SINGLE CRYSTAL SEMICONDUCTOR RESISTORS

Filed Sept. 19, 1960 2 Sheets-Sheet 1

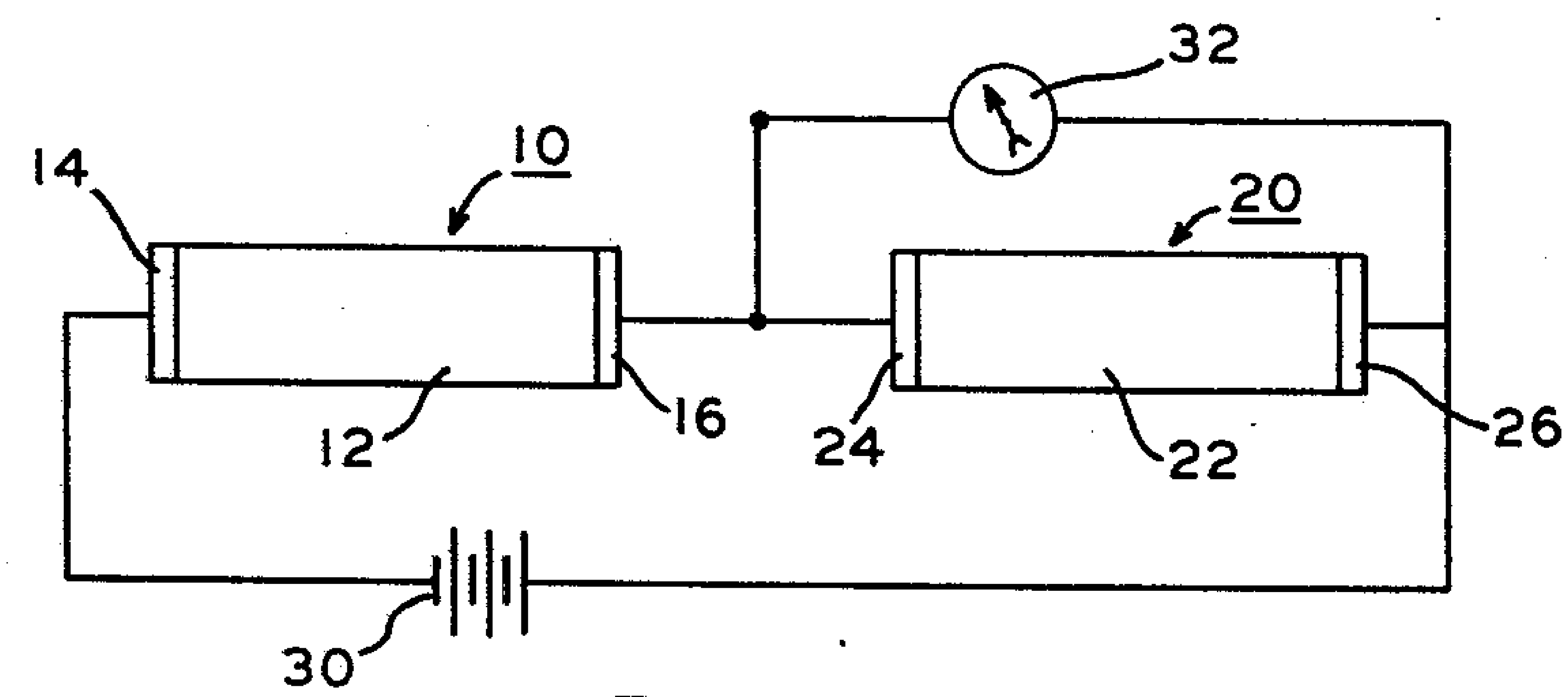

FIG. 1.

