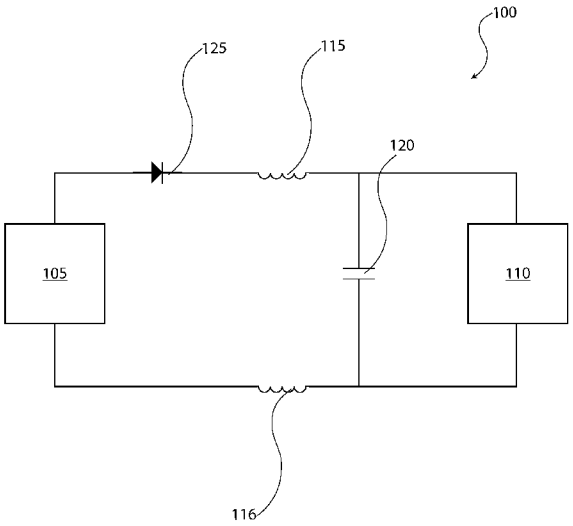


FIG. 1

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ARBITARARY WAVEFORM GENERATION USING NANOSECOND PULSES

Producing high voltage pulses with fast rise times and/or fast fall times is challenging. For instance, to achieve a fast rise time and/or a fast fall time (e.g., less than about 50 ns) for a high voltage pulse (e.g., greater than about 5 kV), the slope of the pulse rise and/or fall must be incredibly steep (e.g., greater than 10^{11} V/s). Such steep rise times and/or fall times are very difficult to produce especially in circuits driving a load with high capacitance. Such pulses may be especially difficult to produce using standard electrical components; and/or with pulses having variable pulse widths, voltages, and repetition rates; and/or within applications having capacitive loads such as, for example, a plasma.

SUMMARY

Some embodiments may include a high voltage waveform generator comprising: a generator inductor; a high voltage nanosecond pulser electrically and/or inductively coupled with the generator inductor, the high voltage nanosecond pulser configured to charge the generator inductor with: a first pulse burst comprising a first plurality of high voltage pulses, each pulse of the first plurality of pulses having a pulse width, the first pulse burst having a first burst period; and a second pulse burst comprising a second plurality of high voltage pulses, each pulse of the second plurality of pulses having a pulse width, the second pulse burst having a second burst period; and a plasma electrically coupled with the nanosecond pulser and the generator inductor, the voltage across the plasma varying according to: a first plasma pulse having a first output pulse width and a first output voltage, the first output pulse width being substantially equal to the first burst period and the first output voltage being substantially proportional to a pulse width of each of the pulses of the first plurality of pulses, and a second plasma pulse having a second output pulse width and a second output voltage, the second output pulse width being substantially equal to the second burst period and the second output voltage being substantially proportional to a pulse width of each of the pulses of the second plurality of pulses.

In some embodiments, either or both the first pulse burst and the second pulse burst has an amplitude greater than 500 V. In some embodiments, either or both the first plasma pulse and the second plasma pulse has an amplitude greater than 500 V.

In some embodiments, the second pulse burst has an amplitude that is different than the amplitude of the first pulse burst. In some embodiments, wherein the amplitude of one or more of the first plurality of high voltage pulses is different

than amplitude of one or more of the other first plurality of high voltage pulses. In some embodiments, wherein the voltage of the first plasma pulse is different than the voltage of the second plasma pulse.

In some embodiments, the high voltage waveform generator may include a pulldown resistor electrically and/or inductively coupled with the generator inductor and the high voltage nanosecond pulser. In some embodiments, the high voltage waveform generator may include a transformer.

In some embodiments, the first burst period and/or the second burst period is less than about 50 ms. In some embodiments, either or both the first plasma pulse and the second plasma pulse establish a potential within the plasma.

In some embodiments, either or both the first plasma pulse and the second plasma pulse accelerate ions within the plasma. In some embodiments, either or both the first plurality of pulses and/or the second plurality of pulses have a frequency greater than about 50 kHz. In some embodiments, at least one pulse of the first plurality of pulses has a pulse width and/or at least one pulse of the second plurality of pulses has a pulse width less than 500 ns.

In some embodiments, the generator inductor comprises stray inductance. In some embodiments, the generator inductor has an inductance less than about 20 μH. In some embodiments, the peak output power is greater than 10 kW. In some embodiments, the plasma is substantially capacitive in nature.

Some embodiments may include a high voltage waveform generator comprising: a generator inductor; a generator capacitor electrically and/or inductively coupled with the generator inductor; a high voltage nanosecond pulser electrically or inductively coupled with the generator inductor and the generator capacitor, the high voltage nanosecond pulser configured to charge the generator inductor with a first pulse burst and a second pulse burst; and a load electrically and/or inductively coupled with the nanosecond pulser, the generator inductor, and the generator capacitor, the voltage across the load varying according to: a first load pulse and/or a second load pulse. In some embodiments, the first pulse burst comprises a plurality of high voltage pulses, each pulse of the plurality of pulses having a first pulse width and a voltage greater than 500 V, the first pulse burst having a first burst period; and/or the second pulse burst may comprise a plurality of high voltage pulses, each pulse of the plurality of pulses having a second pulse width and a voltage greater than 500 V, the second pulse burst having a second burst period. In some embodiments, the first load pulse may have a first output pulse width and a first output voltage, the first output pulse width being substantially equal to the first burst period and the first output voltage being proportional to the first

pulse width, and the second load pulse may have a second output pulse width and a second output voltage, the second output pulse width being substantially equal to the second burst period and the second output voltage being proportional to the second pulse width.

In some embodiments, the first pulse output voltage is greater than 500 V, and the second pulse output voltage is greater than 500 V. In some embodiments, the first pulse output voltage is greater than the second pulse output voltage. In some embodiments, the load comprises a plasma.

In some embodiments, the high voltage waveform generator may include a pulldown resistor electrically and/or inductively coupled with the generator inductor and the high voltage nanosecond pulser. In some embodiments, the high voltage waveform generator may include a transformer. In some embodiments, the first burst period is less than about 1 microsecond, the first pulse width is less than about 200 nanoseconds, and the second pulse width is less than about 200 nanoseconds.

Some embodiments of the invention include a method for generating high voltage waveforms. In some embodiments, the method may include generating a first pulse burst comprising a plurality of high voltage pulses, each pulse of the plurality of pulses having a first pulse width and a voltage greater than 500 V, the first pulse burst having a first burst period; charging a generator inductor with the first pulse burst; outputting a first output pulse having a first output pulse width and a first output voltage, the first output pulse width being substantially equal to the first burst period and the first output voltage being proportional to the first pulse width; generating a second pulse burst comprising a plurality of high voltage pulses, each pulse of the plurality of pulses having a second pulse width and a voltage greater than 500 V, the second pulse burst having a second burst period; charging a generator inductor with the second pulse burst; and outputting a second output pulse having a first output pulse width and a second output voltage, the second output pulse width being substantially equal to the second burst period and the second output voltage being proportional to the second pulse width.

In some embodiments, the first pulse output voltage is greater than 500 V, and the second pulse output voltage is greater than 500 V. In some embodiments, the first pulse output voltage is greater than the second pulse output voltage. In some embodiments, the first output pulse and the second output pulse is provided to a plasma. In some embodiments, the first

burst period is less than about 10 ms, the second burst period is less than about 10 ms, the first pulse width is less than 200 nanoseconds, and the second pulse width is less than 200 nanoseconds.

Some embodiments of the invention may include a high voltage waveform generator comprising: a generator inductor; a generator capacitor electrically and/or inductively coupled with the generator inductor; a high voltage nanosecond pulser electrically and/or inductively coupled with the generator inductor and the generator capacitor, the high voltage nanosecond pulser configured to charge the generator inductor with a first pulse burst and/or a second pulse burst; and a load electrically and/or inductively coupled with the nanosecond pulser, the generator inductor, and the generator capacitor, the voltage across the load varying according to a first load pulse and a second load pulse.

In some embodiments, the first pulse burst may comprise a plurality of high voltage pulses having a first voltage, each pulse of the plurality of pulses having a first pulse width and a voltage greater than 500 V, the first pulse burst having a first burst period. In some embodiments, the second pulse burst may comprise a plurality of high voltage pulses having a second voltage, each pulse of the plurality of pulses having a second pulse width and a voltage greater than 500 V, the second pulse burst having a second burst period.

In some embodiments the first load pulse may have a first output pulse width and a first output voltage, the first output pulse width being substantially equal to the first burst period and the first output voltage being a function of the first pulse width and/or the first voltage. In some embodiments, the second load pulse may have a second output pulse width and a second output voltage, the second output pulse width being substantially equal to the second burst period and the second output voltage being a function of the second pulse width and/or the second voltage.

In some embodiments, the load comprises a plasma. In some embodiments, the first burst period is less than about 10 ms, the second burst period is less than about 10 ms, the first pulse width is less than 200 nanoseconds, and the second pulse width is less than 200 nanoseconds.

Some embodiments of the invention include a high voltage waveform generator comprising a generator inductor; a generator capacitor electrically and/or inductively coupled with the generator inductor; a high voltage nanosecond pulser having one or more solid state switches electrically and/or inductively coupled with the generator inductor and the generator capacitor, the high voltage nanosecond pulser configured to produce a pulse burst having a burst period, the pulse burst

comprising a plurality of pulses having different pulse widths; and a load electrically and/or inductively coupled with the high voltage nanosecond pulser, the generator inductor, and the generator capacitor, the voltage across the load having an output pulse with a pulse width substantially equal to the burst period and the voltage across the load varying in a manner that is substantially proportional with the pulse widths of the plurality of pulses.

In some embodiments, the load comprises a plasma. In some embodiments, at least a subset of the plurality of pulses have pulse widths with increasingly larger widths and the absolute value of the voltage across the load increases. In some embodiments, the pulse burst has an amplitude greater than about 500 V.

BRIEF DESCRIPTION OF THE FIGURES

These and other features, aspects, and advantages of the present disclosure are better understood when the following Disclosure is read with reference to the accompanying drawings.

FIG. 1 is a block diagram of an example high voltage waveform generator according to some embodiments.

FIG. 2 is a block diagram of an example high voltage waveform generator according to some embodiments.

FIGs. 3A and 3B are block diagrams of example high voltage waveform generators according to some embodiments.

FIGs. 4A and 4B are block diagrams of example high voltage waveform generators according to some embodiments.

FIGs. 5A and 5B are block diagrams of example high voltage waveform generators according to some embodiments.

FIG. 6 is a block diagram of an example high voltage waveform generator according to some embodiments.

FIG. 7 is a circuit diagrams of an example high voltage waveform generator according to some embodiments.

FIG. 8 illustrates an example pulser waveform and an example high voltage waveform generator output waveform according to some embodiments.

FIG. 9 illustrates an example pulser waveform and an example high voltage waveform generator output waveform according to some embodiments.

FIG. 10 illustrates an example pulser waveform and an example high voltage waveform generator output waveform according to some embodiments.

FIG. 11 illustrates an example pulser waveform and an example high voltage waveform generator output waveform according to some embodiments.

FIG. 12 illustrates example waveforms within various circuit elements of a high voltage waveform generator according to some embodiments.

FIG. 13 illustrates example waveforms within various circuit elements of a high voltage waveform generator according to some embodiments.

FIG. 14 illustrates example waveforms within various circuit elements of a high voltage waveform generator according to some embodiments.

FIG. 15 illustrates an example pulser waveform and an example high voltage waveform generator output waveform according to some embodiments.

DETAILED DESCRIPTION

Systems and methods are disclosed to generate high voltage waveforms with arbitrary pulse widths, voltages, and/or shapes. In some embodiments, a high voltage waveform generator may include a pulser (e.g., a nanosecond pulser) and a generator circuit. For example, a nanosecond pulser may produce a burst of high voltage pulses having a burst period T_{br} and each pulse of the burst of pulses having a pulse width T_p. The generator circuit may produce an output pulse from the input burst of high voltage pulses. The output pulse, for example, may have a pulse width approximately the same as the burst period T_{br}. The output pulse, for example, may have a voltage that is a function of (e.g., proportional to) the pulse width T_p of each pulse of the burst of pulses. The output pulse, for example, may have a voltage that is a function of (e.g., proportional to) the voltage V_p of the input pulses, or the frequency of the input pulses, f_p.

In some embodiments, the peak power of the output pulses may be greater than about 1 kW, 10 kW, 100 kW, 1,000 kW, 10,000 kW, etc.

In some embodiments, the pulser may produce a burst train. Each burst train, for example, may include a plurality of bursts and each of the plurality of bursts may include a plurality of pulses. Each burst of the plurality of bursts (e.g., N bursts) may have a burst period (e.g., T_{br1}, T_{br2}, T_{br3}, ... T_{brN}). The resulting output of the high voltage waveform generator may include a plurality of pulse widths (e.g., PW_{br1}, PW_{br2}, PW_{br3}, ... PW_{brN}) proportional (e.g., roughly equal) to each burst period. In some embodiments, the burst periods may vary resulting in variable output pulse widths. In some embodiments, the output voltage amplitude may be proportional to the pulse width of each pulse within a burst. The voltage of each output pulse may also be proportional to the voltage and frequency of the input pulse burst.

FIG. 1 is a block diagram of an example high voltage waveform generator 100 according to some embodiments. The high voltage waveform generator 100 may include a nanosecond pulser 105 and a load 110. The nanosecond pulser 105 may be electrically and/or inductively coupled with the load 110 via the diode 125, a generator inductor 115, and/or a generator capacitor 120. An additional inductor 116 may also be included. The shape of the waveform across the load 110 may be set by the pulse width of the nanosecond pulser 105 and/or the pulse frequency (or burst period) of the nanosecond pulser 105, and/or the pulse voltage of the nanosecond pulser 105.

In some embodiments, the additional inductor 116 may not be included. In some embodiments, the additional inductor 116 and the generator inductor 115 may not be included.

The nanosecond pulser 105, for example, may include any device capable of producing pulses greater than 500 V, peak current greater than 10 Amps, and/or pulse widths of less than about 10,000 ns, 1,000 ns, 100 ns, 10 ns, etc. As another example, the nanosecond pulser 105 may produce pulses with an amplitude greater than 1 kV, 5 kV, 10 kV, 50 kV, 200 kV, etc. As another example, the nanosecond pulser 105 may also produces pulse with rise times less than about 5 ns, 50 ns, or 300 ns, etc.

The nanosecond pulser 105 may, for example, include any pulser described in U.S. Patent Application Serial No. 14/542,487, titled "HIGH VOLTAGE NANOSECOND PULSER", which is incorporated into this disclosure in its entirety for all purposes.

The nanosecond pulser 105 may, for example, include any pulser described in U.S. Patent No. 9,601,283, titled "EFFICIENT IGBT SWITCHING", which is incorporated into this disclosure in its entirety for all purposes.

The nanosecond pulser 105 may, for example, include any pulser described in U.S. Patent Application Serial No. 15/365,094, titled "HIGH VOLTAGE TRANSFORMER", which is incorporated into this disclosure in its entirety for all purposes.

The nanosecond pulser 105 may, for example, include a high voltage switch. For example, the nanosecond pulser 105 may, for example, include any switch described in U.S. Patent Application Serial Number 62/717,637, filed August 10, 2018, titled "HIGH VOLTAGE SWITCH WITH ISOLATED POWER", which is incorporated into this disclosure in its entirety for all purposes.

In some embodiments, the nanosecond pulser 105 may include one or more solid state switches such as, for example, an IGBT, a MOSFET, a SiC MOSFET, SiC junction transistor, FETs, SiC switches, GaN switches, photoconductive switch, etc.

