Provisional Patent Application of Robert L. Baer

TITLE: HIGH TEMPERATURE HIGH VOLTAGE SHUNT REGULATOR CIRCUIT

BACKGROUND OF THE INVENTION

Federally Sponsored Research None

Field of the Invention

This invention relates generally to the field of shunt voltage regulator circuits. More specifically, it relates to a shunt voltage regulator circuit suitable for high voltage, low current applications, over a wide temperature range, and especially at elevated temperatures.

Prior Art - Shunt Voltage Regulators

Shunt voltage regulators are components or circuits that are usually connected in parallel with a particular electronic device, or across the input or output terminals of a circuit, to limit the voltage that can be applied across the device or between the terminals. The shunt regulator performs this function by conducting very little current until a preset voltage is reached, at which point the regulator becomes a very low resistance device that conducts a higher current. Many types of shunt voltage regulators are in widespread use today.

U.S. Pat. No. 5,023,543--Tse, U.S. Pat. No. 5,029,295--Bennett et al., U.S. Pat. No. 5,519,313--Wong et al., and U.S. Pat. No. 5,621,307--Beggs, all disclose a version of a temperature compensated voltage regulator. These and similar patents refer to basic low voltage regulator methods to which we will not presume to add, modify or improve.

Prior Art - Zener Diodes

A well known type of shunt voltage regulator is the zener diode. A zener diode exhibits a very high resistance, and thus allows the passage of very small currents, until a predefined reverse threshold voltage, called the "zener" voltage, is applied across it. When the zener voltage is reached and exceeded, current conduction across the zener diode junction interface increases rapidly. Zener diodes are commonly commercially available with zener voltages of about 2 volts to about 200 volts. A problem with zener diodes is that those with zener voltages above about 6 volts exhibit large positive temperature coefficients, and an increase in noise and negative resistance characteristics at low currents; these traits worsen as higher voltage zener diode devices are selected. Lower voltage zener diodes exhibit a negative temperature coefficient, but above about 6 volts true zener breakdown does not occur, with avalanche mode breakdown taking over and imparting a positive temperature coefficient. Thus, high voltage zener diodes are not generally suitable in very low current applications, especially at elevated temperatures.

A number of temperature coefficient correcting schemes involving multiple diodes are possible; included are combinations of higher and lower voltage zener diodes or combinations of lower voltage zener diodes and conventional silicon diodes. While these schemes may compensate the temperature coefficient, all are less than ideal due to space considerations, possible noise problems at very low currents, and the fact that any such temperature coefficient correction can be optimized for only a narrow current range.

A variation is the use of a thermistor as a temperature compensating element for a string of zener diodes. While this scheme can result in a more compact assembly due to the use of just a few high voltage zener diodes, the temperature coefficient optimization can only be made over a very narrow current range, and there remains the likelihood of noise problems at very low currents.

Prior Art - Leaky Diode

One manufacturer (Comprobe) of oil well logging sondes utilized conventional silicon diodes as high voltage regulator devices. The diodes had to be selected for appropriate reverse leakage characteristics, a time consuming process resulting in a low yield of usable devices. The leaky diode high voltage regulator was unreliable and extremely temperature unstable, and its use was long ago discontinued.

Prior Art - Corona Mode Gas Tube Devices

The prior art also includes a gas discharge diode tube operating in the corona mode of discharge. This device operates as a high voltage equivalent of a zener diode, and it functions well with low shunt regulation currents and at high temperatures (characterized to 150° C and usable to 200° C). However, these devices are fragile, expensive, and they require a radioactive component (a beta emitter). They are no longer manufactured, at least in part due to misplaced concerns about their radioactivity. One would have to literally eat such a device in order to sustain any real chance of damage, but even then the more likely injury would be from the broken glass of the tube envelope.