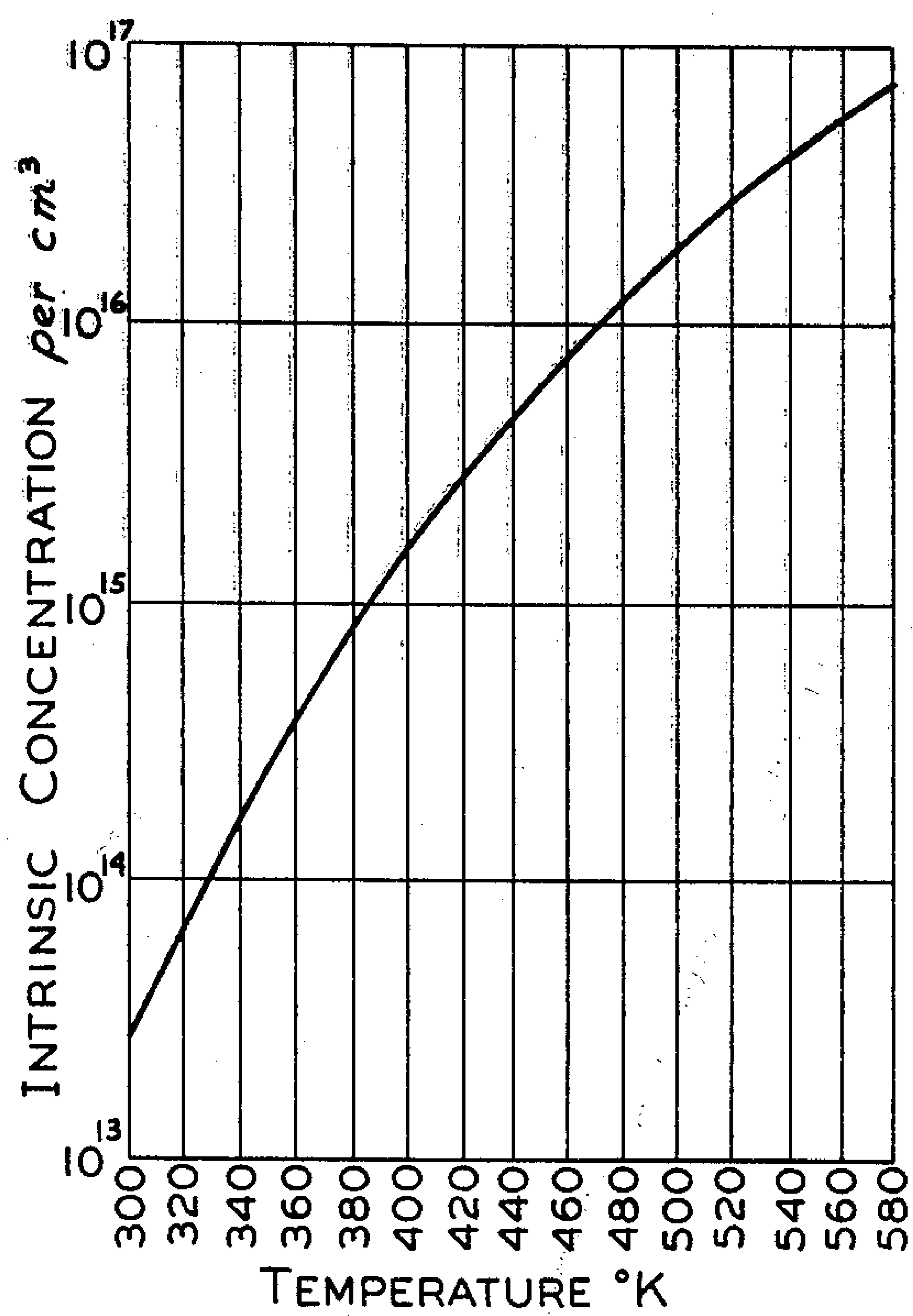

FIG. 3

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SINGLE CRYSTAL SEMICONDUCTOR RESISTORS