In some embodiments, the generator inductor 115, for example, may include any inductor having an inductance less than about 3 μH. In some embodiments, the generator inductor 115 may represent stray inductance within the circuit such as, for example, within leads from the nanosecond pulser to other components in the circuit, or other circuit components. In some embodiments, the generator inductor 115 may have an inductance less than 1 μH, 0.1 μH, and 10 nH, 1 μH, 10 μH, 50 μH, etc.

In some embodiments, the additional inductor 116, for example, may include any inductor having an inductance less than about 3 μH. In some embodiments, the additional inductor 116 may represent stray inductance within the circuit such as, for example, within leads from the nanosecond pulser to other components in the circuit, or other circuit components. In some embodiments, the additional inductor 116 may have an inductance less than 1 μH, 0.1 μH, 10 nH, 1 μH, 10 μH, 50 μH, etc.

The generator capacitor 120, for example, may include any capacitor having a capacitance less than about 1 μF. For example, the generator capacitor 120 may have a capacitance be less than 1 μF, 10 μF, 100 nF, 100 pF, etc. The generator

capacitor 120 may represent stray capacitance within the circuit such as, for example, within the leads, or between other generator circuit components, or it may represent capacitance contained within the load 110.

In this example, when the nanosecond pulser 105 is turned on and produces a high voltage pulse (e.g., a pulse greater than about 500 V, 5 kV, 10 kV, 15 kV, etc.), energy from the pulse is injected into the generator inductor 115. The energy from the generator inductor 115 can then charge the generator capacitor 120. When the nanosecond pulser 105 is turned off, the energy in the generator inductor 115 can continue to charge the generator capacitor 120. If the pulse width of the high voltage pulse is long enough to completely charge the generator capacitor 120, the voltage across the generator capacitor 120 can be twice the voltage of the high voltage pulse. By varying the pulse width, the frequency, and/or the voltage of the high voltage pulses, the voltage across the generator capacitor 120 can be varied. For example, the voltage across the generator capacitor 120 may be proportional to the pulse width, frequency, and/or voltage of the high voltage pulse from the nanosecond pulser 105 as shown by the waveforms shown in FIGs. 8A, 8B, 8C, and 8D.

In some embodiments, the phrase "charge the inductor" can be used to describe energy is passed through the inductor and/or energy is stored within the inductor.

In some embodiments, generator inductor 115 may not be used to regulate how much energy charges the generator capacitor 120. Some energy from the nanosecond pulser 105 may end up in the generator inductor 115, however, much of the energy will just pass through the generator inductor 115 into the generator capacitor 120. Thus, in some embodiments, the generator inductor 115 and/or the additional inductor 116 may not be included.

FIG. 2 is a block diagram of an example high voltage waveform generator 200 according to some embodiments. In this example, the load is a plasma 111. The inductors 115 and/or 116 may not be present, or may consist of just the stray circuit inductance. The capacitance 120 may be part of the plasma's capacitance. The plasma may have a number of unique characteristics, such as, for example, a capacitance, an electron mobility, and an ion mobility that differs from the electron mobility. In this example, output pulses of variable voltages may be applied to the plasma 111. The plasma 111 may include any type of plasma that may include charged ions and/or charged radicals. In some embodiments, the plasma may be used in a semiconductor fabrication process. In some applications, the output pulse amplitude may be used to control the energy of the plasma ions. In some applications, the ions may be used to etch various materials. These materials may include wafers used in

the manμFacture of semiconductors. In some embodiments, the high voltage waveform generator 200 can be used to control the voltage applied across a plasma 111 or a plasma sheath.

FIG. 3A is a block diagram of an example high voltage waveform generator 300 according to some embodiments. In this example, the high voltage waveform generator 300 may include a driving cable 124 such as, for example, a coax cable or a twin lead cable.

In some embodiments, the generator capacitor 120, for example, may be in series with the load 110 as shown by circuit 350 in FIG. 3B.

FIG. 4A is a block diagram of an example high voltage waveform generator 400 according to some embodiments. In this example, the high voltage waveform generator 400 includes a transformer 121 between the nanosecond pulser 105 and the load 110. Either the generator L and or C may be present, and/or C might be in series with the load 110, for example. In some embodiments, the pulse generator 105 may also contain a transformer that may galvanically isolate the pulser output from its input.

In some embodiments, the generator capacitor 120 may be in series with the load 110 as shown in circuit 450 as shown in FIG. 4B.

FIG. 5A is a block diagram of an example high voltage waveform generator 500 according to some embodiments. In this example, the high voltage waveform generator 500 includes a pulldown resistor 130. A switch may also be included in series with the pulldown resistor 130. The pulldown resistor 130 may, for example, include any embodiment described in U.S. Patent Application Serial No. 15/941,731, titled "HIGH VOLTAGE PASSIVE OUTPUT STAGE CIRCUIT", which is incorporated into this disclosure in its entirety for all purposes.

In some embodiments, the generator capacitor 120 may be in series with the load 110 as shown in circuit 550 in FIG. 5B. In some embodiments, the generator capacitor 120 may be part of the load 110 and/or include all or part of the capacitance of the load 110. In some embodiments, the pull down resistor 130 may be placed before the generator capacitor 120, the effective load capacitance 115, and/or the diode 125, i.e. placed closer to generator 105.

FIG. 6 is a block diagram of an example high voltage waveform generator 600 according to some embodiments. In this example, the high voltage waveform generator 600 may include a load having an effective load capacitance 115, an

effective load current generator 140, and/or an effective load diode 142 and an effective system inductance 115. A plasma, for example, may be idealized by the effective current generator 140, the effective load diode 142, and the effective load capacitance 143. In some embodiments, the effective current generator 140 can represent the plasma ion current. In some embodiments, the ion plasma current can flow fairly steadily between the input pulses, for around the duration of the output pulse. In some embodiments, the effective load capacitance 143 can represent the capacitance formed in the plasma. In some embodiments, effective load capacitance 115 can represent the capacitance across the material/item/component being treated by the plasma, for example a semiconductor wafer being etched. In some embodiments, the effective load diode 142 can represent the electron mobility within the plasma, and/or the flow of current through the plasma driven by the input nanosecond pulses, that occurs around the duration of the input pulse burst.

FIG. 7 shows another example high voltage waveform generator 700 according to some embodiments. The high voltage waveform generator 700 can be generalized into five stages (these stages could be broken down into other stages or generalized into fewer stages). The high voltage waveform generator 700 includes pulser and transformer stage 706, a resistive output stage 707, a lead stage 710, a blocking capacitor and DC bias power supply stage 711, and a load stage 110.

In this example, the load stage 110 may represent an effective circuit for a plasma deposition system, plasma etch system, or plasma sputtering system. In some embodiments, the capacitance of capacitor C1 and/or capacitor C12 may be less than about 50 μF, 10 μF, 1 μF, 100 nF, etc. The capacitor C2 may represent the capacitance of the dielectric material upon which a wafer may sit. In some embodiments, the capacitor C2 may be less than about 50 μF, 10 μF, 1 μF, 100 nF, etc. The capacitor C3 may represent the sheath capacitance of the plasma to the wafer. In some embodiments, the capacitor C3 may be less than about 50 μF, 10 μF, 1 μF, 100 nF, etc. The capacitor C9 may represent capacitance within the plasma between a chamber wall and the top surface of the wafer. The current source I2 and the current source I1 may represent the ion current through the sheath.

In this example, the resistive output stage 707 may include one or more inductive elements represented by inductor L1 and/or inductor L5. The inductor L5, for example, may represent the stray inductance of the leads in the resistive output stage 707. Inductor L1 may be set to minimize the power that flows directly from the pulser and transformer stage 706 into resistor R1. In some embodiments, the resistance of resistor R1 can be less than about 2,000 Ohms, 200 Ohms, 20 Ohms, 2 Ohms, etc.

In some embodiments, the inductor L2, inductor L5, and/or inductor L6 may have an inductance less than about 100 μH, 10 μH, 1 μH, 100 nH, etc.

In some embodiments, the resistor R1 may dissipate charge from the load 110, for example, on fast time scales (e.g., 1 ns, 10 ns, 100 ns, 250 ns, 500 ns, 1,000 ns, etc. time scales). The resistance of resistor R1 may be low to ensure the pulse across the load 110 has a fast fall time t_f.

In some embodiments, the resistor R1 may include a plurality of resistors arranged in series and/or parallel. The capacitor C11 may represent the stray capacitance of the resistor R1 including the capacitance of the arrangement series and/or parallel resistors. The capacitance of stray capacitance C11, for example, may be less than 2000 pF, 500 pF, 250 pF, 100 pF, 50 pF, 10 pF, 1 pF, etc. The capacitance of stray capacitance C11, for example, may be less than the load capacitance such as, for example, less than the capacitance of C2, C3, and/or C9.

In some embodiments, a plurality of pulser and transformer stages 706 can be ganged up in parallel and coupled with the resistive output stage 707 across the inductor L1 and/or the resistor R1. Each of the plurality of pulser and transformer stages 706 may each also include diode D1 and/or diode D6. In some embodiments, the inductance of inductor L1 can be less than about 1,000 μH, 100 μH, 10 μH, etc.

In some embodiments, the capacitor C8 may represent the stray capacitance of the blocking diode D1. In some embodiments, the capacitor C4 may represent the stray capacitance of the diode D6.

In some embodiments, the DC bias power supply stage 711 may include DC a voltage source V1 that can be used to bias the output voltage either positively or negatively. In some embodiments, the capacitor C12 isolates/separates the DC bias voltage from the resistive output stage and other circuit elements. The capacitor C12 may be referenced as either a blocking capacitor and/or a bias capacitor. In some embodiments, capacitor C12 may comprise a single capacitive element, or numerous capacitive elements combined. In some embodiments, capacitor C12 may allow for a potential shift from one portion of the circuit to another. In some embodiments, the potential shift capacitor C12 establishes may be used to hold a wafer in place using electrostatic forces. In some embodiments, the capacitance of capacitor C12 may be less than about 1000 μF, 100 μF, 10 μF, 1 μF, etc.

Resistance R2 may protect/isolate the DC bias supply from the high voltage pulsed output from the pulser and transformer stage 706. In some embodiments, the DC bias power supply stage may contain additional elements such as switches, diodes, and capacitors, to help keep the electrostatic forces holding a wafer in place fairly constant in time, as the output pulse cycles on and off such as, for example, U.S. Patent Application Serial Number 62/711,406, filed August 10, 2018, titled "NANOSECOND PULSER BIAS COMPENSATION", which is incorporated into this disclosure in its entirety for all purposes.

In some embodiments, the pulser and transformer stage 706 may include a plurality of switches and a plurality of signal generators. A plurality of switches, for example, may allow the nanosecond pulser to produce higher frequency pulses.

In some embodiments, the voltage source V2 provides a consistent DC voltage that is switched by switch S1. Switch S1, for example, may include one or more solid state switches such as, for example, an IGBT, a MOSFET, a SiC MOSFET, SiC junction transistor, FETs, SiC switches, GaN switches, photoconductive switch, etc. Switch S1 may switch so fast that the switched voltage may never be at full voltage. For example, if voltage source V2 provides a DC voltage of 500 V, then the switch S1 may be turned on and turned off so quickly that the voltage across the switch is less than 500 V. In some embodiments, a gate resistor coupled with the switch S1 may be set with short turn on pulses.

FIG. 8A illustrates an example pulser waveform and FIG. 8B illustrates an example high voltage waveform generator output waveform according to some embodiments. In this example, the waveform produced by the pulser include two bursts: a first burst with a burst period B_1 with each pulse having a pulse width T_1; and a second burst with a burst period B_2 with each pulse having a pulse width T_2. The waveform output is the output of the waveform generator based on the waveform produced by the pulser. In this example, the waveform generator outputs two pulses: a first pulse having a pulse width PW_1 and a voltage V_1; and a second pulse having a pulse width PW_2 and a voltage V_2. In this example, the PW_1 is the same length as the burst period B_1 within 10%; and the first pulse voltage V_1 is a function of (e.g., proportional to) the pulse width T_1. In addition, the PW_2 is the same length as the burst period B_2 within 10%; and the first pulse voltage V_2 is a function of (e.g., proportional to) the pulse width T_2. PW_1 and PW_2 may have widths that deviate from B_1 and B_2 due to circuit phase delays, and the charging and discharging of various circuit elements. However, the input and output lengths are strongly correlated, with the input burst lengths being used to control the output pulse lengths. Load properties will also impact the exact

correlation between the input burst width and the output pulse width. The flatness of the output pulses may also vary based on the circuit elements selected, and/or may show a natural oscillation/response to the input pulses that comprise the burst.

In some embodiments, the time between pulses can be any value. In some embodiments, the time between pulses can be on the order of the pulse width of an individual pulse.

In some embodiments, the frequency of the pulses within each burst may be greater than about 1 kHz, 10 kHz, 100 kHz, 1,000 kHz, etc.

FIG. 8C illustrates an example pulser waveform and FIG. 8D illustrates an example high voltage waveform generator output waveform according to some embodiments. In this example, the input waveforms are inverted in comparison with those shown in FIG. 8A, resulting in inverted output waveforms shown in FIG. 8D. In this example, the pulse widths of the output pulses PW_1 and PW_2 are substantially similar to the burst period B_1 and B_2. The waveforms shown in FIGs. 9, 10, and 11 can likewise be inverted. . The flatness of the output pulses may also vary based on the circuit elements selected, and/or may show a natural oscillation/response to the input pulses that comprise the burst.

FIG. 9A illustrates an example waveform produced by the pulser and FIG. 9B illustrates an example high voltage waveform generator output waveform according to some embodiments. In this example, the first two pulses of the first burst of the pulser output as shown in FIG. 9A are shorter than the other pulses within the burst. This results in an output pulse that slowly ramps up to V_2 or V_1 as shown in FIG. 9B. This may be done to limit the peak output current and/or energy from the pulser.

The output waveforms shown in FIGs. 8B, 8D, and 9B may be referred to as a form of 'bi-level' control, where the intent is to apply a series of 1 or more output pulses of one voltage alternating with a series of one or more output pulses with a different voltage. For example, this may allow high energy ions to interact with a surface/material, followed by low energy ions interacting with a surface/material.

FIG. 10A illustrates an example waveform produced by the pulser and FIG. 10B illustrates an example high voltage waveform generator output waveform according to some embodiments. In this example, the pulse width of each pulse within a burst increases linearly as shown in FIG. 10A resulting in an output waveform voltage that similarly decreases linearly as shown in FIG. 10B.

FIG. 11A illustrates an example waveform produced by the pulser and FIG. 11B illustrates an example high voltage waveform generator output waveform according to some embodiments. In this example, three bursts having three different burst widths and the pulses within each burst have different pulse widths as shown in FIG. 11A. This results in three output pulses with three different pulse widths and different voltages as shown in FIG. 11B.

The shape of the output waveform can be dictated by the pulse width of each pulse within a burst and/or the burst width. Any shape of output waveform may be produced by varying these parameters. Such shapes may be repeated and interleaved with any other set of output pulse shapes, and may be done so in a repetitive manner. In some embodiments, the shape of the output waveform can be controlled/set by varying the voltage of the individual pulses. Varying the pulse width may vary the pulse voltage as well.

In some embodiments, multiple nanosecond pulsers may be phased together. For example, the nanosecond pulser 105 may include one or more pulsers phased together in parallel. This may, for example, generate output pulses from the waveform generator at higher frequencies.