Prior Art - U.S. Pat. No. 5,949,122--Scaccianoce

U.S. Pat. No. 5,949,122--Scaccianoce discloses an integrated circuit that provides thermal compensation for a series string of avalanche mode zener diodes, in which several bipolar transistors are connected as V_{BE} multipliers. While this circuit provides temperature-stable high voltage regulation, it may not work well at very low collector currents. This is because the bipolar transistors are connected in a common emitter configuration, in which the collector current (I_C) in each transistor is equal to the base current (I_B) multiplied by the common emitter gain (H_{FE}) of the transistor. The value of H_{FE} for a typical bipolar transistor is in the range of about 10 to about 200. Since the collector current in the Scaccianoce device is the shunt regulation current, the base current would be between 0.5% and 10% of the shunt regulation current. Thus, at low shunt regulation currents (i.e., up to about 500 microamps), the base current would be at or near the value of the collector cutoff current (the collector-to-base leakage current, or I_{CBO}) for typical bipolar transistors. There are bipolar transistors with values of I_{CBO} low enough to allow the Scaccianoce device to work at low shunt regulation currents, but the value of I_{CBO} exhibits a large positive temperature coefficient, especially at temperatures above about 100° C. Thus, as a practical matter, a device constructed in accordance with the Scaccianoce disclosure to operate at low shunt regulation currents would be limited to operation at temperatures of 125° C or less. Another objection is the use of darlington connected transistors, which exaggerates I_{CBO} leakage problems by the current gain of another transistor. Furthermore, the design requires costly adjustment of each and every thermal compensation device used in the unit. Note that operation above 150° C is questionable, since very few components are specified above 125° C, and none above 175° C. Further note that the temperature compensation units are physically distanced from the zener units, resulting in poor compensation when temperature gradients are present. Large temperature gradients are also encouraged due to the virtual impossibility of placing each zener diode in thermal contact with a corresponding Vbe multiplier. Also note that without careful diffusion schedules, the zeners can be noisy at low currents.

Prior Art - U.S. Pat. No. 6,222,350--Mosley

U.S. Pat. No. 6,222,350--Mosley discloses a high voltage shunt regulator circuit comprising high voltage zener diodes connected in series with a thermal compensation device made by the use of a FET amplifying its own gate to source voltage. This Mosley apparatus also includes the use of a string of noisy avalanche mode zener diodes at currents that virtually guarantee negative resistance and the specter of oscillation or other noise. Furthermore, the design may require costly adjustment of each and every thermal compensation device used in the unit. Note that operation above 150° C is questionable, since very few components are specified above 125° C, and none above 175° C. Further note that the FET temperature compensation units are physically distanced from the zener units, resulting in poor compensation when temperature gradients are present. Large temperature gradients are also encouraged by the teaching due to the virtual impossibility of placing each zener diode in thermal contact with a corresponding FET gate-source voltage multiplier. Temperature testing of such a unit made by Titan, done by a division of Halliburton, shows voltage excursions across the shunt regulator exceeds the voltage excursions of the power supply; that is to say, this configuration makes things worse during and after temperature changes. The data indicates that it can take about an hour for the Mosley/Titan regulator configuration to stabilize.

SUMMARY OF THE INVENTION

Summary of the Invention - Objects and Advantages of the Invention

One object and advantage of the present invention is to provide an improved stable high voltage regulation method and apparatus that can operate with low shunt regulation currents over a wide temperature range, and especially at elevated temperatures, as well as changes in temperature.

Further objects and advantages of the present invention are to provide a device that meets said operational criteria in a space-efficient and shock-resistant package.

Still further objects and advantages will become apparent from a consideration of the ensuing description and drawing.

Summary of the Invention

Broadly, the present invention is a high voltage shunt regulator circuit made with a plurality of a high voltage device with a predetermined reverse-conduction threshold connected in series with a thermal compensation device, where these two elements are thermally connected. Each high voltage device comprises a zener diode with a controlled avalanche characteristic that reduces or eliminates negative resistance and noise, and each thermal compensation device may be either a gate threshold amplifier or a Vbe multiplier, which includes a resistive voltage divider and a FET as the gate threshold amplifier or a bipolar transistor as a Vbe multiplier.

In the case of the FET gate threshold amplifier, the voltage divider is formed by first and second resistors connected in series between first and second terminals of the gate threshold amplifier, with a FET having its drain connected to the first terminal, its source connected to the second terminal, and its gate connected to an intermediate tap of the voltage divider. This thermal compensation device is thus biased so as to substantially track the temperature coefficient of the zener. The zener diode provides high voltage regulation, while the thermal compensation device exhibits a negative temperature coefficient that substantially offsets the positive temperature coefficient of the zener diode. As a matter of practical interest at high temperatures, the major problems occur due to increasing leakage across the FET channel; it is presumed that the Zener diode would have similar increase in leakage, which would decrease the avalanche current. As long as these leakages are less than total shunt current, the regulation characteristics are not severely degraded.

In the case of the bipolar transistor Vbe amplifier, the voltage divider is formed by first and second resistors connected in series between first and second terminals of the Vbe amplifier, with a bipolar transistor having its collector connected to the first terminal, its source connected to the second terminal, and its base connected to an intermediate tap of the voltage divider. This thermal compensation device is thus biased so as to substantially track the temperature coefficient of the zener. The zener diode provides high voltage regulation, while the thermal compensation device exhibits a negative temperature coefficient that substantially offsets the positive temperature coefficient of the zener diode. . As a matter of practical interest at high temperatures, the major problems occur due to increasing leakage across the collector-base junction. This leakage can become a substantial percentage of the divider current that is used to bias the base. As such, the gain of the Vbe amplifier will decrease and the temperature compensation will thereby degrade as the temperature increases above some value that cannot be pre-determined.