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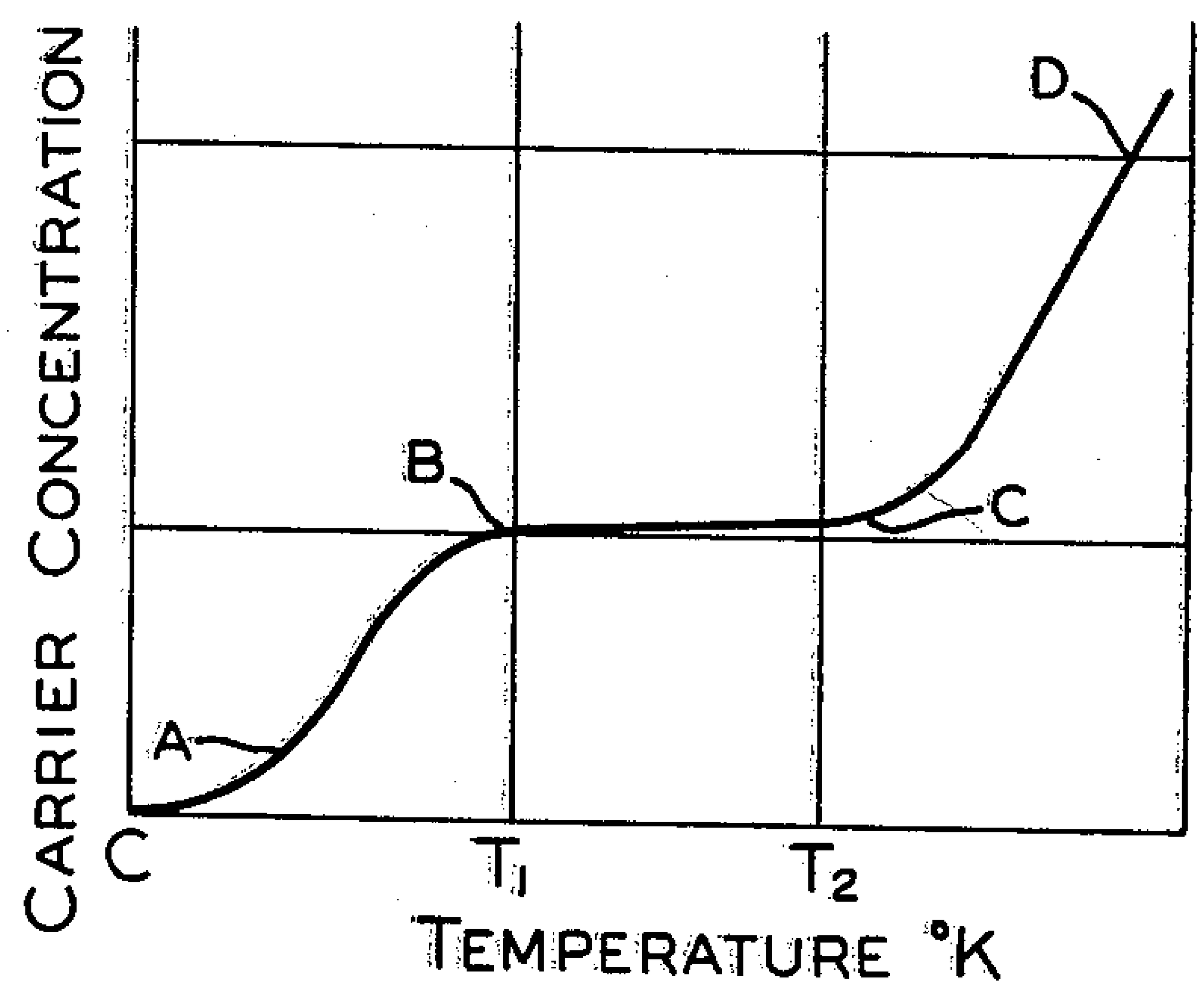