FIG. 12 illustrates example waveforms within various circuit elements of a high voltage waveform generator according to some embodiments. The waveforms shown in FIG. 12 relate to the components shown in FIG. 7.

FIG. 13 and FIG. 14 illustrates example waveforms within various circuit elements of a high voltage waveform generator according to some embodiments. The waveforms shown in FIG. 12 relate to the components shown in FIG. 7.

In some embodiments, a high voltage waveform generator may use real time feedback to adjust the output voltage of an output waveform. For example, a circuit can determine that the voltage of an output waveform is lower than expected, in response the pulse width of the nanosecond pulser may be adjusted to produce the desired output pulse. Alternatively, the number of pulses within a burst may be adjusted, and/or their frequency may be adjusted.

In some embodiments, a plurality of pulsers may be used in a high voltage waveform generator 750. For example, a first pulser and a second pulser can be phased together with one or more switches. Linking together these pulses can be done to increase the frequency of the pulses provided to the load. In some embodiments, each of the pulsers may produce a different drive voltage.

In some embodiments, the resistor at the gate of one or more MOSFETs within the pulser may be selected to enable a working range between high levels and low levels in bi-level operation. In some embodiments, the resistor at the gate of one or more MOSFETs may provide short circuit protection. In some embodiments, different gate voltages may be applied to one or more MOSFETs within the pulser.

In some embodiments, the turn on time of one or more switches within the nanosecond pulser 105 may result in lower output voltage from the pulser when the pulse width is less than the rise time. This is illustrated in FIG. 15C. V_3, for example, may be 5kV or greater and V_4, for example, may be greater than 200 volts.

A pulser may include a high voltage DC input and a low voltage DC waveform for controlling the solid-state switches or gate voltage. The waveform shown in FIG. 15A shows the gate voltage with two bursts each having a burst period, B_1 and B_2, and the pulses within each burst having a different pulse width. The waveform in FIG. 15B shows example pulses produced by the pulser (e.g., the voltage across R1 in FIG. 7). The voltage of the pulses within the first burst are at V_1 and the pulses within the second burst are at V_2. The pulse voltages in the second burst are lower because the gate voltage pulse widths are shorter. Specifically, the gate voltage pulses are sufficiently short that the pulser switches do not have time to fully turn on, (e.g., reach their peak output voltage) before the pulse switches are turned back off by the gate input pulse. The waveform in FIG. 15D is the voltage across the switch in the pulser (e.g., switch S1 in FIG. 7). The switches are gated on for a sufficiently short period that the voltage across the switch is never able to fall to the low level that it would normally be for a switch fully turned on and in full conduction. The resulting output waveform shown in FIG. 15C has two voltage levels. The second voltage level is a function of the pulse width of the gate voltage waveform (FIG. 15A). Because the pulse widths of the second pulses are shorter than the switch rise time, or the switch turn-on time, or the switch time needed to reach full conduction, lower voltage pulses are produced by the pulser. The second voltage level in FIG. 15C is a function of the pulse width and the voltage produced by the pulser shown in FIG. 15B. The gate resistance of one or more switches in the pulser may determine the rise time and voltage of the pulses provided by the pulser.

In some embodiments, the output voltage shown in FIG. 15C is a function of single pulses shown in FIG. 15A. In some embodiments, output voltage control is provided using the switches to control output voltage. Some embodiments may enable very fast, nanosecond timescale, output voltage modulation, at bi-level voltage output. This can, for example, allow for fast voltage modulation (e.g., greater than 1 MHz).

Numerous specific details are set forth herein to provide a thorough understanding of the claimed subject matter. However, those skilled in the art will understand that the claimed subject matter may be practiced without these specific details. In other instances, methods, apparatuses or systems that would be known by one of ordinary skill have not been described in detail so as not to obscure claimed subject matter.

Some portions are presented in terms of algorithms or symbolic representations of operations on data bits or binary digital signals stored within a computing system memory, such as a computer memory. These algorithmic descriptions or representations are examples of techniques used by those of ordinary skill in the data processing arts to convey the substance of their work to others skilled in the art. An algorithm is a self-consistent sequence of operations or similar processing leading to a desired result. In this context, operations or processing involves physical manipulation of physical quantities. Typically, although not necessarily, such quantities may take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared or otherwise manipulated. It has proven convenient at times, principally for reasons of common usage, to refer to such signals as bits, data, values, elements, symbols, characters, terms, numbers, numerals or the like. It should be understood, however, that all of these and similar terms are to be associated with appropriate physical quantities and are merely convenient labels. Unless specifically stated otherwise, it is appreciated that throughout this specification discussions utilizing terms such as "processing," "computing," "calculating," "determining," and "identifying" or the like refer to actions or processes of a computing device, such as one or more computers or a similar electronic computing device or devices, that manipulate or transform data represented as physical electronic or magnetic quantities within memories, registers, or other information storage devices, transmission devices, or display devices of the computing platform.

The system or systems discussed herein are not limited to any particular hardware architecture or configuration. A computing device can include any suitable arrangement of components that provides a result conditioned on one or more inputs. Suitable computing devices include multipurpose microprocessor-based computer systems accessing stored software that programs or configures the computing system from a general purpose computing apparatus to a specialized computing apparatus implementing one or more embodiments of the present subject matter. Any suitable programming, scripting, or other type of language or combinations of languages may be used to implement the teachings contained herein in software to be used in programming or configuring a computing device.

Embodiments of the methods disclosed herein may be performed in the operation of such computing devices. The order of the blocks presented in the examples above can be varied—for example, blocks can be re-ordered, combined, and/or broken into sub-blocks. Certain blocks or processes can be performed in parallel.

The use of "adapted to" or "configured to" herein is meant as open and inclusive language that does not foreclose devices adapted to or configured to perform additional tasks or steps. Additionally, the use of "based on" is meant to be open and inclusive, in that a process, step, calculation, or other action "based on" one or more recited conditions or values may, in practice, be based on additional conditions or values beyond those recited. Headings, lists, and numbering included herein are for ease of explanation only and are not meant to be limiting.

The terms "first" and "second" are not necessarily used to identify the absolute or very first or second of sequence of items. Rather, these terms are used solely to label an item and a different or subsequent item unless the meaning is clear that the terms are meant to specify a specific order or absolute position. The order of the items labeled with "first" and "second" may or may not be the absolute order and/or may include other items in between.

While the present subject matter has been described in detail with respect to specific embodiments thereof, it will be appreciated that those skilled in the art, upon attaining an understanding of the foregoing, may readily produce alterations to, variations of, and equivalents to such embodiments. Accordingly, it should be understood that the present disclosure has been presented for purposes of example rather than limitation, and does not preclude inclusion of such modifications, variations and/or additions to the present subject matter as would be readily apparent to one of ordinary skill in the art.

CLAIMS

That which is claimed:

1. A high voltage waveform generator comprising:

a generator inductor;

a high voltage nanosecond pulser electrically and/or inductively coupled with the generator inductor, the high voltage nanosecond pulser configured to charge the generator inductor with:

a first pulse burst comprising a first plurality of high voltage pulses, each pulse of the first plurality of pulses having a pulse width, the first pulse burst having a first burst period; and

a second pulse burst comprising a second plurality of high voltage pulses, each pulse of the second plurality of pulses having a pulse width, the second pulse burst having a second burst period; and

a plasma coupled with the nanosecond pulser and the generator inductor, the voltage across the plasma varying according to:

a first plasma pulse having a first output pulse width and a first output voltage, the first output pulse width being substantially equal to the first burst period and the first output voltage being substantially proportional to a pulse width of each of the pulses of the first plurality of pulses, and

a second plasma pulse having a second output pulse width and a second output voltage, the second output pulse width being substantially equal to the second burst period and the second output voltage being substantially proportional to a pulse width of each of the pulses of the second plurality of pulses.

2. The high voltage waveform generator according to claim 1, wherein either or both the first pulse burst and the second pulse burst has an amplitude greater than 500 V.

3. The high voltage waveform generator according to claim 1, wherein either or both the first plasma pulse and the second plasma pulse has an amplitude greater than 500 V.

4. The high voltage waveform generator according to claim 1, wherein the second pulse burst has an amplitude that is different than the amplitude of the first pulse burst.

5. The high voltage waveform generator according to claim 1, wherein the amplitude of one or more of the first plurality of high voltage pulses is different than amplitude of one or more of the other first plurality of high voltage pulses.

6. The high voltage waveform generator according to claim 1, wherein the voltage of the first plasma pulse is different than the voltage of the second plasma pulse.

7. The high voltage waveform generator according to claim 1, further comprising a pulldown resistor electrically and/or inductively coupled with the generator inductor and the high voltage nanosecond pulser.

8. The high voltage waveform generator according to claim 1, further comprising a transformer.

9. The high voltage waveform generator according to claim 1, wherein the first burst period and/or the second burst period is less than about 50 ms.

10. The high voltage waveform generator according to claim 1, wherein either or both the first plasma pulse and the second plasma pulse establish a potential within the plasma.

11. The high voltage waveform generator according to claim 1, wherein either or both the first plasma pulse and the second plasma pulse accelerate ions within the plasma.

12. The high voltage waveform generator according to claim 1, wherein either or both the first plurality of pulses and/or the second plurality of pulses have a frequency greater than about 50 kHz.

13. The high voltage waveform generator according to claim 1, wherein at least one pulse of the first plurality of pulses has a pulse width and/or at least one pulse of the second plurality of pulses has a pulse width less than 500 ns.

14. The high voltage waveform generator according to claim 1, wherein the generator inductor comprises stray inductance.

15. The high voltage waveform generator according to claim 1, wherein the generator inductor has an inductance less than about 20 μH.

16. The high voltage waveform generator according to claim 1, wherein the peak output power is greater than 10 kW.

17. The high voltage waveform generator according to claim 1, wherein the plasma is substantially capacitive in nature.

18. A method for generating high voltage waveforms within a plasma, the method comprising:

generating a first pulse burst comprising a first plurality of high voltage pulses, each pulse of the first plurality of pulses having a pulse width and a voltage greater than 500 V, the first pulse burst having a first burst period;

charging a generator inductor with the first pulse burst;

outputting a first output pulse having a first output pulse width and a first output voltage, the first output pulse width being substantially equal to the first burst period and the first output voltage being substantially proportional to the pulse width of each of the first plurality of pulses;

generating a second pulse burst comprising a plurality of high voltage pulses, each pulse of the second plurality of pulses having a pulse width, the second pulse burst having a second burst period;

charging a generator inductor with the second pulse burst; and

outputting a second output pulse having a first output pulse width and a second output voltage, the second output pulse width being substantially equal to the second burst period and the second output voltage being substantially proportional to the pulse width of each of the second plurality of pulses.

19. The method according to claim 18, wherein the first output pulse and the second output pulse are applied to a plasma.

20. The method according to claim 18, wherein the first output pulse and the second output pulse accelerate ions within a plasma.

21. The method according to claim 18, wherein charging the generator inductor comprises passing energy through the generator inductor.

22. The method according to claim 18, wherein at least one pulse of the first plurality of pulses has a pulse width and/or at least one pulse of the second plurality of pulses has a pulse width less than 500 ns.

23. The method according to claim 18, wherein at least one pulse of the first plurality of pulses has a different pulse width and/or at least one pulse of the second plurality of pulses has a different pulse width.

24. The method according to claim 18, wherein the amplitude of one or more of the first plurality of pulses is different than amplitude of one or more of the other first plurality of pulses.

25. A high voltage waveform generator comprising:

a generator inductor;

a high voltage nanosecond pulser having one or more solid state switches electrically coupled with the generator inductor, the high voltage nanosecond pulser configured to produce a pulse burst having a burst period, the pulse burst comprising a plurality of pulses having different pulse widths; and

a plasma electrically coupled with the high voltage nanosecond pulser and the generator inductor, the voltage across the plasma having an output pulse with a pulse width substantially equal to the burst period and the voltage across the plasma varying in a manner that is substantially proportional with the pulse widths of the plurality of pulses.

26. The high voltage waveform generator according to claim 25, wherein at least a subset of the plurality of pulses have pulse widths with increasingly larger pulse widths and the absolute value of the voltage across the plasma increases.

27. The high voltage waveform generator according to claim 25, wherein at least a subset of the plurality of pulses have pulse widths with decreasingly smaller pulse widths and the absolute value of the voltage across the plasma decrease.

28. The high voltage waveform generator according to claim 25, wherein the voltage across the plasma accelerates ions within the plasma.