Either method allows efficient operation at temperatures at least as high as about 175.degree. C, at low shunt regulation currents, i.e., on the order of about 60 .mu.amps to about 500 .mu.amps. Use of the FET as a temperature compensator allows efficient operation at temperatures at least as high as about 185.degree. C. Placing both elements in a single package with close thermal coupling gives the advantages of very low sensitivity to thermal gradients, a distinct advantage to the teaching by Mosley, as well as similar advantages to the teaching by Scaccianoce.

Use of a plurality of these units to build a high voltage shunt regulator in a small space is easily implemented by constructing such units in a small surface mount package. Zener diodes with low noise operation may be fabricated with selected diffusion schedules and materials, and can exhibit low noise over low shunt regulation currents of about 2 nanoamps up to about 5 milliamps. However, the present invention is preferably realized by optimization in the 60 microamp to about 500 microamp range.

The zero temperature coefficient point of current regulation can be adjusted over a wide range, thereby allowing the use in a wide variety of applications.

Because each temperature compensated voltage regulator unit is in a very small package, the regulation of high voltages in relatively high temperature environments may be achieved with efficient use of space, and the use of multiple units keeps the thermal dissipation low, thereby decreasing temperature rise of each unit. Furthermore, the use of solid-state components provides a high degree of resistance to mechanical shocks and vibrations.

DESCRIPTION OF THE DRAWING

Brief Description of the Drawings

FIG. 1 is a circuit diagram of a temperature compensated regulator module or element constructed in accordance with a preferred embodiment of the present invention.

Drawing Reference Numerals and Letters

1	Zener	8	Terminal
2	Temperature Compensating Device	D	Drain
3	Terminal	G	Gate
4	Terminal	S	Source
5	Terminal	R1	Resistor
6	FET	R2	Resistor
7	Terminal		

FIG. 2 is a circuit diagram of a 900 volt regulator constructed, using these modules, in accordance with a preferred embodiment of the present invention.

Drawing Reference Numerals and Letters

1	Zener	8	Terminal
2	Temperature Compensating Device	D	Drain
3	Terminal	G	Gate
4	Terminal	S	Source
5	Terminal	R1	Resistor
6	FET	R2	Resistor
7	Terminal		
20	High voltage regulator	21	Regulator Module
22	Regulator Module	23	Regulator Module
24	Regulator Module	25	Regulator Module
26	Regulator Module		

FIG. 3 is a circuit diagram of a temperature compensated regulator module or element constructed in accordance with the secondary embodiment of the present invention.

Drawing Reference Numerals and Letters

11	Zener	18	Terminal
12	Temperature Compensating Device	C	Collector
13	Terminal	B	Base
14	Terminal	E	Emitter
15	Terminal	R11	Resistor
16	Bipolar transistor	R12	Resistor
17	Terminal		

FIG. 4 is a circuit diagram of a 900 volt regulator constructed, using these modules, in accordance with the secondary embodiment of the present invention.

Drawing Reference Numerals and Letters

11	Zener	18	Terminal
12	Temperature Compensating Device	C	Collector
13	Terminal	B	Base
14	Terminal	E	Emitter
15	Terminal	R11	Resistor
16	Bipolar transistor	R12	Resistor
17	Terminal		
30	High voltage regulator	31	Regulator Module
32	Regulator Module	33	Regulator Module
34	Regulator Module	35	Regulator Module
36	Regulator Module		

DETAILED DESCRIPTION OF THE INVENTION

The present invention, in its preferred embodiment, exploits an advantageous characteristic of good thermal coupling between a zener and a FET mounted in close proximity in a small package. Proper biasing of the FET allows matching of thermal characteristics. This can be done for any given current flowing through the zener, and can be adjusted so that a usable range of currents through the zener will exhibit a low temperature coefficient.

This thermally coupled combination of zener and FET is a module that is the basic building block used to construct a high voltage regulator. In FIG.1, a FET gate-source voltage amplifier 2, suitable for use in the present invention to achieve the above-mentioned goal, in close proximity to zener diode 1, is shown. The voltage amplifier 2 comprises a FET 6 having a drain D, a gate G, and a source S. The drain D is connected to a first terminal 3, and the source S is connected to a zener diode 1 at terminal 5. The zener is also connected to final terminal 8. The FET 6 shown in FIG.1 is an N channel FET; it will be understood that a P channel FET can be used instead, with circuit modifications that will readily suggest themselves to those skilled in the pertinent art.

