

[54] **MINIMIZED TEMPERATURE
COEFFICIENT VOLTAGE STANDARD
MEANS**

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[58] Field of Search **317/235 Q, 235 T; 307/318, 310, 317**

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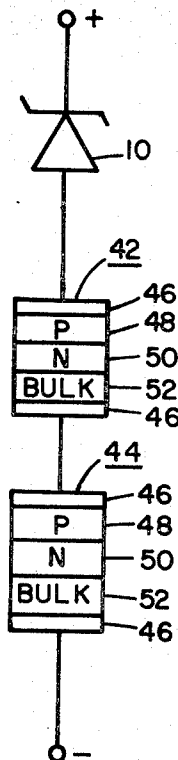
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ABSTRACT

To minimize the change in breakdown voltage of the series connection of one or more reverse biased diodes and one or more forward biased diodes with change in temperature, bulk semiconductive material is connected in series with a reverse biased diode or may be made part of the forward or reverse biased diode, or may be added to the material thereof.

6 Claims, 9 Drawing Figures



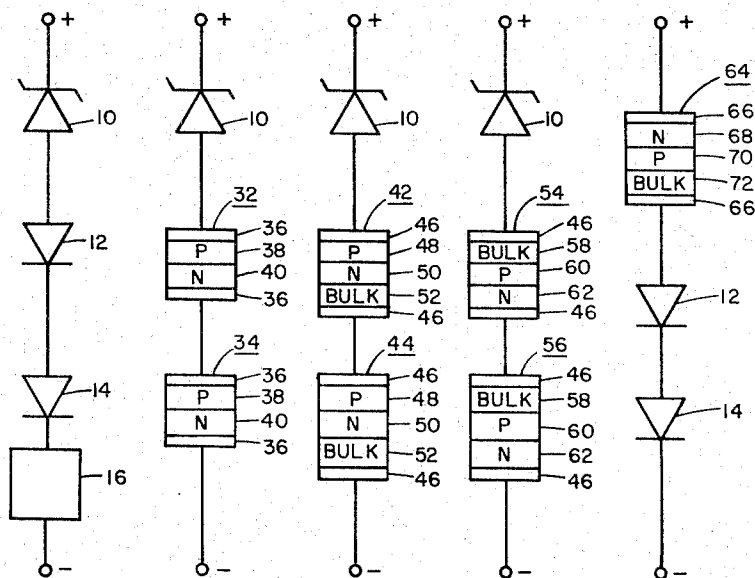
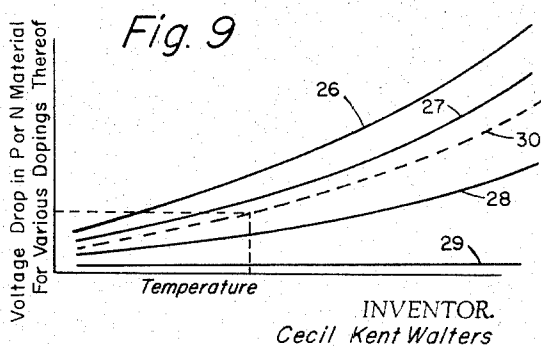
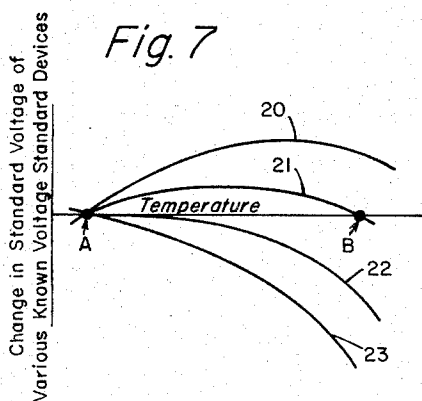
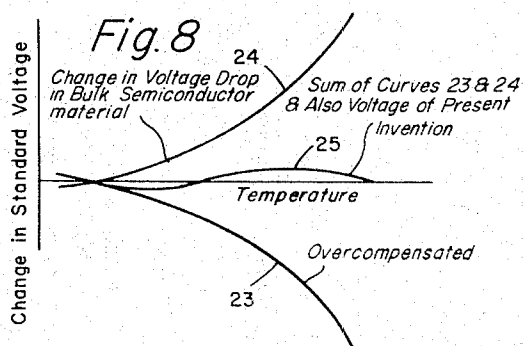
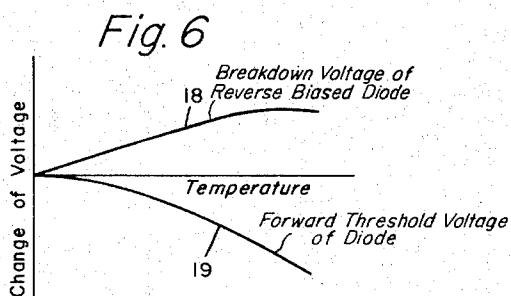