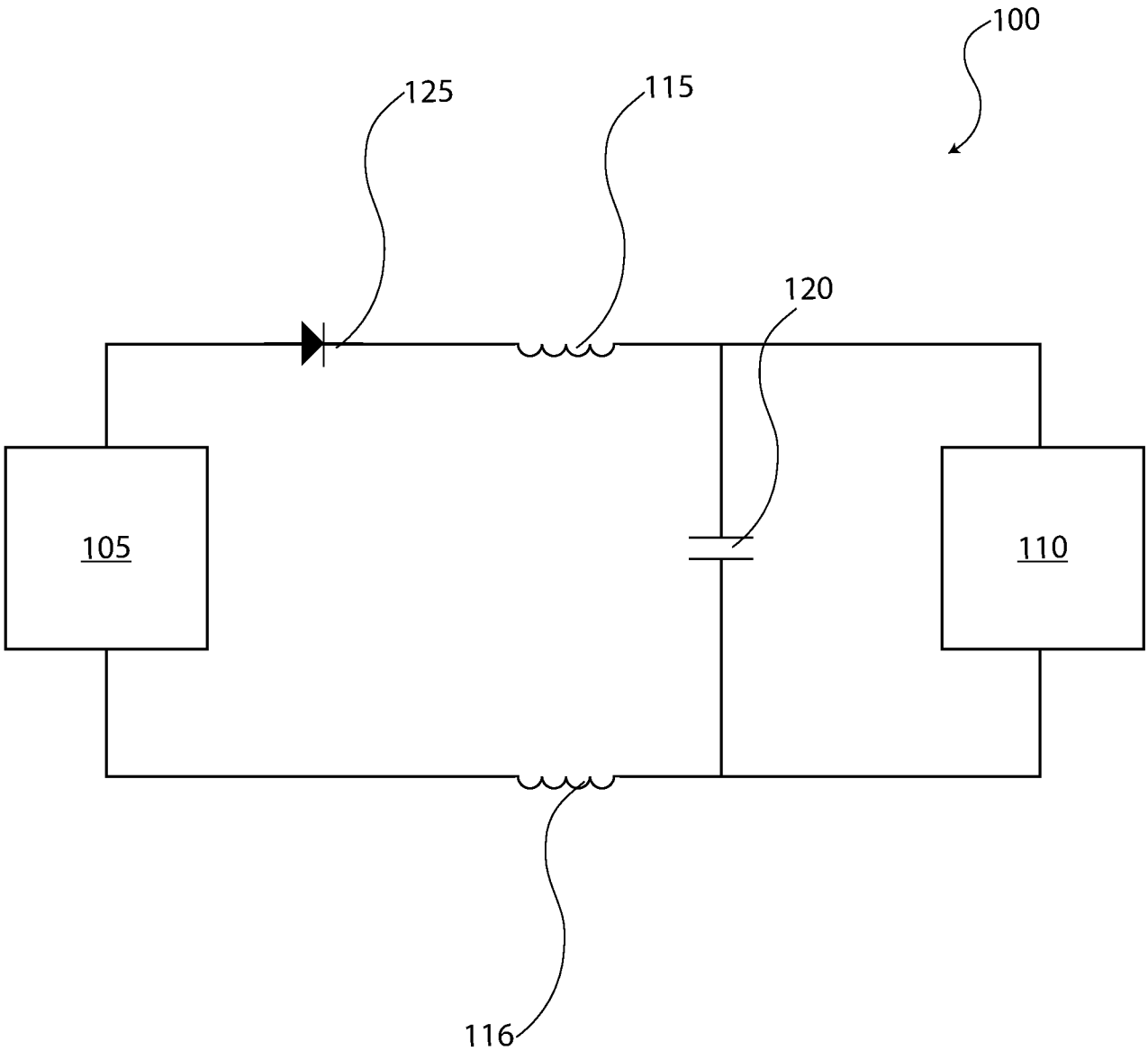


FIG. 1

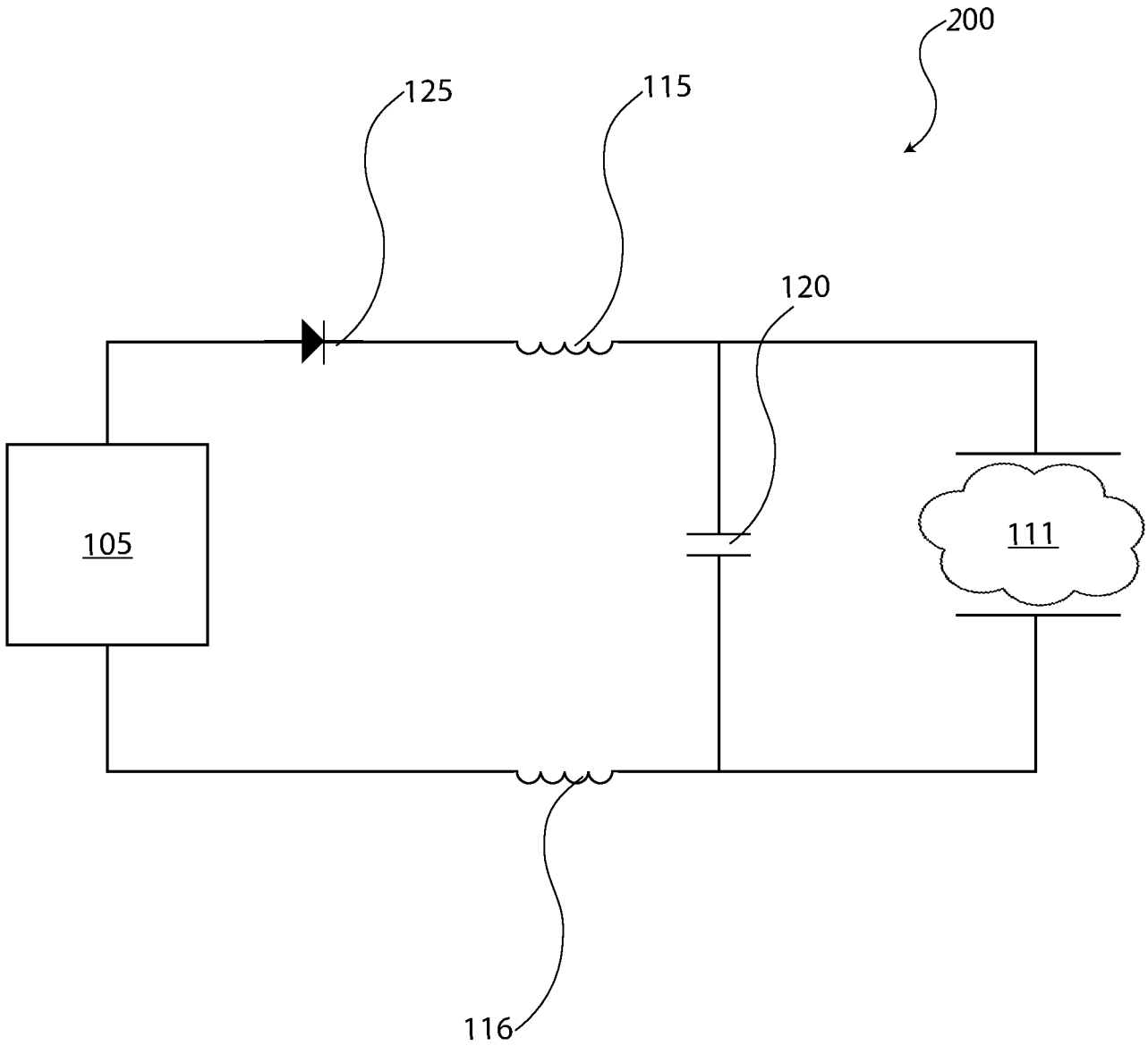


FIG. 2

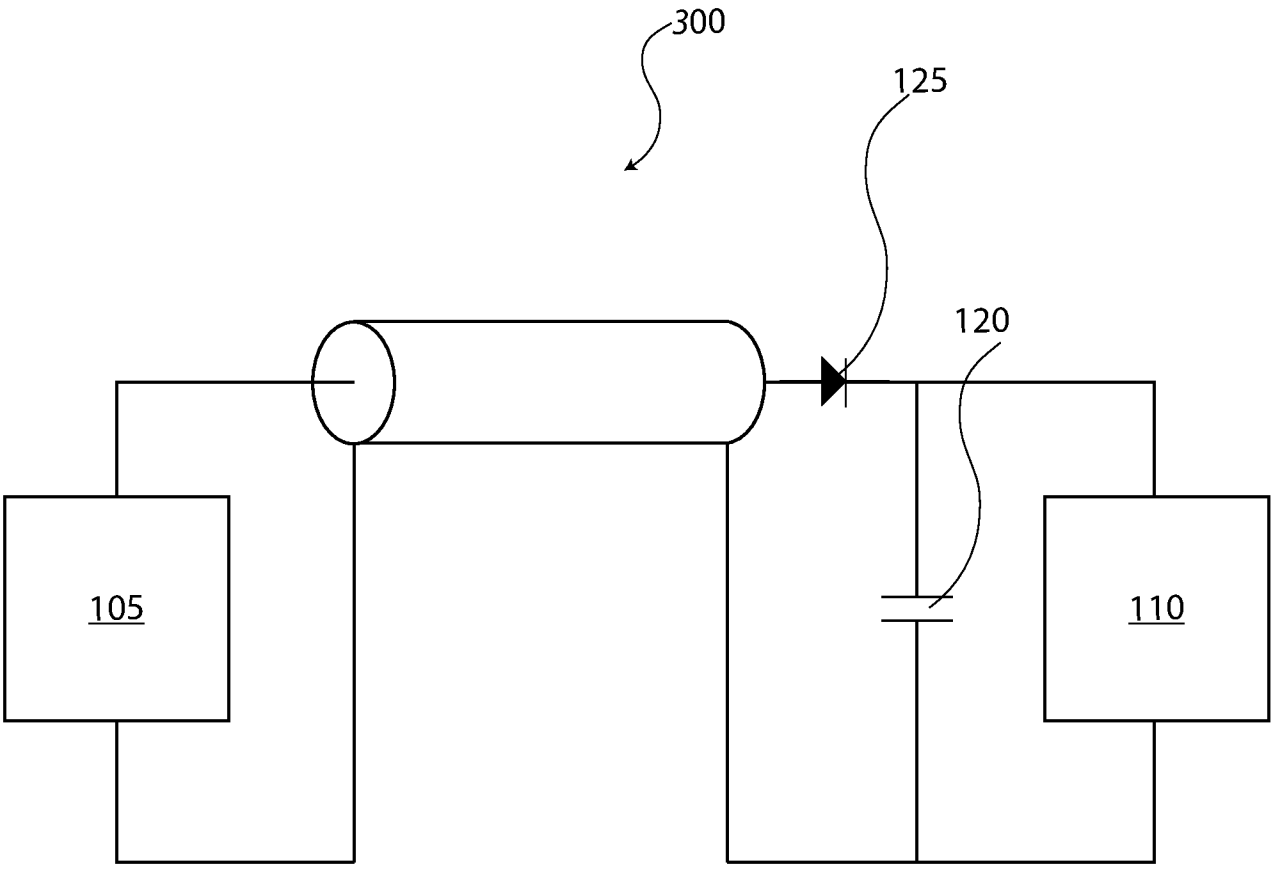


FIG. 3A

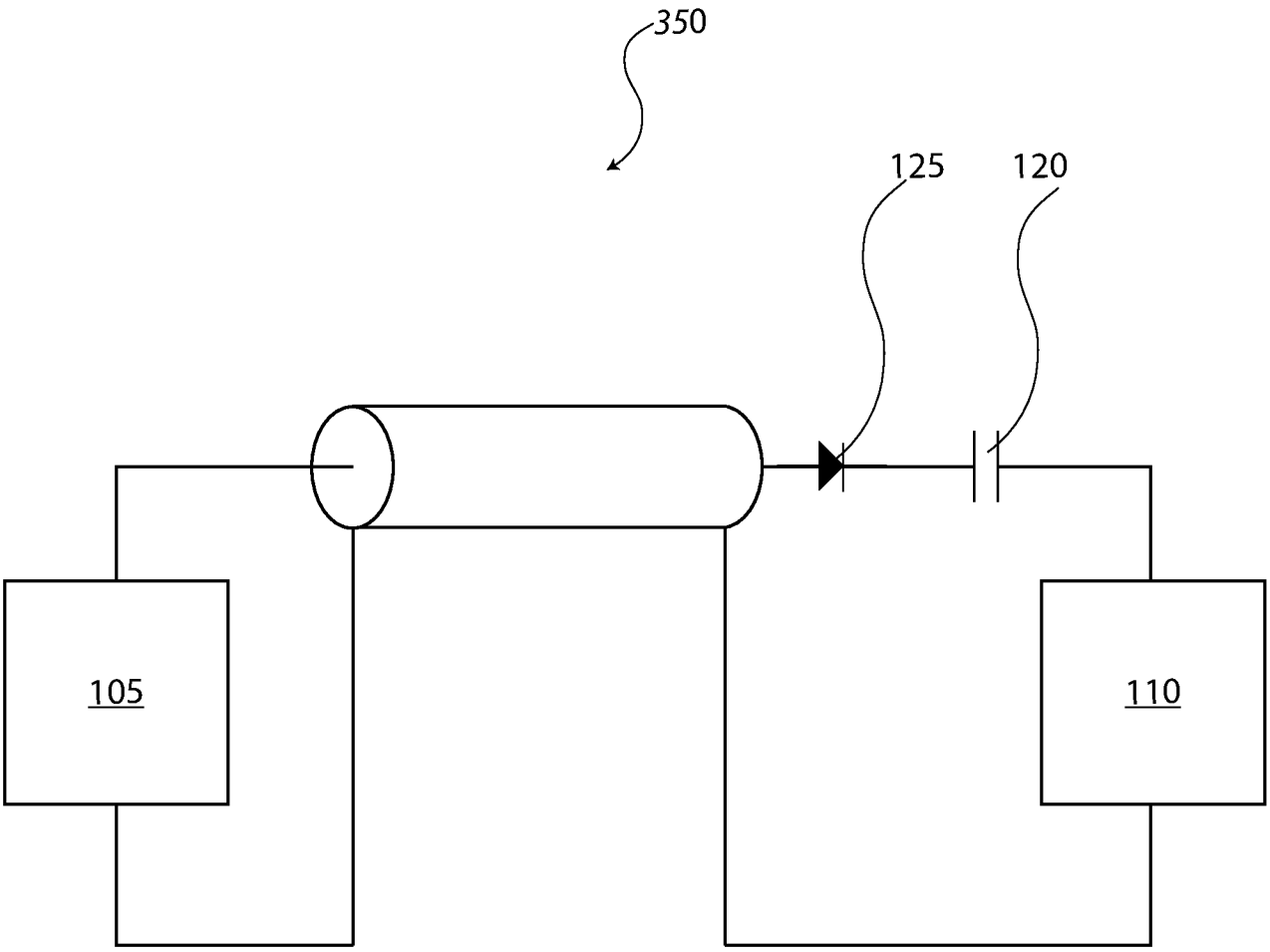


FIG. 3B

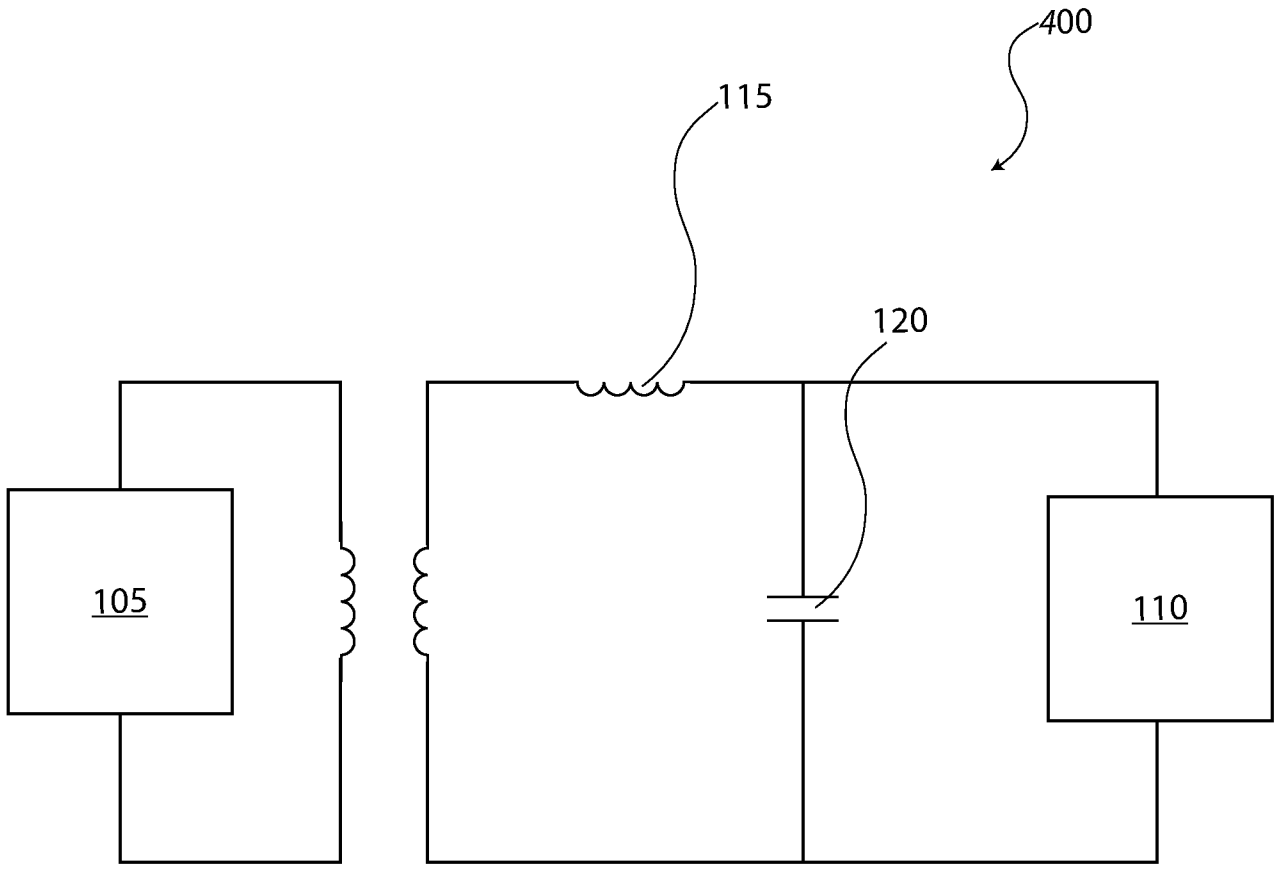


FIG. 4A

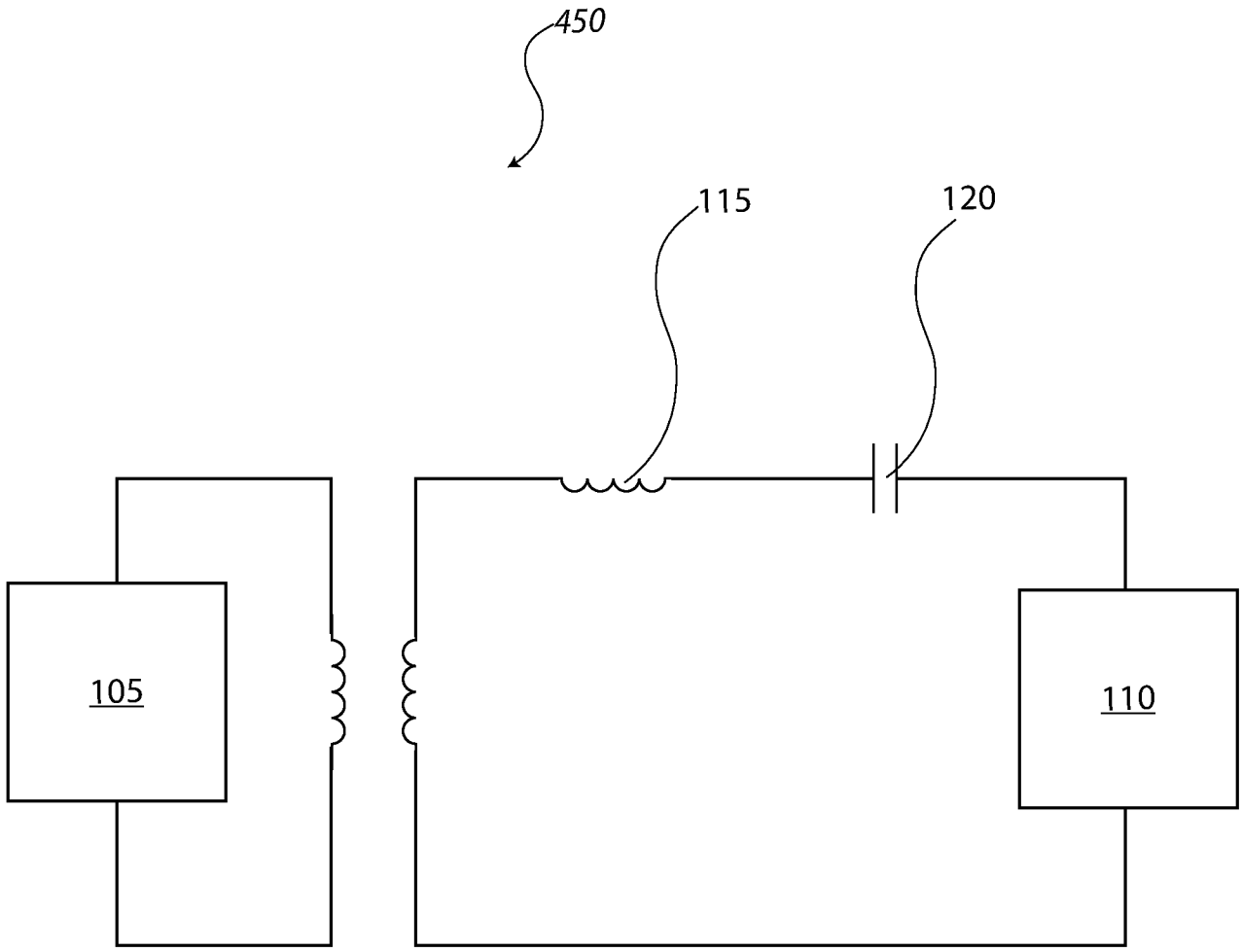


FIG. 4B