The voltage divider comprises a first resistor R1 connected between the drain D at terminal 3 and the gate G of the FET 6 at terminal 4. A second resistor R2 is connected between the source S at terminal 5 and terminal 4. Variations across this composite voltage divider drive the gate G of FET 6, changing its conductivity in a manner that amplifies gate-source temperature variations. This amplification is selected to match temperature variations of the zener voltage. Tracking is maintained over temperature via good thermal coupling due to close physical proximity.

FIG.2 shows the use of a plurality of these temperature compensated modules as used to construct a high voltage regulator 20. Note that only six modules, 21, 22, 23, 24, 25 and 26 are shown, it is understood that from one to fifty or more modules may be connected in series to achieve the desired regulation voltage, and this can be done in an efficient and space saving manner, due to the small package size that is possible for construction of the basic module.

Although a specific example of a preferred embodiment of the invention has been described in detail above, the principles of the present invention will be readily employed in voltage regulator circuits having a wide range in the values of their operational parameters (e.g., total regulated voltage, shunt regulation current, ambient operating temperature). Thus, voltage regulator circuits in accordance with the present invention will be easily designed, with reference to the instant disclosure, by those skilled in the pertinent art to accommodate a wide variety of needs and applications.

The present invention, in its secondary embodiment, exploits an advantageous characteristic of good thermal coupling between a zener and a bipolar transistor mounted in close proximity in a small package. Proper biasing of the bipolar transistor allows matching of thermal characteristics. This can be done for any given current flowing through the zener, and can be adjusted so that a usable range of currents through the zener will exhibit a low temperature coefficient.

This thermally coupled combination of zener and bipolar transistor is a module that is the basic building block used to construct a high voltage regulator. In FIG.3, a bipolar transistor gate-source voltage amplifier 12, suitable for use in the present invention to achieve the above-mentioned goal, in close proximity to zener diode 11, is shown. The voltage amplifier 12 comprises a bipolar transistor 16 having a collector C, a base B, and a source S. The collector C is connected to a first terminal 13, and the emitter E is connected to a zener diode 11 at terminal 15. The zener is also connected to final terminal 18. The bipolar transistor 16 shown in FIG. 3 is an NPN bipolar transistor; it will be understood that a PNP bipolar transistor can be used instead, with circuit modifications that will readily suggest themselves to those skilled in the pertinent art.

The voltage divider comprises a first resistor R11 connected between the collector C at terminal 13 and the base B of the bipolar transistor 16 at terminal 14. A second resistor R12 is connected between the emitter E at terminal 15 and terminal 14. Variations across this composite voltage divider drive the base B of bipolar transistor 16, changing its conductivity in a manner that amplifies base-emitter temperature variations. This amplification is selected to match temperature variations of the zener voltage. Tracking is maintained over temperature via good thermal coupling due to close physical proximity.

FIG.4 shows the use of a plurality of these temperature compensated modules as used to construct a high voltage regulator 30. Note that only six modules, 31, 32, 33, 34, 35 and 36 are shown, it is understood that from one to fifty or more modules may be connected in series to achieve the desired regulation voltage, and this can be done in an efficient and space saving manner, due to the small package size that is possible for construction of the basic module.

Although a specific example of a preferred embodiment of the invention has been described in detail above, the principles of the present invention will be readily employed in voltage regulator circuits having a wide range in the values of their operational parameters (e.g., total regulated voltage, shunt regulation current, ambient operating temperature). Thus, voltage regulator circuits in accordance with the present invention will be easily designed, with reference to the instant disclosure, by those skilled in the pertinent art to accommodate a wide variety of needs and applications.

While a specific secondary embodiment has been described herein, it will be appreciated that a number of variations and modifications may suggest themselves to those skilled in the pertinent art. For example, while the preferred embodiment described herein uses an NPN bipolar transistor, PNP bipolar transistors may also be used, with circuit modifications that would be readily apparent to those skilled in the pertinent art. These and other variations and modifications should be considered within the spirit and scope of the present invention, as defined in the claims that follow.

CLAIMS

I claim:

1. A voltage regulator circuit for operation through a temperature range from as low as about -80° C to about 175° C or above, with a shunt regulation current of no more than about 500 microamps comprising a plurality of:

   a high voltage device having a predetermined reverse conduction threshold voltage; and a thermal compensation device connected in series with the high voltage device, the thermal compensation device comprising a gate threshold amplifier including a voltage-controlled resistive device having a negative temperature coefficient.