Fig.1 Fig.2 Fig.3 Fig.4 Fig.5



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MINIMIZED TEMPERATURE COEFFICIENT VOLTAGE STANDARD MEANS

This is a continuation of application Ser. No. 856,646, Cecil K. Walters, entitled "Minimized Temperature Coefficient Voltage Standard Means" filed Sept. 10, 1969, now abandoned and assigned to the same assignee as the subject application.

BACKGROUND

This invention relates to voltage standard means.

It is known to connect in series one or more reverse biased diodes and one or more forward biased diodes to produce a voltage standard means whose temperature coefficient of change of voltage standard is reduced. However, since the breakdown voltage of the reverse biased diode and the forward threshold voltage of the forward biased diode do not change linearly with temperature but along nonlinear curves whose nonlinearity each has a negative rate of change of slope with increasing temperature, a zero temperature coefficient voltage standard means, or even one whose temperature coefficient varies linearly, is not at present obtainable. Such presently known voltage standard means of minimum temperature coefficient will usually exhibit its nominal standard voltage at about -55°C and also at about $+150^{\circ}\text{C}$, with a small increase in voltage up to the middle of the range from either temperature extreme. The mentioned temperature extremes are merely examples and may be varied from one to another voltage standard means.

SUMMARY

According to the invention, bulk semiconductor material is connected in series with the voltage standard means comprising the series connection of one or more reverse biased diodes and one or more forward biased diodes, the resistance of the bulk material, which also changes with change in temperature, compensating for the change of voltage standard provided by the voltage standard means. The bulk semiconductive material may be part of the material comprising the forward or the reverse biased diode or diodes, or the bulk material may be added to a diode or may be added as a separate piece or portion or chip to the series combination.

DESCRIPTION

The invention will be better understood upon reading the following description in connection with the accompanying drawing in which

FIGS. 1 to 5 illustrate several embodiments of the invention, and

FIGS. 6 to 9 are curves which are useful in explaining the operation of the device of FIGS. 1 to 5.

Turning first to FIG. 1, a diode 10 is connected in series with the diodes 12 and 14 and with a piece of bulk semiconductive material 16 which may be lightly N or P-doped. The cathode of the diode 10 is connected to the positive terminal of a source (not shown) and the anode of the diode 10 is connected to the anode of a diode 12, while the cathode of the diode 12 is connected to the anode of a diode 14 whose cathode is connected by way of the piece of bulk semiconductive material 16 to the negative terminal of the source. Each of the diodes 12 and 14 includes a PN junction. While only two diodes 12 and 14 are shown, as many thereof may be used with one or more reverse biased diodes,

such as a diode 10, which also include PN junctions, as is desirable.

As is known, when the elements 10, 12, and 14, the element 16 being omitted, are connected in series with a resistor (not shown) across a source which is high enough to break down the reverse biased diode 10, then a standard voltage appears across the diode 10 and the variations of the standard voltage with temperature is reduced if the standard voltage is taken across the diode 10 and one or more of the forwardly biased diodes 12 and 14. In the embodiment of the invention in FIG. 1, which includes the bulk semiconductor material 16, the variation of the standard voltage is still further reduced if the standard voltage is taken across the diodes 10, 12, and 14 and the bulk semiconductive material 16. The manner of choosing the resistance of the bulk semiconductor material 16 will now be explained.