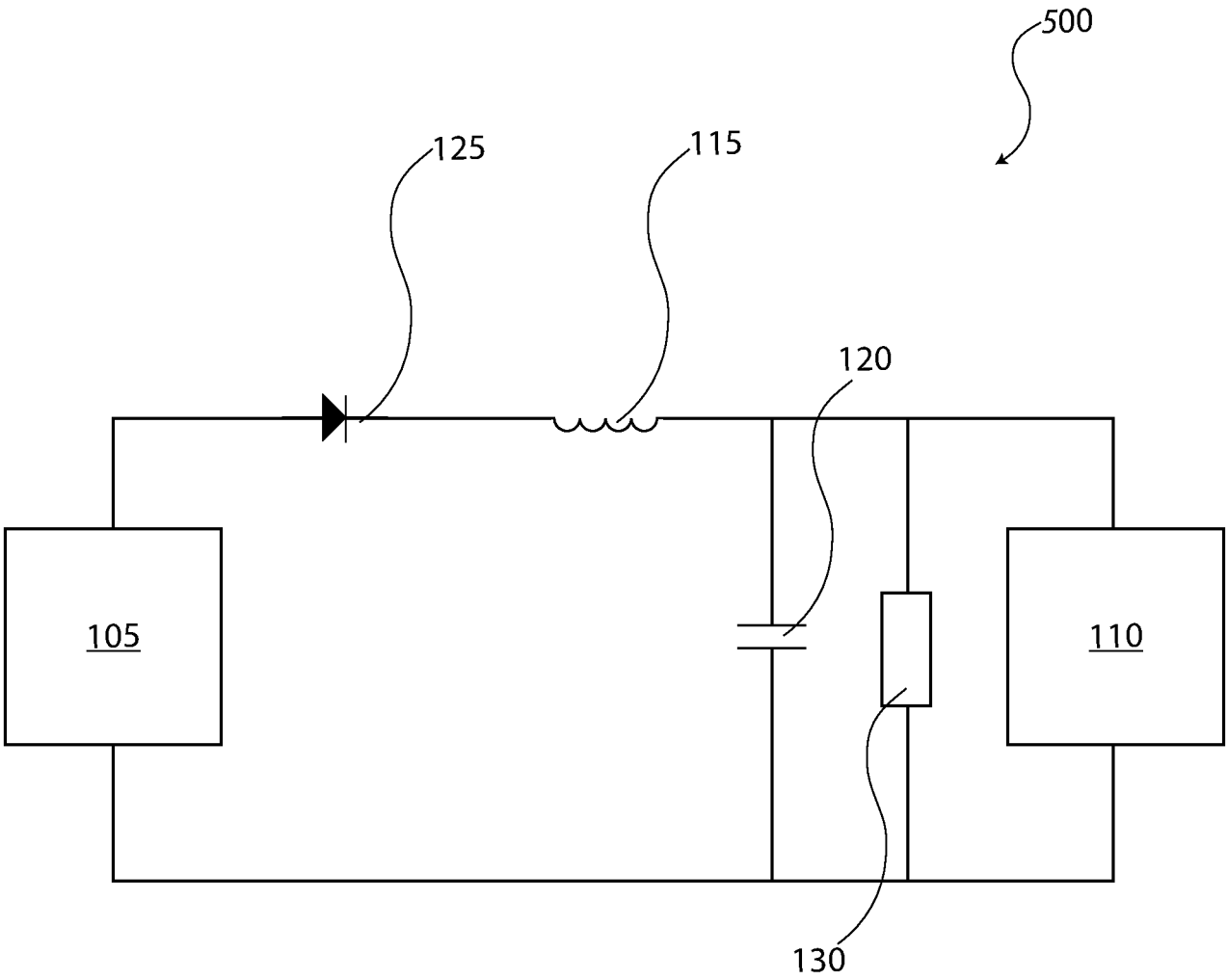


FIG. 5A

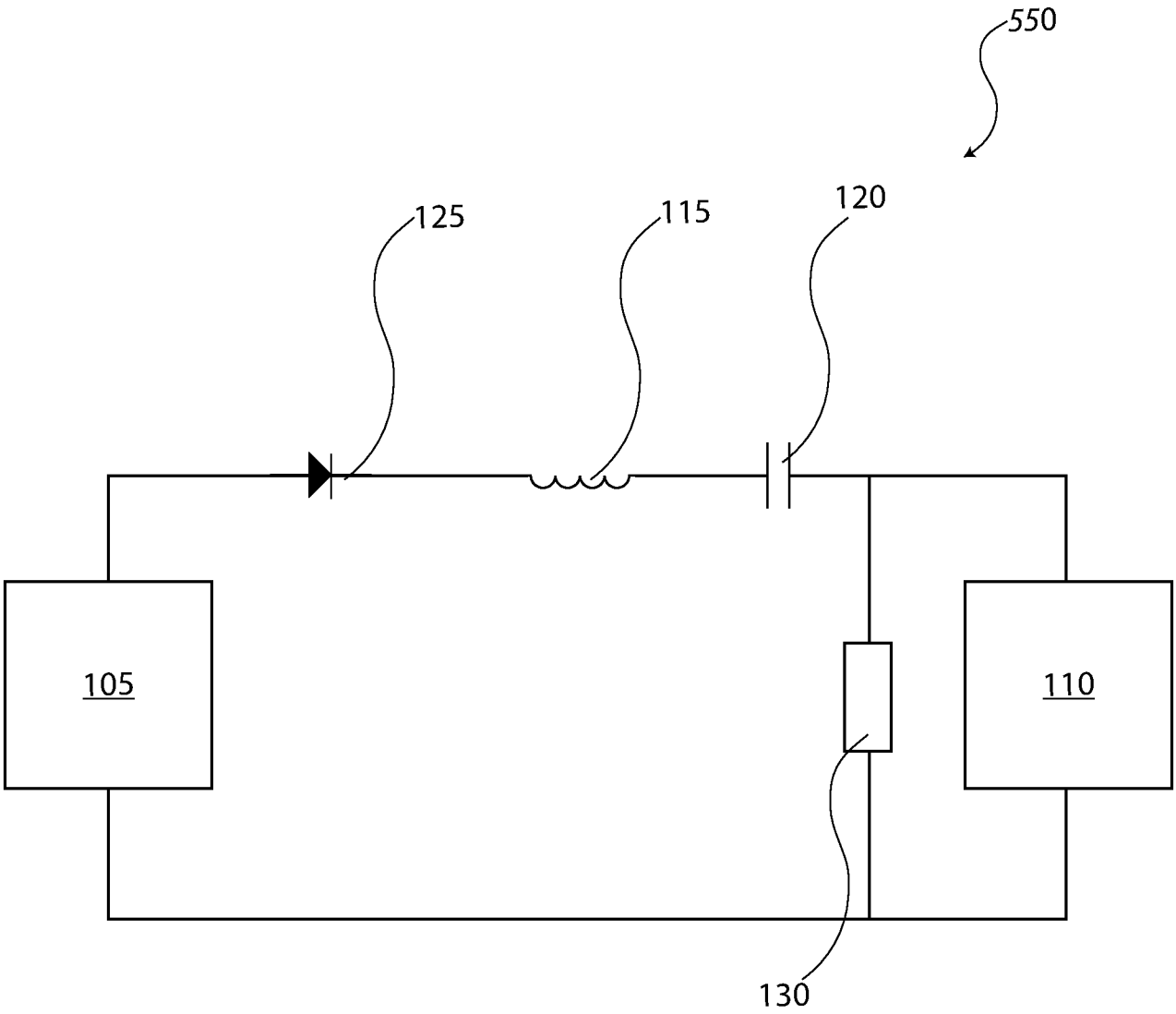


FIG. 5B

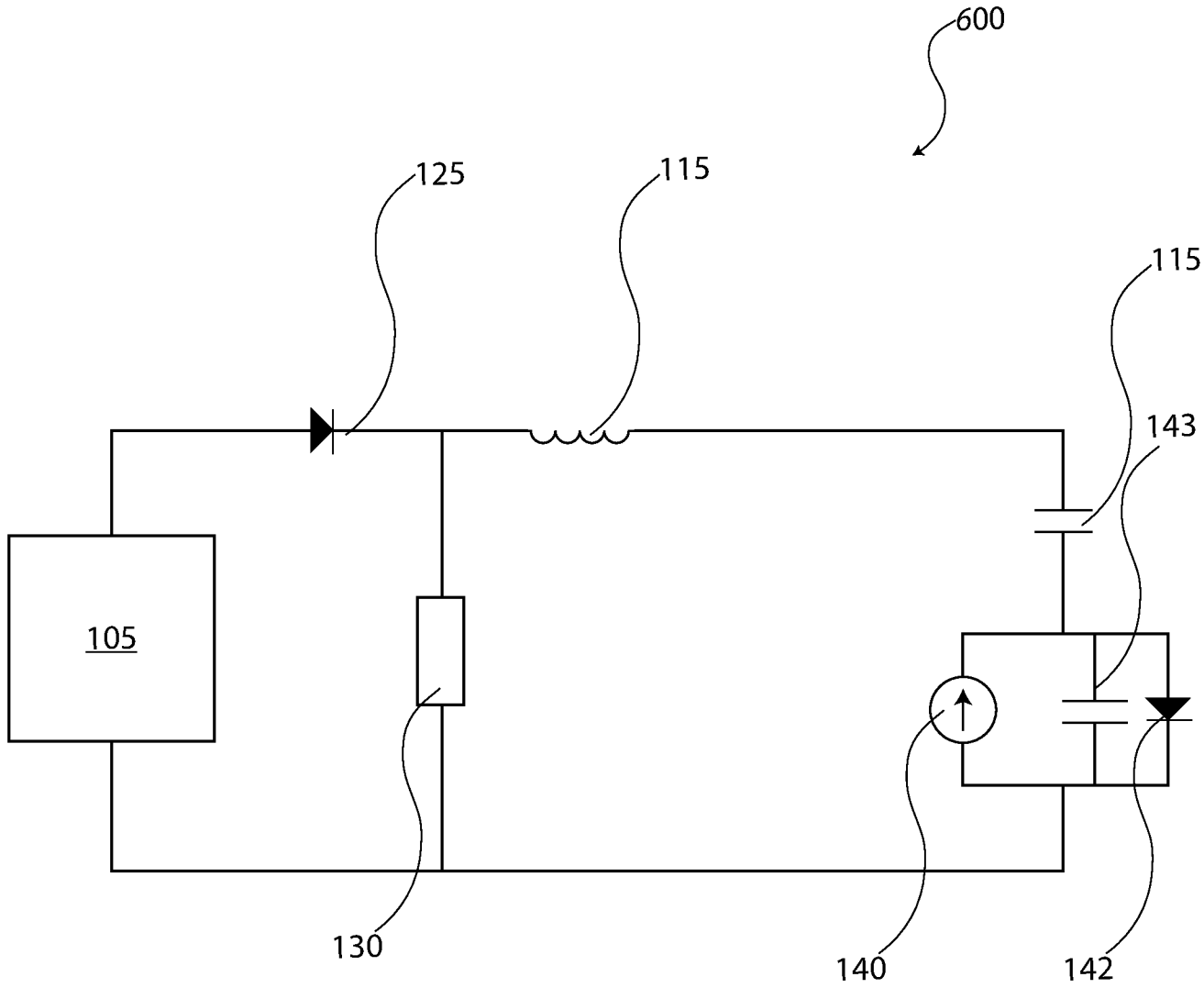


FIG. 6

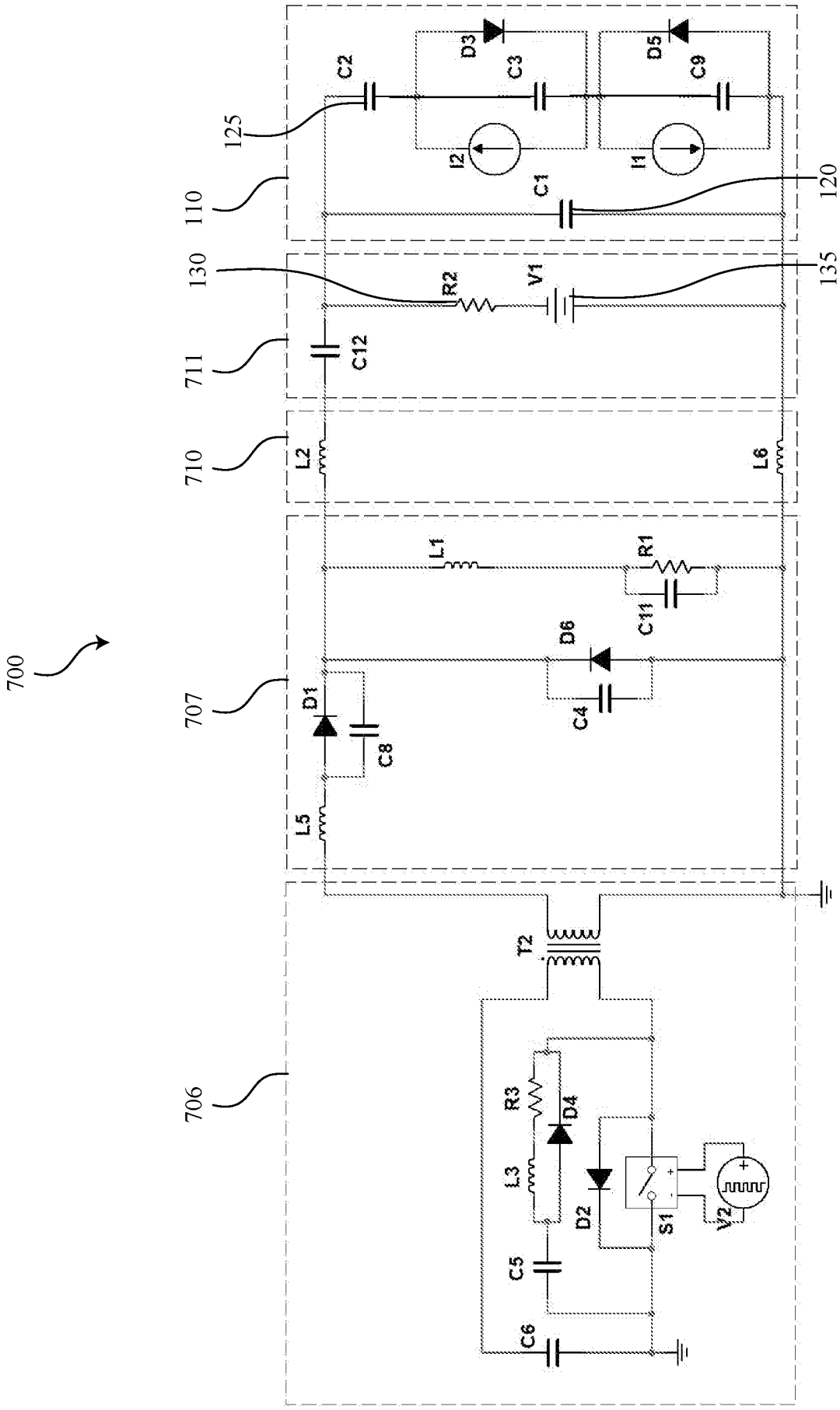

700
706
707
710
711
110
130
125
120
135
C1
C2
C3
C4
C5
C6
C8
C9
C11
C12
D1
D2
D3
D4
D5
D6
I1
I2
L1
L2
L3
L5
L6
R1
R2
R3
S1
T2
V1
V2