2. The voltage regulator circuit of claim 1, wherein the reverse conduction threshold voltage device is a zener.

3. The voltage regulator circuit of claim 1, wherein the thermal compensation device is a FET.

4. The voltage regulator circuit of claim 1, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

5. The voltage regulator circuit of claim 2, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

6. The voltage regulator circuit of claim 3, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

7. A voltage regulator circuit for operation through a temperature range from as low as about -80° C to about 175° C or above, with an optimized shunt regulation current set between about 60 microamps and about 500 microamps comprising a plurality of:

a high voltage device having a predetermined reverse conduction threshold voltage; and a thermal compensation device connected in series with the high voltage device, the thermal compensation device comprising a gate threshold amplifier including a voltage-controlled resistive device having a negative temperature coefficient.

8. The voltage regulator circuit of claim 7, wherein the reverse conduction threshold voltage device is a zener.

9. The voltage regulator circuit of claim 7, wherein the thermal compensation device is a FET.

10. The voltage regulator circuit of claim 7, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

11. The voltage regulator circuit of claim 8, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

12. The voltage regulator circuit of claim 9, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

13. A voltage regulator circuit for operation through a temperature range from as low as about -80° C to about 175° C or above, with a shunt regulation current of no more than about 500 microamps comprising a plurality of:

a high voltage device having a predetermined reverse conduction threshold voltage; and a thermal compensation device connected in series with the high voltage device, the thermal compensation device comprising a base-emitter voltage amplifier including a voltage-controlled resistive device having a negative temperature coefficient.

14. The voltage regulator circuit of claim 13, wherein the reverse conduction threshold voltage device is a zener.

15. The voltage regulator circuit of claim 13, wherein the thermal compensation device is a bipolar transistor.

16. The voltage regulator circuit of claim 13, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

17. The voltage regulator circuit of claim 14, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

18. The voltage regulator circuit of claim 15, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

19. A voltage regulator circuit for operation through a temperature range from as low as about -80° C to about 175° C or above, with an optimized shunt regulation current set between about 60 microamps and about 500 microamps comprising a plurality of:

a high voltage device having a predetermined reverse conduction threshold voltage; and a thermal compensation device connected in series with the high voltage device, the thermal compensation device comprising a gate threshold amplifier including a voltage-controlled resistive device having a negative temperature coefficient.

20. The voltage regulator circuit of claim 19, wherein the reverse conduction threshold voltage device is a zener.

21. The voltage regulator circuit of claim 19, wherein the thermal compensation device is a bipolar transistor.

22. The voltage regulator circuit of claim 19, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

23. The voltage regulator circuit of claim 20, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

24. The voltage regulator circuit of claim 21, wherein the circuit operates with a shunt regulation current of between about 60 microamps and about 500 microamps.

ABSTRACT

A high voltage shunt regulator circuit includes a high voltage reverse-conduction threshold device, in counterbalance with a thermal compensation device connected in parallel with voltage sensing resistors. The high voltage device is a single reverse-conduction threshold device, preferably a zener. The thermal compensation device preferably consists of a voltage divider formed by a first resistor connected from the drain and the gate of a FET and continues to

a second resistor connected to the source. The thermal compensation device alternately consists of a voltage divider formed by a first resistor connected from the collector and the base of a bipolar transistor and continues to a second resistor connected to the emitter. The operating bias of the thermal compensation device is adjusted to substantially track the temperature coefficient of the zener. This can be done for any given current flowing through the zener, and can be adjusted so that a usable range of currents will exhibit a low temperature coefficient. The zener and the FET or transistor are constructed in close thermal proximity and in a small package. A plurality of these elements is used to construct a high voltage shunt regulator.