In FIG. 6, the curve 18 indicates the change in breakdown voltage of a reversely biased diode with change in temperature. It is noted that the breakdown voltage increases relatively uniformly into the higher temperatures and then the breakdown voltage increases more and more slowly. The curve 19 shows the decrease in forward threshold voltage for current flow of a forwardly biased diode with change in temperature thereof. It is noted that the threshold voltage decreases slowly at first and then decreases more rapidly as the temperature is further increased. Therefore, the change in the breakdown voltage of the diode 10 and of the forward threshold of the diodes such as 12 and 14 are opposite in magnitude and can offset each other, but these changes are not linear nor are they similar and so they cannot completely offset each other along the whole range of temperatures. It is noted that the slope of the curve 18 may be such, for certain breakdown voltages of a reversely biased diode, that more than one forwardly biased diode must be connected in series with the one reverse biased diode to further decrease the change of standard voltage with changes in temperature.

When reverse biased diode 10 is connected in series with one or more forwardly biased diodes (but without having the bulk piece of semiconductor material 16 in the circuit) and the change in standard voltage provided thereby is plotted against temperature, curves such as that of FIG. 7 are produced. The ordinate scale of FIG. 6 may typically be in volts while the ordinate scale in FIG. 7 may be typically millivolts.

The curve 20 is produced when an insufficient degree of compensation is utilized from forward biased diodes. The curve 21 is the optimum condition obtainable without using the bulk semiconductor 16. It is noted that at points A and B which correspond to about -55°C and to about $+150^{\circ}\text{C}$, the series circuit including a reverse biased diode and one or more forwardly biased diodes provides exactly the desired standard voltage while the furthest extent of the departure of the curve 21 from the desired value is a small positive amount. The curves 22 and 23 are obtained when too much compensation is obtained from forward biased diodes for a particular reverse biased diode and without using the present invention. In the curves 20, 21 and 22 and 23 of FIG. 7, the point A is arbitrarily chosen as the ordinate reference for these curves.

The curve 23 of FIG. 7 is again shown in FIG. 8. The curve 24 of FIG. 8 is exponential in nature and indicates the change in resistance, or the change in voltage

drop at a constant current, of a bulk piece of lightly N or P doped intrinsic semiconductor material on a linear ordinate scale. Therefore, the change of the voltage drop with temperature indicated by the curve 24, which is always positive, is very small at low temperatures and increases rapidly with temperature. When a bulk piece of semiconductor material such as the semiconductor 16 with properties indicated by the curve 24 of FIG. 8 is connected as shown in FIG. 1 in series with the diode 10 and the two diodes 12 and 14, the three diodes 10, 12, and 14 having properties indicated by the curve 23, then the resultant curve 25 of change of voltage standard is less, all along the temperature range of interest, than the optimum curve 21 of FIG. 7. Therefore, by proper choice of the resistance of the bulk semiconductor material 16 to have a curve such as the curve 24, the temperature variation of a voltage standard device may be greatly improved. The voltage versus temperature characteristics for the bulk silicon material 16 are illustrated in FIG. 9 for various effective drift resistance. These curves are a consequence of the resistivity properties of silicon versus temperature in the extrinsic region.