FIG. 7

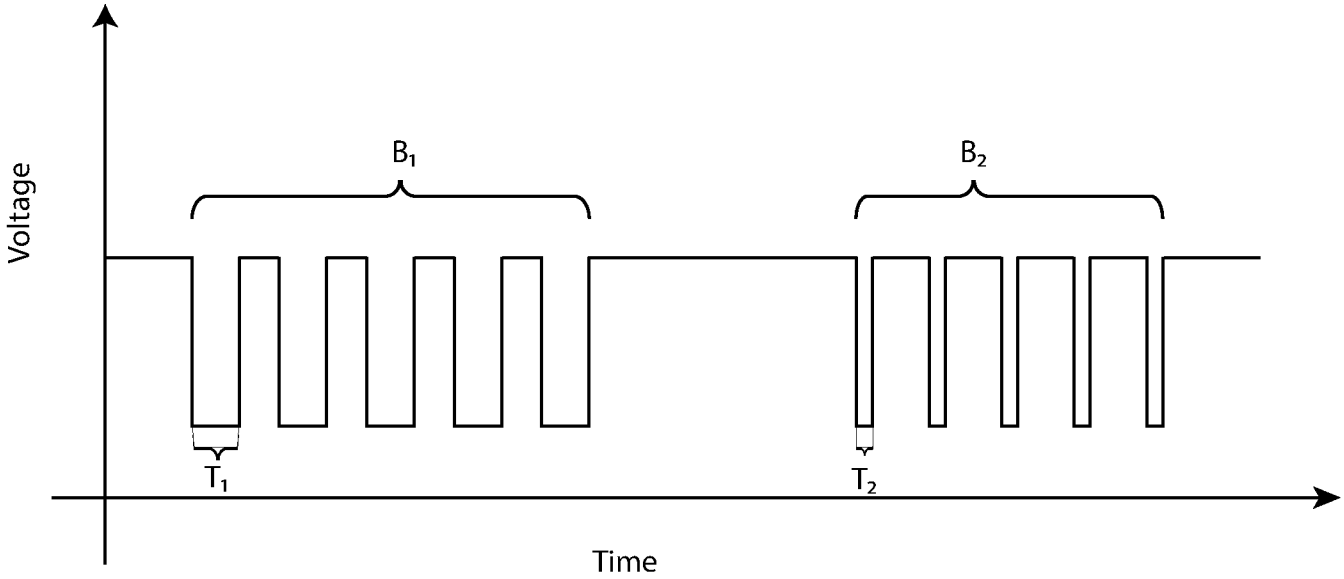


FIG. 8A

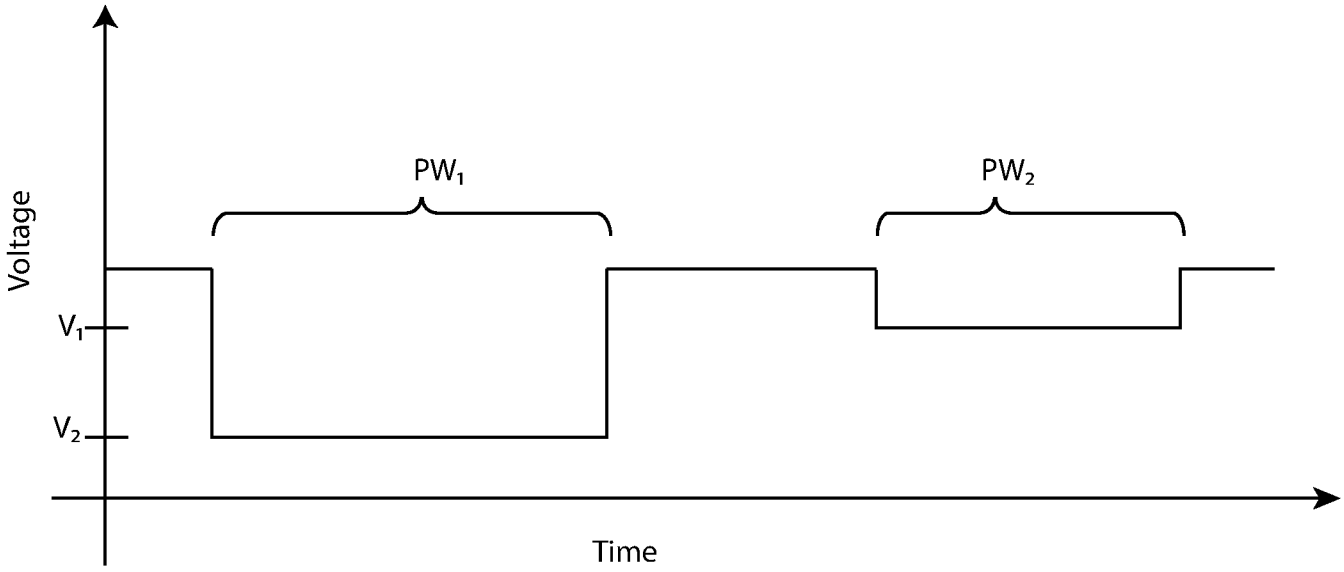


FIG. 8B

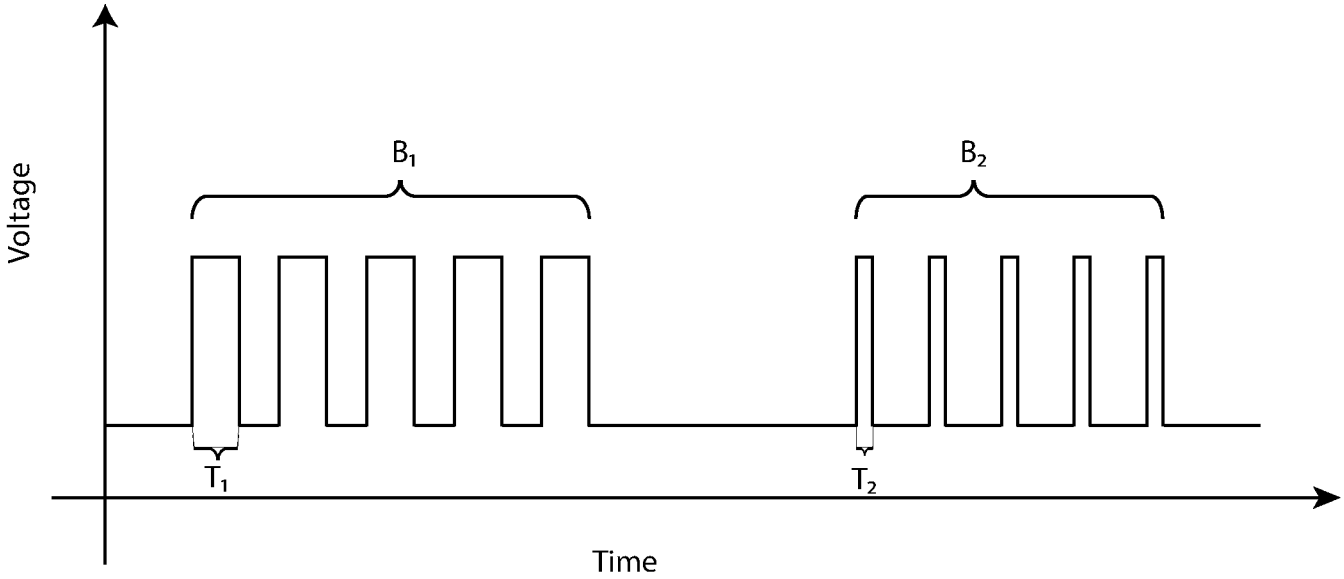


FIG. 8C

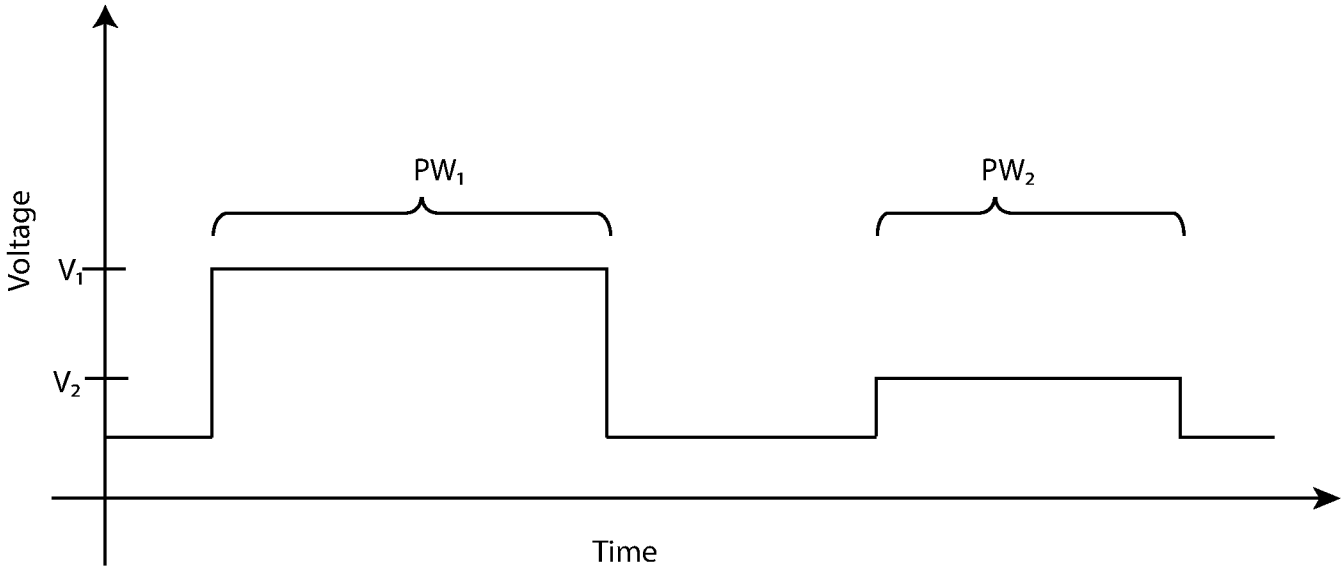


FIG. 8D

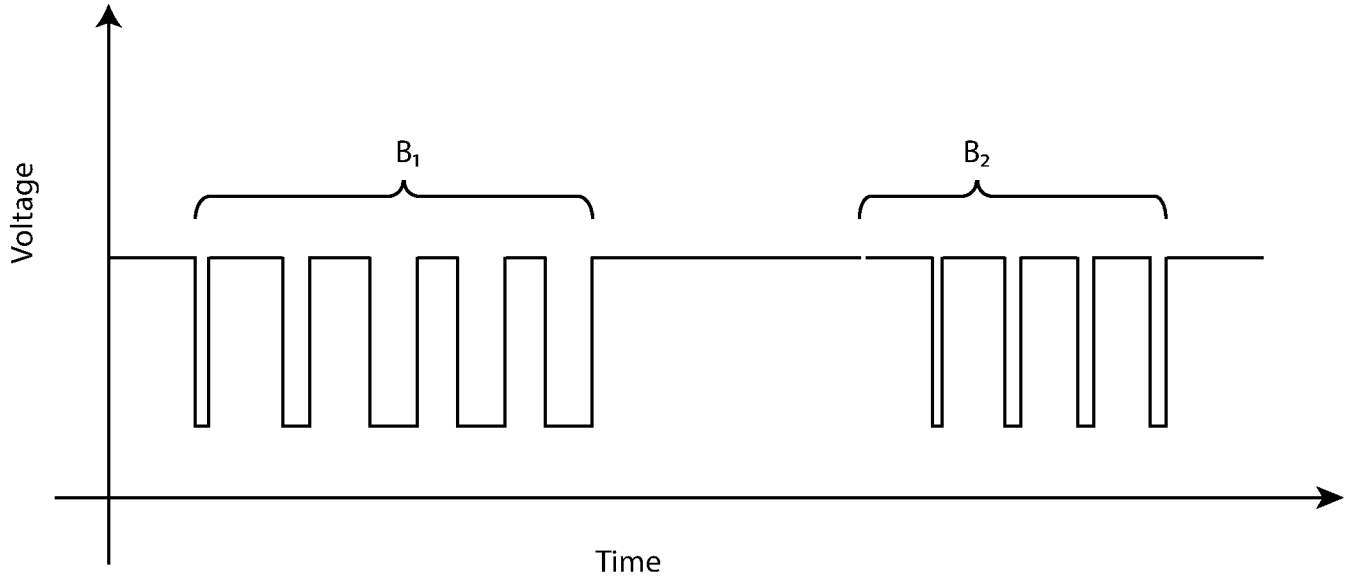


FIG. 9A

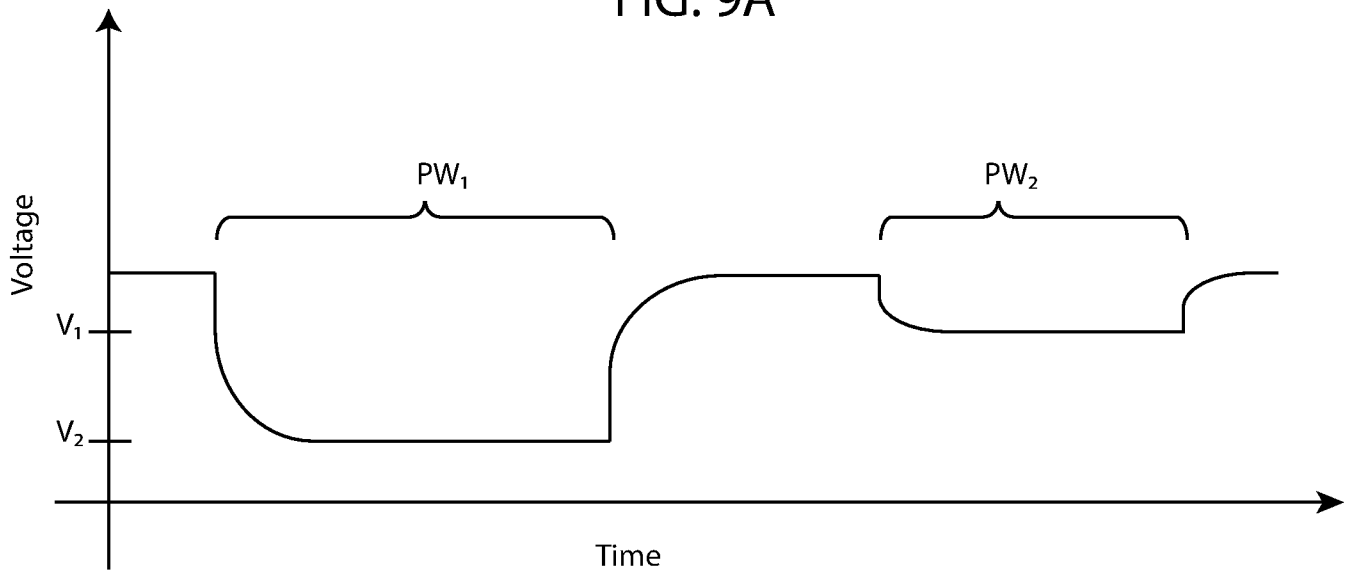


FIG. 9B

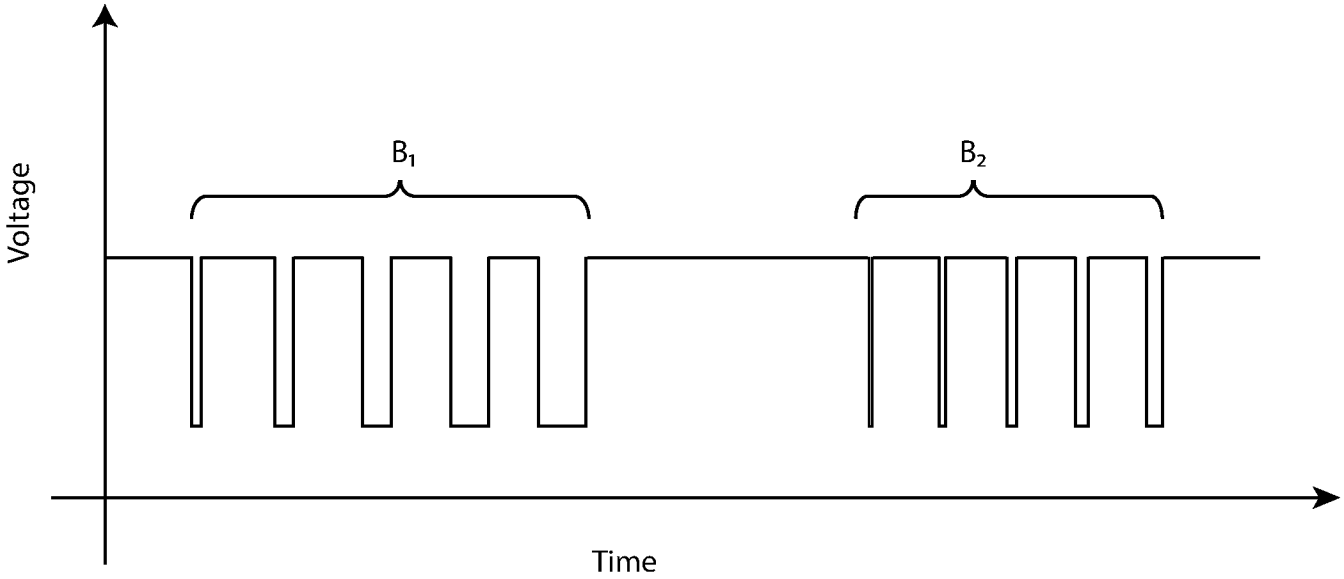


FIG. 10A