FIG. 2

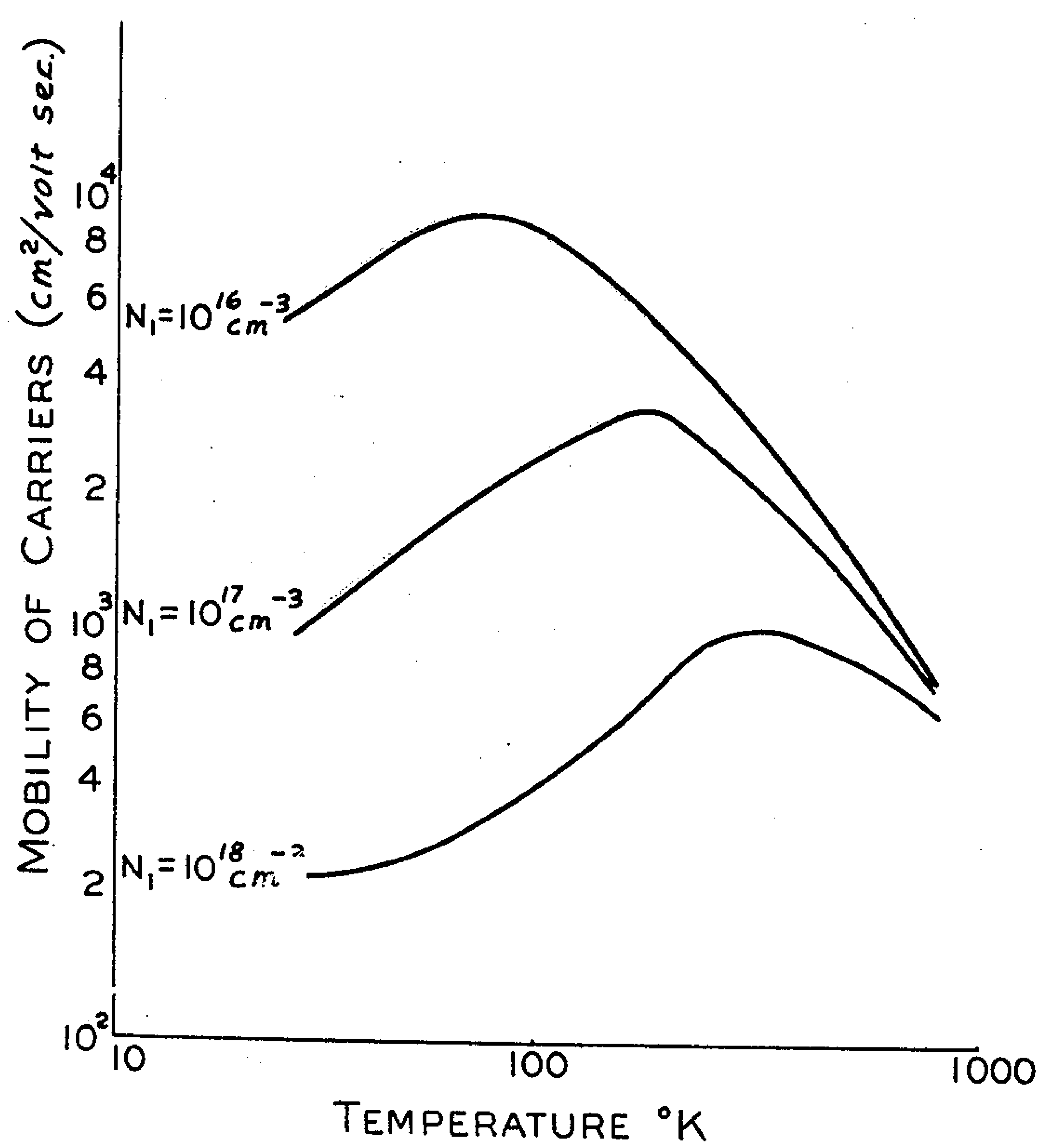

FIG. 4

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SINGLE CRYSTAL SEMICONDUCTOR RESISTORS

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This invention relates to a resistance element and more particularly to a resistance element made from a single crystal semiconductive material.

Electrical resistors are made of a material which provides an electrical resistance to a current passing between contacts attached to the resistor body. The conduction of current through the resistor body requires certain characteristics of the body. For example, three characteristics which are of importance when passing current through the resistor body are the magnitude of the resistance, the temperature coefficient of the resistance, and the stability or constancy of the resistance value over a period of time either in use or awaiting use.

Previous resistors have shortcomings which affect the above characteristics. Wire-wound resistors are made up of a ductile material formed into a type of convolute construction and are generally limited to low resistance values. In using many windings to increase the resistance, an inductance is set up in the wire-wound resistor and this is objectionable in certain applications of the resistor.

Film resistors avoid the inductance of the wire-wound resistors, but have other objectionable features. The film resistors show instability of resistance characteristics over a period of time because of the contact resistance between the grain boundaries within the respective film. These films typically consist of polycrystalline particles in which the actual resistance is located to a large extent at the grain boundaries between the separate particles or films. The grain boundary resistances are subject to change either while the resistor is in use or awaiting use. Such changes affect the resistance of the resistor containing the resistance film. One cause of change in the grain boundary resistances is absorbing gas in the film material. Minute amounts of absorbed gas have been found to affect the grain boundary resistance and this is particularly true in the case of semiconductive materials.

Thus, it is seen that polycrystalline bodies absorb gases at the grain boundaries and this results in resistance changes so that the resistors made of polycrystalline material are sensitive to minute amounts of absorbed gases. This makes the film type of resistor undesirable. Also the absorption of gas is noticeable in the so-called printed resistance layers which are made up of conductive particles dispersed within a resin which is then polymerized by heating after it has been applied to a surface for support.