It may not be necessary to add a separate piece of bulk resistive material 16 to a voltage standard circuit according to another feature of this invention, since sufficient bulk portions or regions of semiconductor material may be included in each forwardly biased diode to perform the function of the separate bulk semiconductor 16 of FIG. 1. In FIG. 2, the reversely biased diode 10 is connected in series with two forwardly biased diodes 32 and 34. Each of the diodes 32 and 34 comprises electrodes 36 and P material 38 and N material 40, the P and the N material together providing the PN junction. The voltage drop in the diodes 32 and 34 has several components as comprised by the very small voltage due to contact resistance, the forward voltage drop of the PN junction, and the degree of voltage drop in these diodes due to the bulk resistance thereof as determined by Ohm's law using the drift current and bulk resistance within the confines of the diode geometry of the diodes 32 and 34. Due to the effect of the diffusion of the minority carriers on the apparent resistance of the diode, the drift current resistance and consequent voltage drop which obeys Ohm's law of the diodes 32 and 34 is difficult to calculate. It is measured as follows.

As noted above, the voltage drop in the diode has three components, the ohmic contact resistance voltage drop, the forward PN junction voltage drop, and the voltage drop due to drift current flow therein. To measure the contact resistance voltage drop, a diode 32 or 34 is picked which is thought to have sufficient drift resistance to reduce the variation of the voltage standard means with temperature changes of which it is to be a part, to a minimum value. Then another diode (which is to be used only for measurement purposes) which has the same geometry as the diode 32 or 34 but in which the P and N regions are so heavily doped that the voltage drop due to the drift current flow therein is very small, is provided. A 60-cycle alternating current is imposed on a direct current, the peak-to-peak amplitude of the alternating current being about 10 percent of the average direct current, and this so modulated direct current is passed through the heavily doped diode and the voltage thereacross is measured. This voltage is equal to the dynamic voltage drop in the heavily doped diode which is the sum of the ohmic contact re-

sistance voltage drop and the forward voltage drop in the PN junction, there being no or very little dynamic drift current voltage drop in this test diode. Since the forward voltage drop of the PN junction is known, the contact voltage drop is obtained by subtraction, and this value is taken as the contact voltage drop of the diode 32 or 34 which is actually to be used. Then the modulated direct current is applied across the diode 32 or 34 and the voltage drop thereacross is measured. The sum of the ohmic contact resistance voltage drop and the forward PN voltage drop is subtracted from the last mentioned measured voltage drop and the remainder is multiplied by 10 (since the test current was 10 percent modulated) to obtain the dynamic voltage drop in the diode 32 and 34 to the drift current in the diode. The temperature at which these measurements are made is also observed.

The curve of voltage change with change in temperature of the diodes 32 and 34 is obtained from curves such as those of FIG. 9. In FIG. 9, each of the curves 26, 27, 28, and 29 indicate changes of voltage drop in semiconductor material, either N or P doped, for various concentrations of N or P doping with changes in temperature. The coordinates comprising the measured and multiplied voltage drop (mentioned hereinabove) and the observed temperature will fall on one of these curves 26, 27, 28, or 29 or on an extension of one of these curves or on an interpolated curve. Let it be assumed that this point indicated by these coordinates does not fall on any of these curves but on a point therebetween such as on the dotted curve 30. The dotted curve 30, as suggested above, is obtained by interpolation between the curves 27 and 28, and this curve 30 shows the actual change of voltage drop with temperature in the actual diode which was tested, 32 or 34. If this curve is the same in shape as the curve 24 of FIG. 8, then one diode 34 will produce the maximum improvement in the shape of the curve 25 of FIG. 8. However, if the shape of the curve 30 and the shape of the curve 24 is not the same, then one or more of the curves 30 may be added together if necessary to provide a curve of the shape 24 of the FIG. 8 for those cases where a plurality of diodes should be provided in series in a circuit such as that of FIG. 2 to produce the curve 25 of FIG. 8. However, it may be found that neither one diode 32 of the type tested or a plurality of these in series will give a curve of the shape of the curve 24 of FIG. 8 whereby it may be necessary to change the drift resistance of the diode that is used. In this case other diodes which have different doping including gold doping or which have been subjected to gamma radiation to raise the drift resistance of the diodes may be used. It will be understood that in this manner a diode or diodes 32 and 34 may be found which when connected in series with the reversely biased diode 10 will produce a voltage standard means having an optimum change of standard voltage with a change in temperature such as the curve 25 of FIG. 8.