FIG. 1

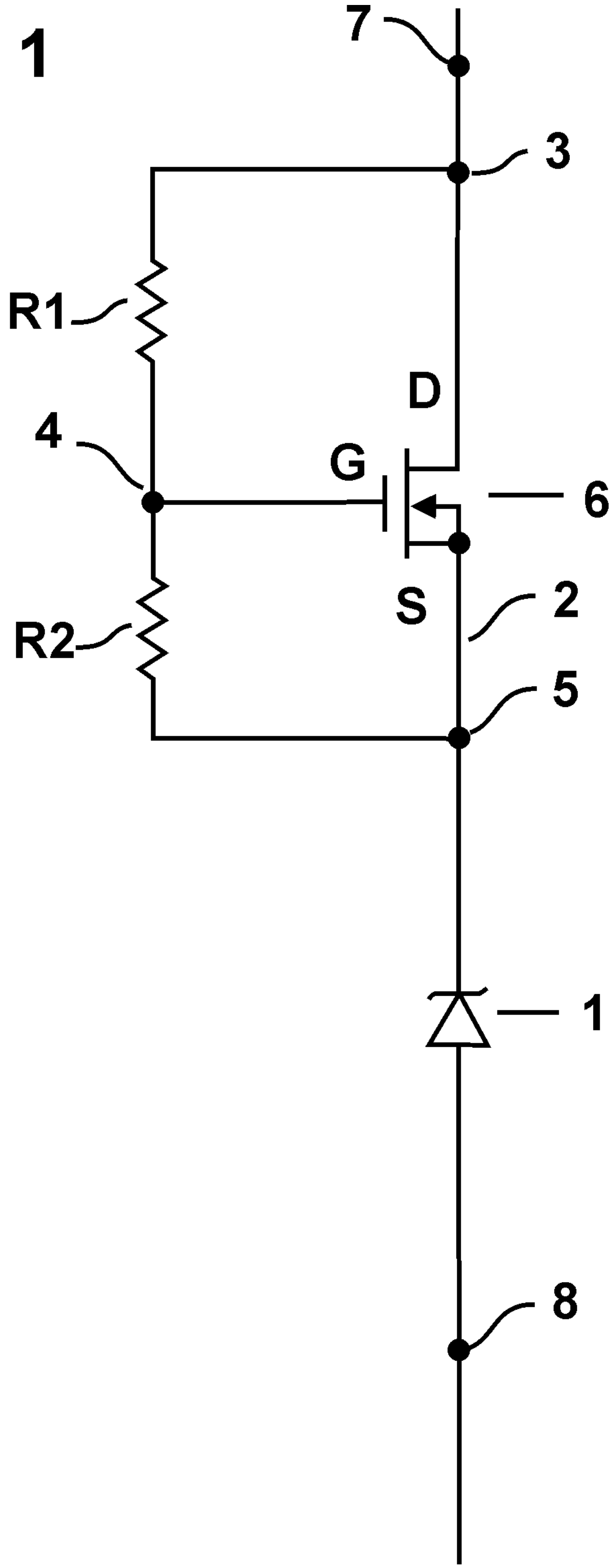


FIG. 2

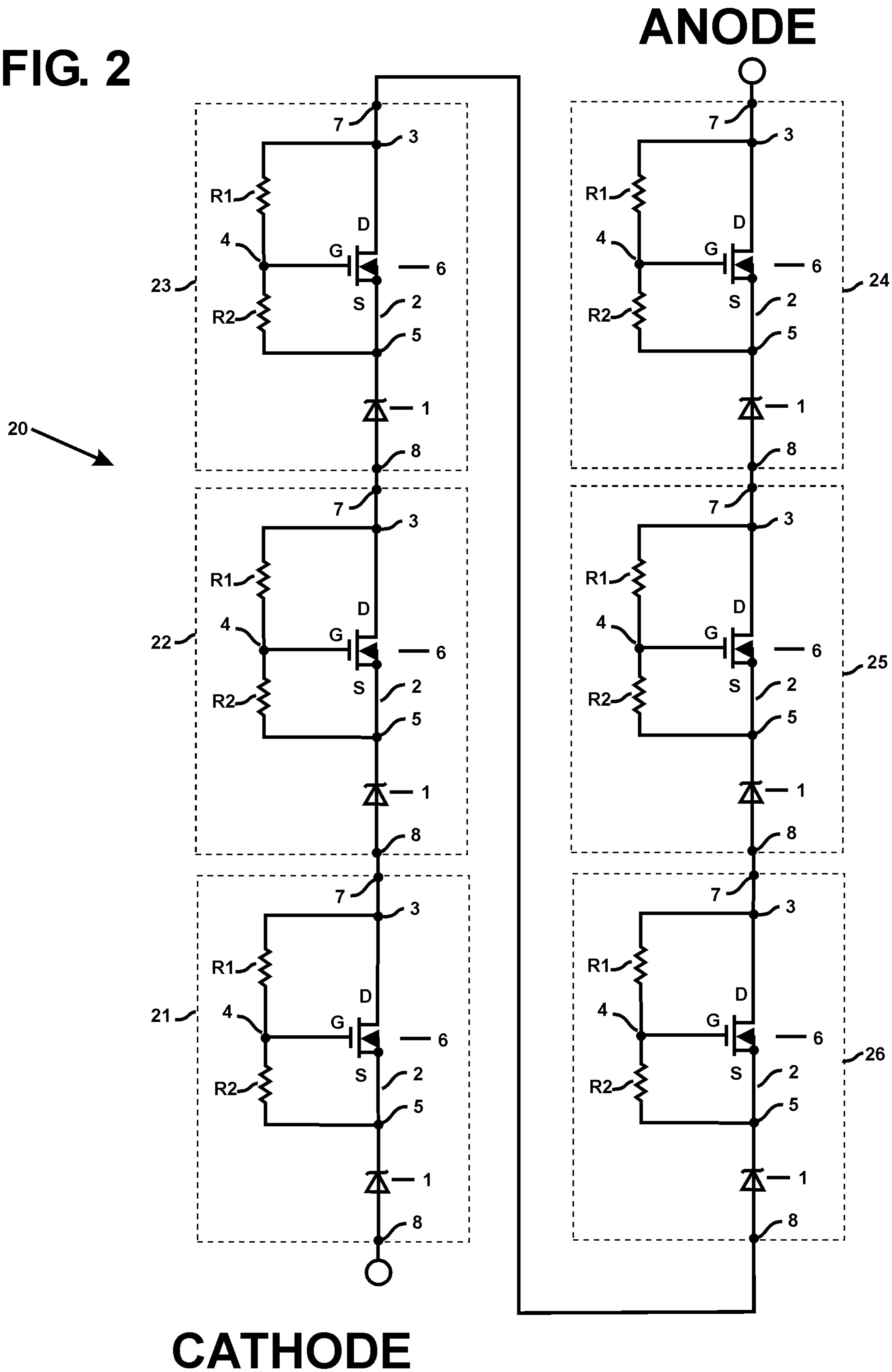