It has been found that a satisfactory semiconductor resistor can be made from a single crystal of a semiconductive material provided with two ohmic contacts on the shaped single crystal piece. The ohmic contacts are attached to the single crystal semiconductor by alloying satisfactory metal contacts to the single crystal semiconductor at separate points on the semiconductor body. The metal must satisfy certain requirements to be satisfactory. For example, it must provide a conductivity of the same type as the conductivity of the semiconductor. Ohmic contacts to a p-type semiconductor body, such as

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made of indium doped germanium, are produced by alloying indium contacts to the body. Similarly, ohmic contacts to an n-type conductivity germanium body may be provided by a lead-arsenic alloy attached to the semiconductor by alloying.

The single crystal structure of the semiconductor body avoids the grain boundaries of a polycrystalline material. This eliminates the problems arising from grain boundary resistance in such polycrystalline material. In turn, the stability or longevity of the resistance characteristics are enhanced.

Further, other considerations involved in the design of resistors are helped by using a single crystal semiconductor as the resistor.

The resistance of a homogeneous material having two ohmic contacts is a product of two factors. One factor is related to the geometry of the material and the other factor is the resistivity of the material. For instance, assuming a resistance body has the shape of a bar of cross-sectional area Q and length L and is provided with contacts at diametric points on the bar, the resistance of the body will be $R=\rho L/Q$ where ρ is the resistivity of the material. The temperature coefficient of the resistance of such a body results mainly from that of the specific resistance ρ, as the influence of thermal expansion on the geometrical factor is negligible and may be disregarded.

Referring to a semiconductive material, the material may be doped to obtain a specific resistivity having a very small temperature dependance within a certain temperature region. It has been found that such a material is then very suitable for constructing a resistor of small temperature coefficient, according to this invention. It is preferable to use the term specific conductivity which is simply the reciprocal of the specific resistivity. The specific conductivity of a semiconductor with only one type of carrier is the product of three quantities. These are: (1) the concentration of charge carriers, (2) the charge of these carriers and (3) the mobility of these carriers.

For a resistor of long life under load, it is preferred to use an electronic semiconductor rather than an ionic semiconductor. Ionic conduction leads to a chemical degradation of the resistor by electrochemical action. In the case of electronic semiconductors, the charge carriers may be either electrons or holes having a charge of 1.6×10^{-19} coulombs. Semiconductors occur where both electrons and holes are present in comparative numbers and also where only electrons or only holes are present. If both electrons and holes are present, the electrical conductivity is the sum of the above-mentioned two expressions, one relating to the electrons and the other to the holes. In what follows electrons or holes will be referred to as carriers or carriers of charge.

Of the three factors which bear on the specific conductivity of the semiconductor only the charge of the carrier is clearly independent of temperature. Thus, to secure a material with a zero temperature coefficient it is necessary to provide a material in which the carrier concentration and the carrier mobility are independent of temperature. It has been found that the concentration of the carriers in semiconductors containing suitable impurities will increase with temperature up to a point where all the impurities are ionized and the concentration of carriers does not increase. Only at much higher temperatures the concentration of carrier increases again due to additional carriers created in the semiconductor.

The mobility is limited by scattering of the carriers in the crystal. This scattering occurs by the regular crystal lattice and by impurities. The scattering by lattice vibration increases with temperature. The scattering by impurities decreases with temperature. By selecting a suitable impurity concentration a mobility of the carriers independent of temperature will be obtained. Thus, there is a certain temperature range for a given impurity concentration where the temperature coefficient of mobility is zero due to this combination of two scattering effects.

It is an object of this invention to provide a resistor of a single crystal of semiconductive material having a low temperature coefficient of resistivity and good stability.

This and other objects of this invention will become more apparent upon consideration of the following description taken together with the accompanying drawings in which:

FIG. 1 is a diagram of a circuit including a representation of a resistor of this invention;

FIG. 2 is a chart illustrating the dependence of the concentration of mobile carriers of charge in the semiconductor material of this invention on temperature;

FIG. 3 shows the variation with temperature of the mobility of mobile carriers of charge in the semiconducting material of this invention for three impurity concentrations; and

FIG. 4 shows the variation with temperature of the intrinsic concentration of carriers of charge in germanium.

The resistor of this invention uses the bulk resistance of a single crystal and for practical purposes employs a semiconducting material of high specific resistivity. The material of this invention has a low temperature coefficient of resistivity, which low temperature coefficient is realized in the temperature range where all impurities in the semiconductive material are thermally ionized. That is, the range of operation of this material as a resistor is above the temperature of complete ionization of the impurities in the semiconductive material but below the temperature at which intrinsic conduction in the material sets in. The electrical resistance of the material according to this invention is temperature independent over a portion of this range.