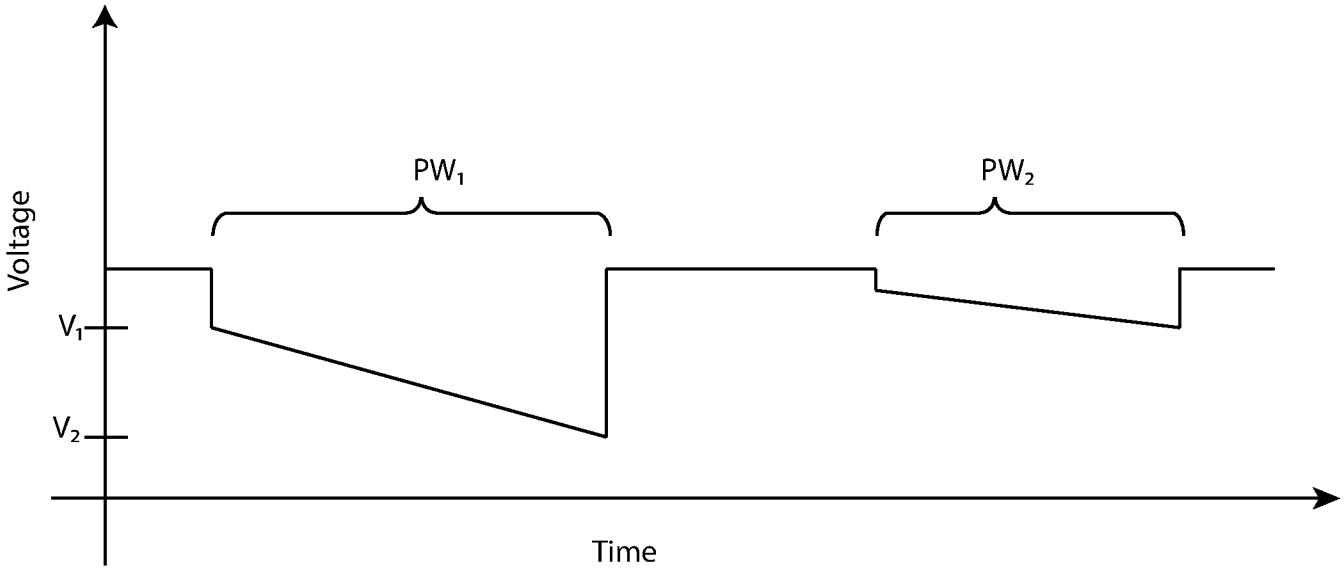


FIG. 10B

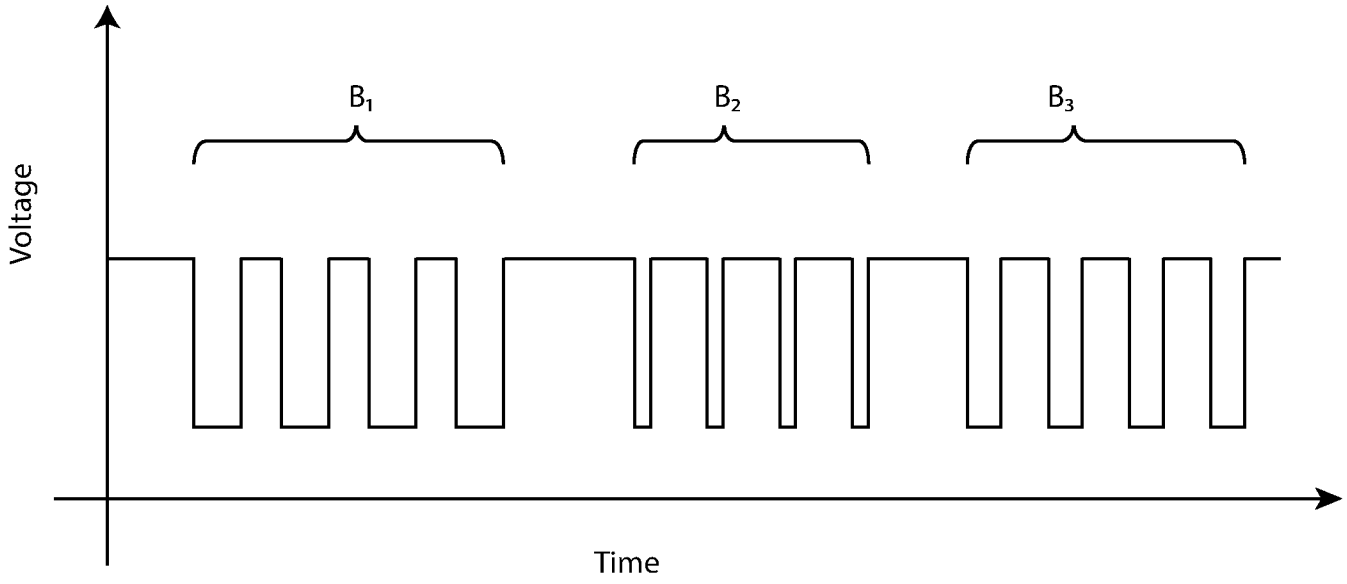


FIG. 11A

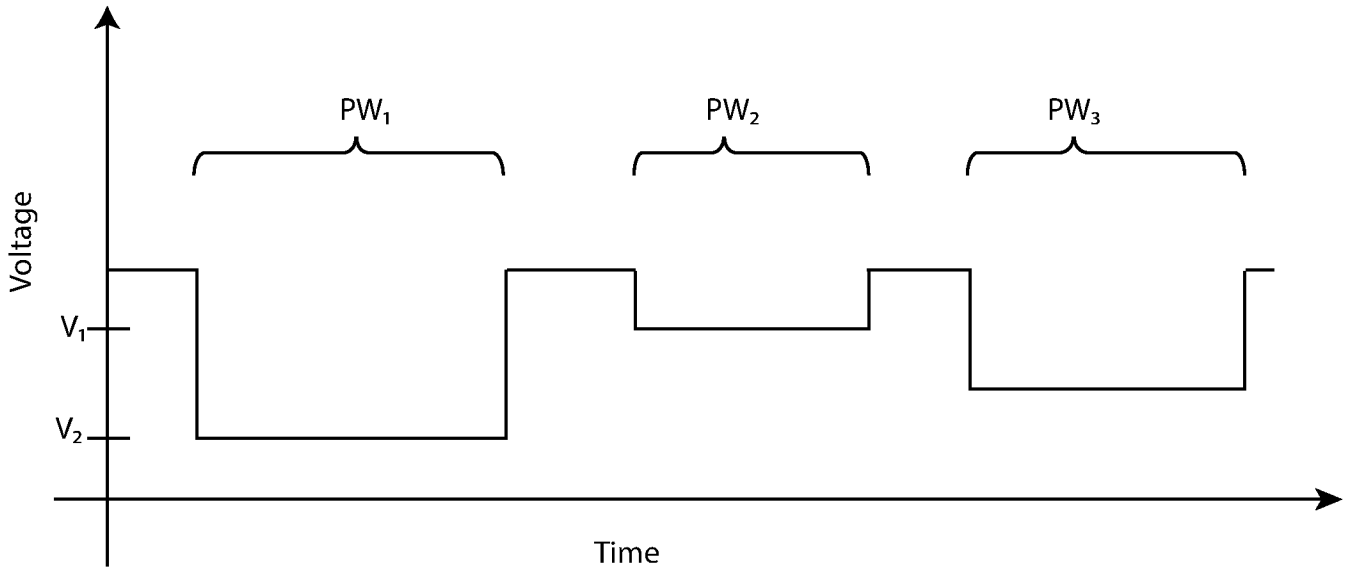


FIG. 11B

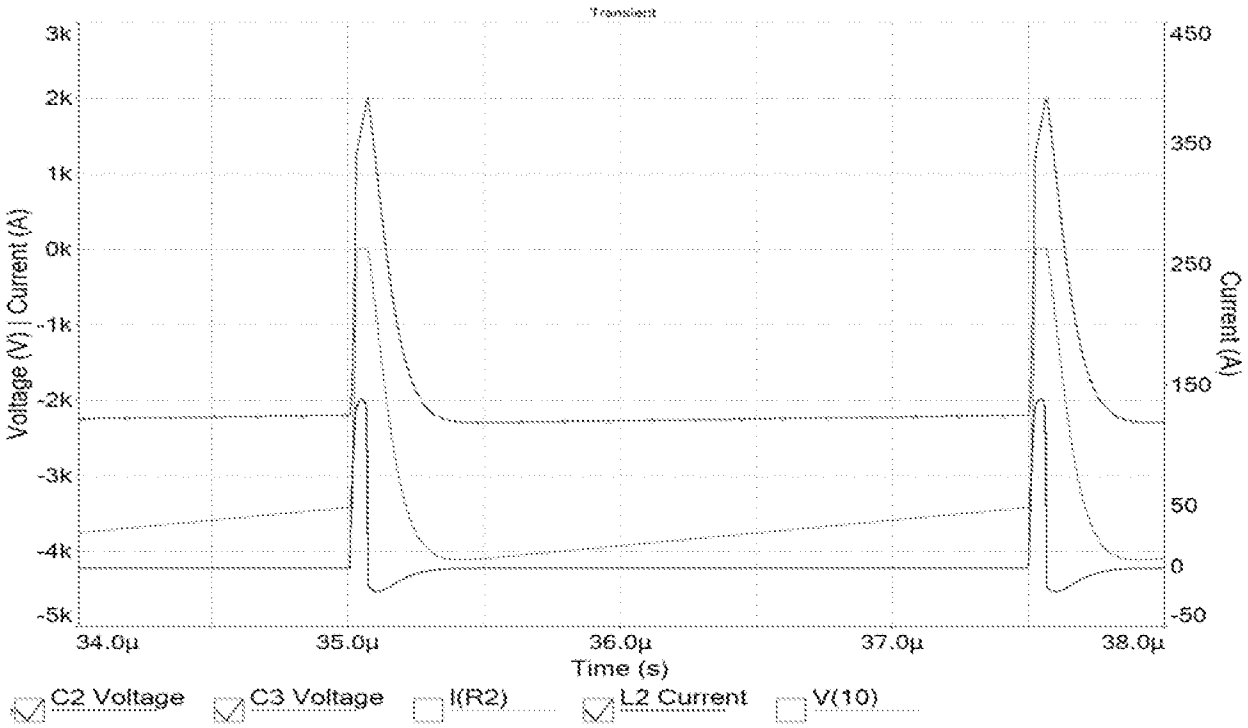

Transient
3k
2k
1k
0k
-1k
-2k
-3k
-4k
-5k
Voltage (V) | Current (A)
450
350
250
150
50
0
-50
Current (A)
34.0µ
35.0µ
36.0µ
37.0µ
38.0µ
Time (s)
C2 Voltage
C3 Voltage
I(R2)
L2 Current
V(10)