Another way in which the necessary drift current resistance can be produced by the proper number of forwardly biased diodes is illustrated in FIG. 3. In this embodiment, the reversely biased diode 10 is connected in series with forwardly biased diodes 42 and 44. The diodes 42 and 44 each comprise electrodes 46, P regions 48, N regions 50, the N and P regions together providing PN junctions and lightly N-doped regions 52 of appropriately selected resistance. The material 52

may be added to the N material 50 in a known manner as by growing it epitaxially, away from the PN junction so that it is more than a diffusion length therefrom.

Similarly, as shown in FIG. 4, lightly P-doped bulk material 58 may be added to the P material 60 of the diodes 54 and 56 which have electrodes 46 and N region 62 and which may be connected in series with a reversely biased diode 10.

Furthermore, the lightly doped material may be added to the reversely biased diode 64 of FIG. 5 to either electrode thereof. As shown in FIG. 5, the lightly P-doped material is added to the P material 70 of the reversely biased diode 64 having electrode 66 and N material 68 and which is connected to the series with forwardly biased diodes 12 and 14. While not shown, lightly N-doped material may be added to the N material 68 of the reversely biased diodes 64 of FIG. 5 if desired. In the embodiments of FIGS. 3 to 5, whether the bulk material is added to the forwardly biased or the reversely biased diode or to the N material or to the P material or to all of these, the suitability of the diodes for reducing the change in voltage standard due to a change in temperature thereof may be measured in a manner explained above in connection with FIG. 2 and if the diode is found not to contribute the necessary amount of drift resistance, the diode may be changed by increasing or decreasing the thickness of the bulk material or, if necessary, by providing other diodes having the correct voltage drop due to drift current therein.

While in FIGS. 2 to 4, the required amount of drift resistance is supplied in equal fractional amounts by each of the several forwardly biased diodes that are used, since in this manner less varieties of diodes need be provided, if desired, one forwardly biased diode or one reversely biased diode may itself provide all the drift current resistance needed to minimize the change in standard voltage with the change in temperature.

What is claimed is:

1. A voltage standard means comprising:
 - at least one diode which includes P doped and N doped material and a PN junction and which is adapted to be reversely biased;
 - at least a second diode which also includes P doped and N doped material and a PN junction and which is adapted to be forwardly biased;
 - bulk semiconductive material comprising impurity doped material of a predetermined impurity con-

centration for a predetermined resistivity integrally included with the material of said second diode and spaced from said forwardly biased PN junction by at least one diffusion length;

- a series combination including said one diode, said second diode and said bulk material;
- said one diode being reversely poled with respect to said second diode in said series circuit;
- the combination of said one diode and said at least a second diode having a non-linear characteristic curve between the voltage thereacross and increasing temperature and with a continuously negative changing slope;
- said continuously negative changing slope having a continuously negative absolute value;
- said bulk semiconductor material having a non-linear characteristic curve between the voltage thereacross and increasing temperature and with a continuously positively changing slope;
- said continuously positively changing slope having a continuously positive absolute value;
- said characteristic curves beginning at substantially zero reference voltage at a predetermined initial temperature; and
- said negative and said positive absolute values being essentially equal at respective same temperatures.

2. The voltage standard means according to claim 1 wherein the characteristic of said bulk semiconductive material is exponential.

3. The voltage standard means according to claim 1 in which a plurality of second diodes which are adapted to be forwardly biased are provided and in which a fractional share of said bulk semiconductive material is integrally included with the material comprising each of said forwardly biased PN junctions.

4. A voltage standard means according to claim 1 wherein at least one of said at least a second diode and said bulk semiconductive material comprises gold doped material.

5. A voltage standard means according to claim 1 wherein at least one of said at least a second diode and said bulk semiconductive material comprises irradiated material.

6. A voltage standard means according to claim 14 wherein said irradiated material is gamma radiation irradiated material.

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