The temperature above which impurities are fully ionized in a semiconductor is usually, but not necessarily, below the temperature at which intrinsic conduction sets in. For our patent a material has to be selected where the first mentioned temperature is below the second mentioned temperature. This assures a temperature range where the concentration of carriers does not vary substantially with temperature. When the material is operated in this temperature range as a resistor the temperature coefficient of resistance will be fairly small. In order to further decrease the temperature coefficient of the resistance, the operating temperatures must be chosen within the previously described temperature interval at or near the point where the temperature dependence of impurity scattering and of lattice scattering compensate each other.

As the impurity scattering which affects the mobility of carriers decreases with the increase of temperature and the lattice scattering increases with increasing temperature, in each resistivity semiconductive material there is a range of temperatures within which the mobility of carriers is temperature independent.

The novel features which are believed characteristic of the invention are set forth in the appended claims. The invention itself may be best understood in reference to the drawings.

Referring to FIG. 1 the invention is shown embodied in two semiconductor resistors **10** and **20**, each consisting of a bar of a semiconducting body **12** and **22** according to this invention. Low resistance electrodes **14**, **16** and **24**, **26** are attached to the ends of bodies **12** and **22** respectively and leads attach the resistors to each other and to a source potential **30**. The arrangement shown can be used as a voltage divider and the low temperature coefficient of resistance of the semiconductor resistors of this invention assures an output voltage which varies very little with temperature, assuming that the power source is temperature independent. The operation of the circuit is represented by the meter **32** in the output of the circuit.

The use of low resistance electrodes to the semiconducting body assures that the resistance arises from the geometry of the body and the resistivity of the semiconducting material. The use of a single crystalline semiconducting body assures that the resistivity of the body arises from the bulk of the material as contrasted to grain boundaries. According to this invention the material of the single crystalline semiconducting body has to be selected from materials which fulfill the requirement of zero temperature coefficient of resistivity in the range of operation of the resistor. The selection of such materials is illustrated by reference to FIG. 2. FIG. 2 shows a chart indicating the dependence on temperature of the carrier concentration in the bulk of a single crystal semiconductor as may be used for this invention. As mentioned previously, the carrier concentration is one of the factors determining the electric resistivity of the material, the other factor being the mobility of the carriers, to be discussed later.

This invention teaches a selection of a material for a semiconducting resistor with a carrier concentration independent of temperature over the operating range and a mobility of carriers varying as little as possible over the operating temperature range. In the material whose carrier concentration is shown in FIG. 2, a carrier concentration which is practically independent of temperature is seen in the range between the points B and C. This temperature independent carrier concentration arises from the fact that the carriers come from impurities which are practically all ionized at temperatures above the point B. Above the point C additional carriers are generated not from impurities but in the semiconductor lattice, and this causes the carrier concentration to increase with temperature and the resistivity to decrease with temperature. In the range between the points A and B the carrier concentration increases with temperature because an increasing fraction of impurities is ionized. The carrier concentration between the points B and C of FIG. 2 is equal to the concentration of impurities in the semiconductor crystal. For instance, adding $10^{16}/cm.^3$ antimony impurities to a germanium crystal will provide 10^{16} electrons at room temperature which are available for carrying current through the crystal. Room temperature happens to lie between the points B and C of FIG. 2 in the case of germanium doped by impurities as mention above. The temperature corresponding to the point C can be determined by reference to FIG. 3 which shows the carrier concentration in impurity free germanium as a function of temperature. This so-called intrinsic carrier concentration arises from ionization in the germanium lattice. It will be seen from FIG. 3 that a carrier concentration level of $10^{16}/cm.^3$ is reached at a temperature of 470° K., that is 197° C. Thus for the germanium crystal containing $10^{16}/cm.^3$ antimony impurities, the temperature T_2 corresponding to the point C in FIG. 2 will be approximately 200° C.