FIG. 12

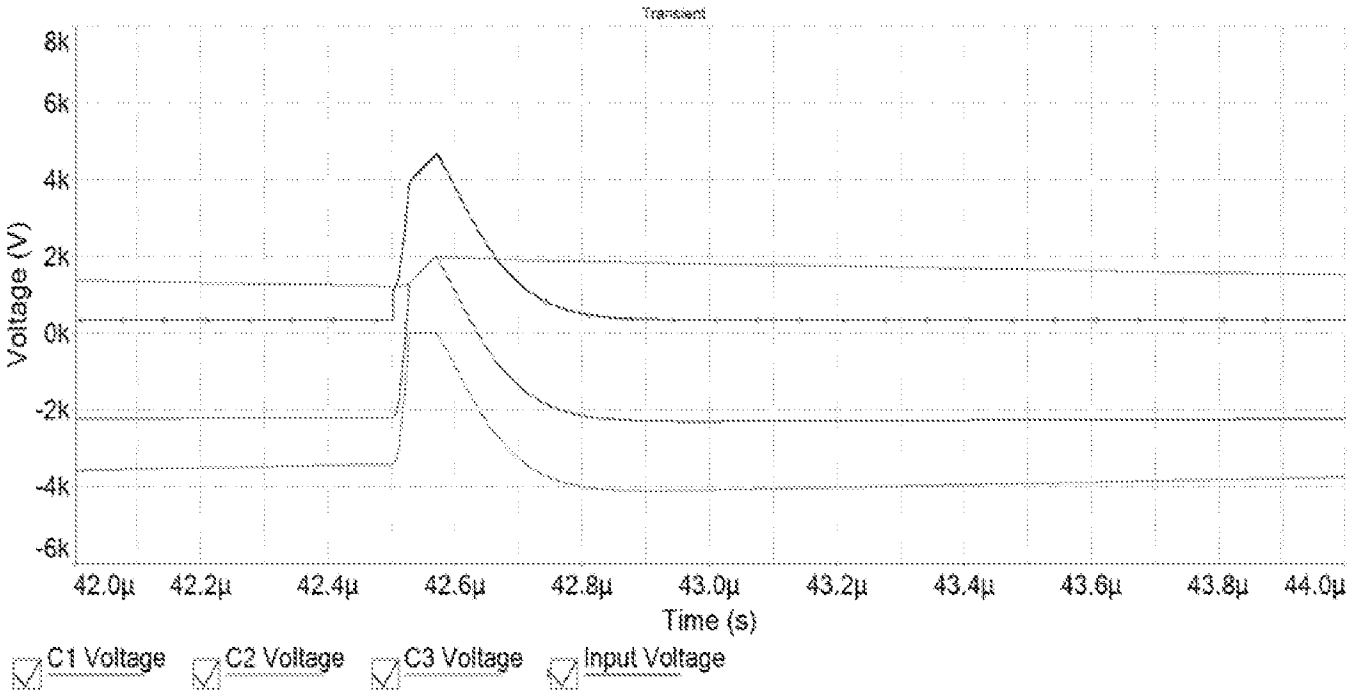

Transient
8k
6k
4k
2k
0k
-2k
-4k
-6k
Voltage (V)
42.0µ
42.2µ
42.4µ
42.6µ
42.8µ
43.0µ
43.2µ
43.4µ
43.6µ
43.8µ
44.0µ
Time (s)
C1 Voltage
C2 Voltage
C3 Voltage
Input Voltage

FIG. 13

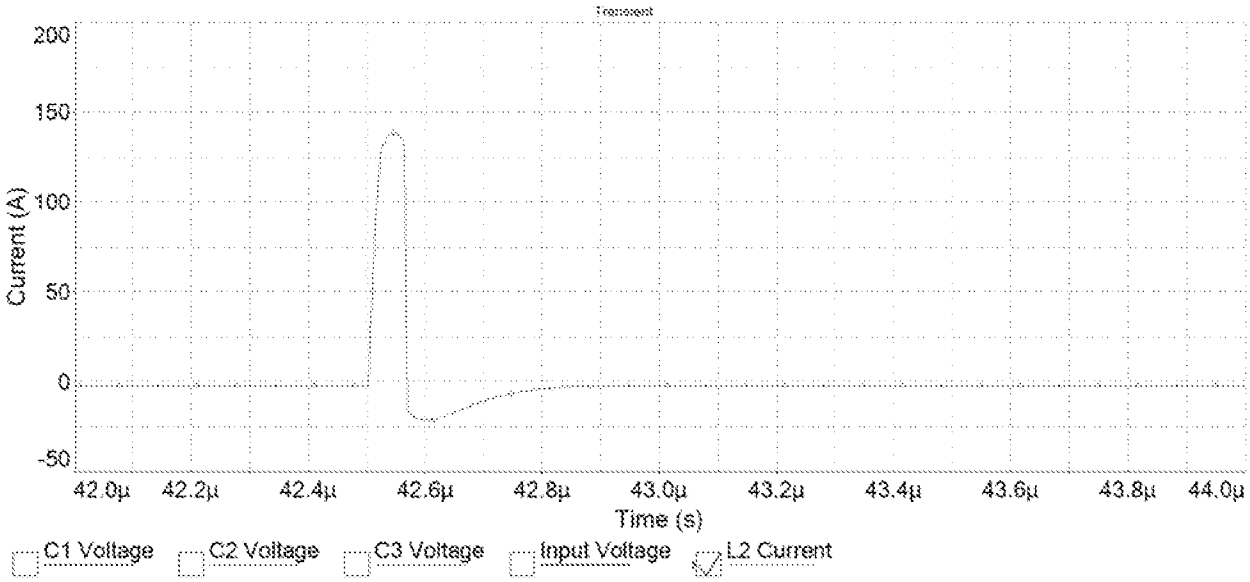

Transient
200
150
100
50
0
-50
Current (A)
42.0µ
42.2µ
42.4µ
42.6µ
42.8µ
43.0µ
43.2µ
43.4µ
43.6µ
43.8µ
44.0µ
Time (s)
C1 Voltage
C2 Voltage
C3 Voltage
Input Voltage
L2 Current

FIG. 14

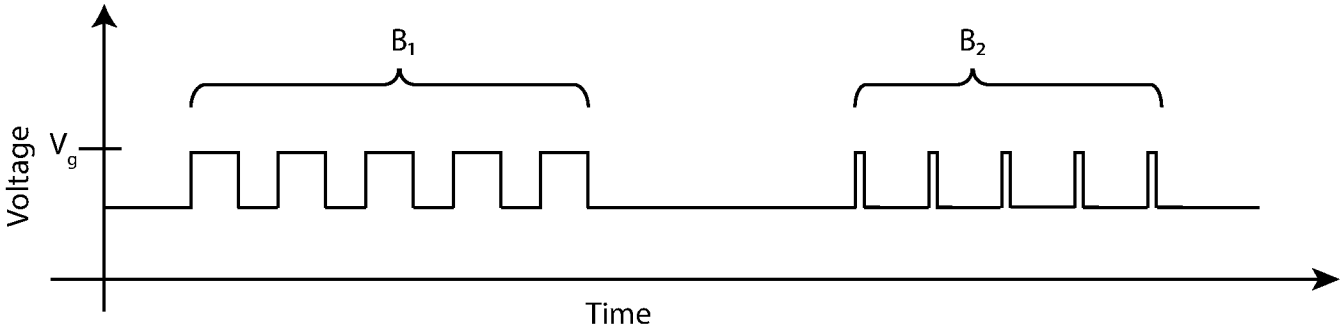


FIG. 15A

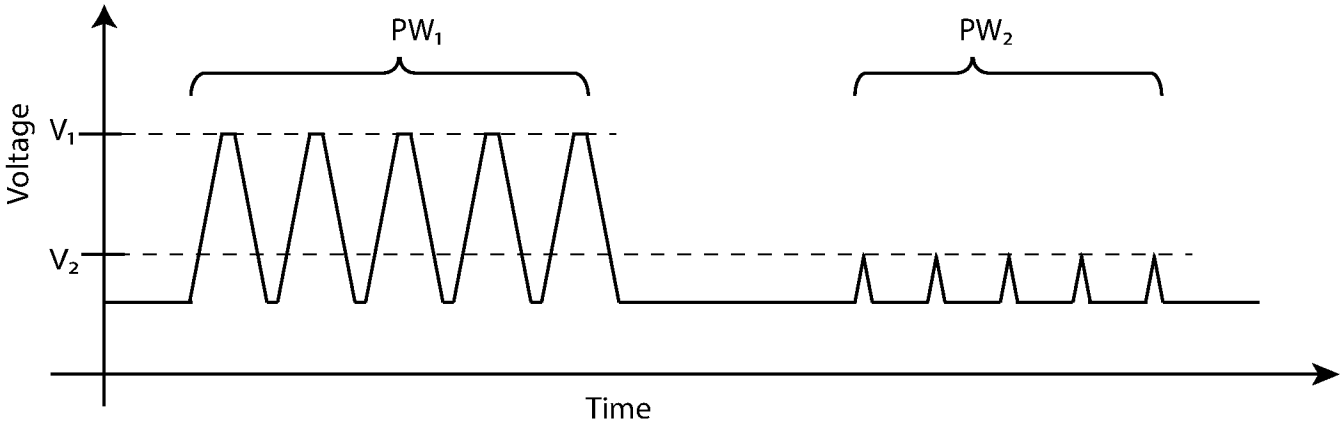


FIG. 15B

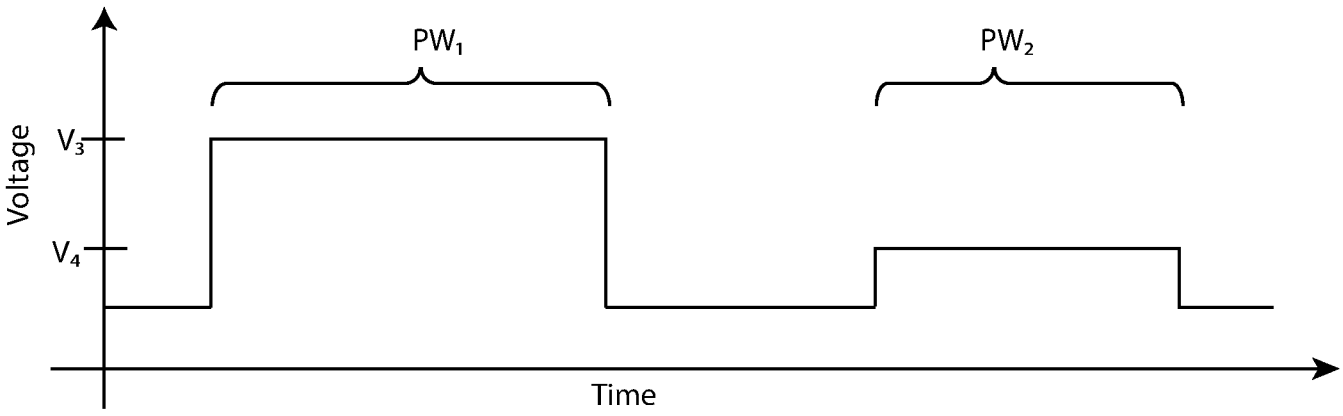


FIG. 15C

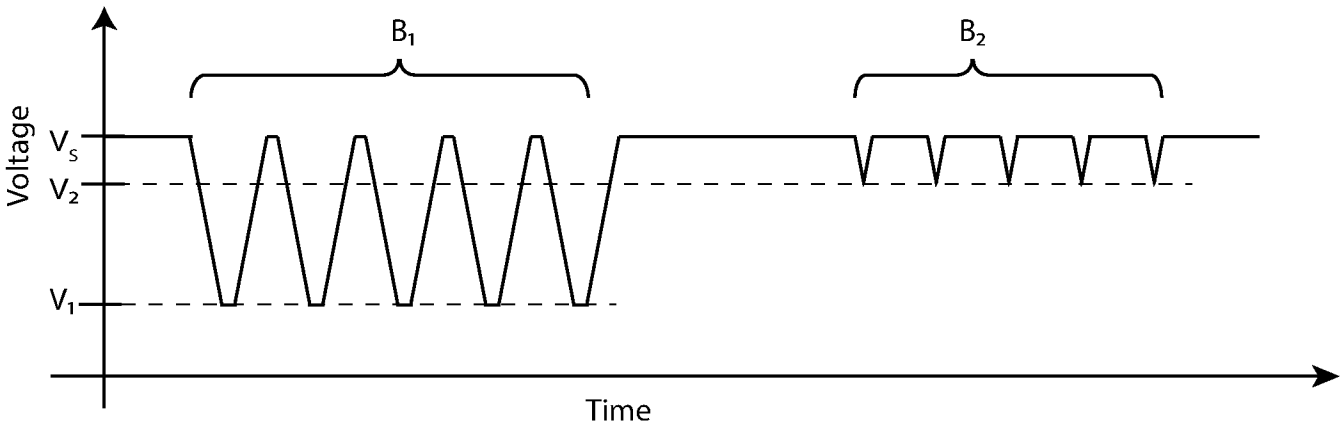


FIG. 15D

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US18/48206

A. CLASSIFICATION OF SUBJECT MATTER

IPC - H03K 3/01, 3/017, 3/57, 3/72, 17/56, 7/08 (2018.01)

CPC - H03K 3/01, 3/017, 3/57, 3/72, 17/56, 7/08

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)
See Search History document

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2010/069317 A1 (FJORDBACK, M et al.) June 24, 2010; the entire document	1-28
A	US 2015/0130525 A1 (EAGLE HARBOR TECHNOLOGIES INC.) May 14, 2015; the entire document	1-28
A	US 2009/0108759 A1 (TAO, F et al.) April 30, 2009; the entire document	1-28
A	US 5,118,969 A (IKEZI, H et al.) June 2, 1992; the entire document	1-28
A	US 2002/0180276 A1 (SAKUMA, T et al.) December 5, 2002; the entire document	1-28

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"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	Date of mailing of the international search report
18 October 2018 (18.10.2018)	01 NOV 2018
Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774