FIG. 3

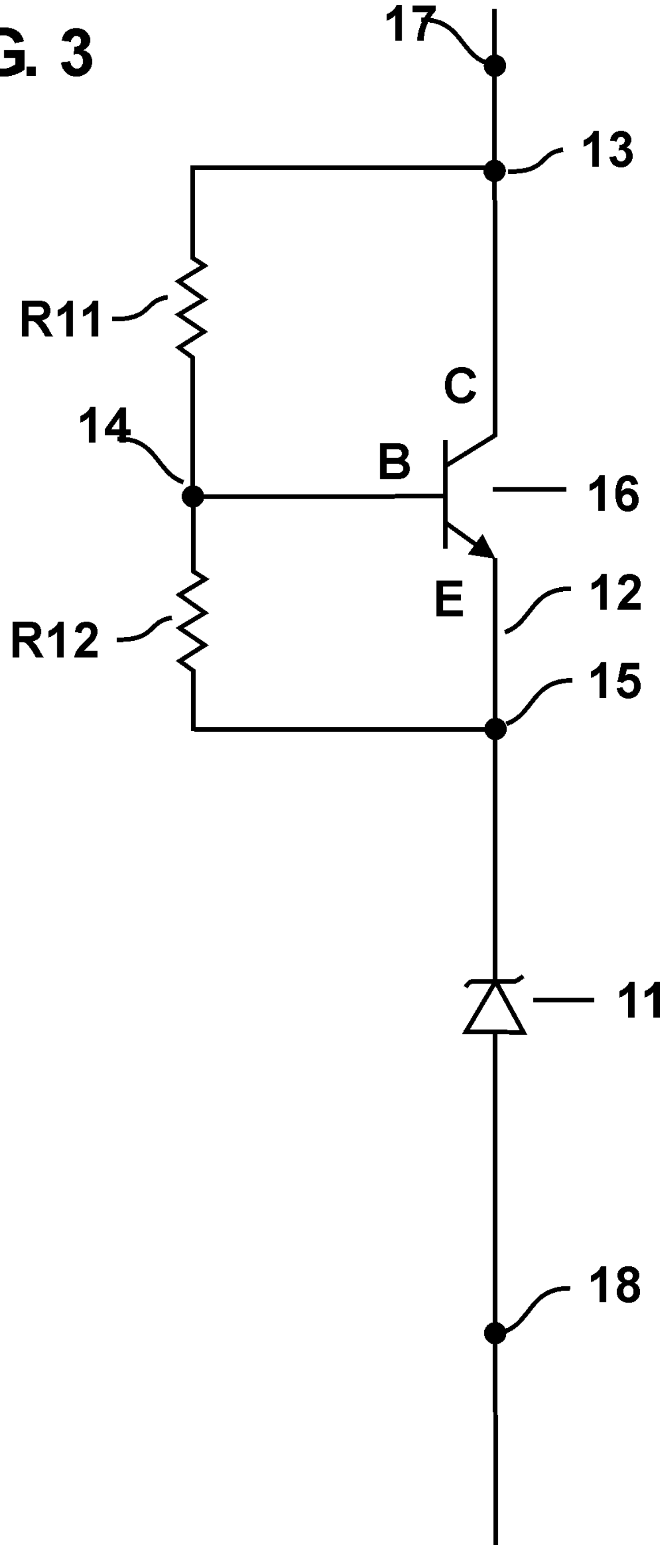
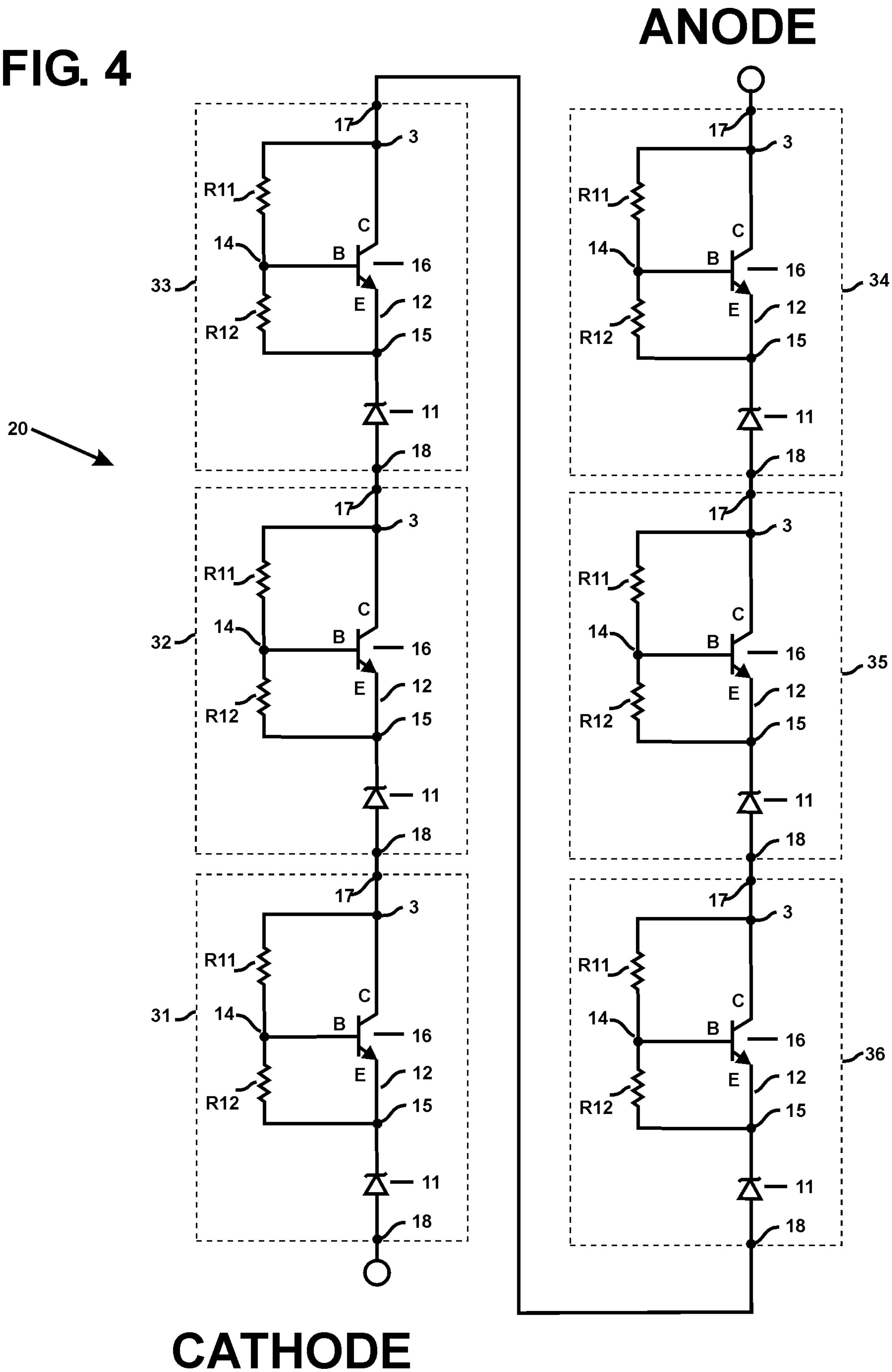


FIG. 4


ANODE
CATHODE
20
31
32
33
34
35
36
R11
R12
B
C
E
3
11
12
14
15
16
17
18