The carrier concentration in the semiconductive material as a function of temperature as illustrated in FIGS. 2 and 3 is not the only characteristic determining the temperature dependence of the semiconducting single crystal resistor. As pointed out above, the other characteristic is the mobility of the carriers and this characteristic is shown in FIG. 4 for the case of N-type germanium, that is, the carriers being electrons. Three curves are shown in FIG. 4, each curve pertaining to a different impurity concentration, N_I, in the crystal. These impurities can be, for instance, phosphorus, antimony or arsenic. It will be seen that each curve has a maximum which is reached at a certain temperature, said temperature depending on the impurity doping level of the crystal. For instance, at the doping level of 10^{16}/cm.^{3} the maximum lies below 100° K. while at the doping level of 10^{18}/cm.^{3} the maximum lies around 300° K., i.e. room temperature. The maximum of the mobility as a function of temperatures results from the fact that at temperatures lower than corresponding to the maximus, the mobility is determined by impurity scattering; while at temperatures above the maximum, the mobility is determined by lattice scattering. Therefore the mobility at temperatures below the maximum varies considerably with the impurity concentration of the crystal as seen in FIG. 4, but the mobility of the carriers above the maximum approaches the same value with increasing temperature and is independent of the impurity concentration of the crystal. The fact that impurity scattering decreases with increasing temperature but lattice scattering increases with increasing temperature leads to the opposite signs of the temperature coefficient of mobility in the ranges where impurity scattering and lattice scattering, respectively, are predominant.

On reference to FIGS. 2, 3 and 4 the selection of a suitable semiconducting material for a single crystal semiconductor resistor can be demonstrated as follows: Assume that one desires an operating range around a temperature T_0, let us say room temperature. First we have to make sure that this temperature is below the temperature T_2 shown in FIG. 2 where intrinsic conduction sets in. According to FIG. 3, at room temperature, i.e., 300° K., the intrinsic carrier concentration is a few times 10^{13}/cm.^{3}. Thus doping levels of more than 10^{14} impurities/cm.^{3} would be sufficient to assure that the temperature T_2 where intrinsic conduction sets in is above the operating temperature. Generally speaking, the temperature T_2 should be substantially over the operating temperature to permit a substantial range of safe operation of the resistor above the normal operating temperature.

Next, we have to make sure that the temperature of operation is above the temperature T_1 in FIG. 2 where all the impurities are ionized. No graph of ionization of impurities as a function of temperature for germanium has been given in this specification because it is well known in the art that in germanium all the impurities of the type phosphorous, antimony and arsenic are ionized at temperatures higher than −50° C. provided that no other impurities are present in the crystal. Thus with a phosphorous, antimony, or arsenic concentration of larger than 10^{14}/cm.^{3} in germanium we are sure that all impurities are ionized at room temperature and that no appreciable intrinsic carrier concentration is present; i.e., we are in the temperature range between the points B and C of FIG. 2.

As a third step we have to select the impurity concentration to provide a mobility of zero temperature coefficient in the operating range i.e., room temperature (300° K.) in our example. Considering FIG. 4, it is seen that this requires an impurity concentration near 10^{18}/cm.^{3}, the lowest of the three curves shown. With an impurity concentration of 10^{18}/cm.^{3} the point C of FIG. 2 where intrinsic conduction becomes dominant moves to temperatures above 700° K. (400° C.) as may be seen by extrapolating FIG. 3. Thus intrinsic conduction will not set in over a considerable temperature range above the operating temperature.

The conductivity of the material just discussed can be calculated by multiplying carrier concentration times mobility times electron charge, providing the value $10^{18}/\text{cm.}^3 \times 10^3/\text{cm.}^2/\text{volt sec.} \times (1.6)10^{-19}$ amp. sec.= 160 ohm^{-1} cm.$^{-1}$. Its reciprocal value is the resistivity and this can be used in conjunction with geometrical factors mentioned previously to provide the resistance value desired.

The selection of germanium as an example of a semiconducting material for the purposes of this patent should not necessarily imply that this patent is restricted to germanium, or even that germanium is the most desirable semiconducting material for constructing resistors according to this patent. For instance, silicon is more suitable than germanium due to the lower mobility of the carriers and due to a lower intrinsic carrier concentration than in germanium at the same temperature.

This invention provides a resistor having both high resistance values compared to metal resistors and low temperature coefficient. Among these and other advantages is the good life of the product resistor due to its low aging or high stability. These advantages obtain from the choice of suitable single crystal material of this invention as combined into the resistor which in turn is included in an electrical circuit.

This application is a continuation-in-part of application Serial No. 365,475 now Patent No. 2,953,759.

What is claimed is:

1. An electrical resistance device comprising a circuit including in combination a single crystal of uniformly semiconductive material which is electrically conductive by means of impurity atoms in said crystal which are essentially homogeneously distributed through said crystal in a concentration of greater than 10^{14} per cubic centimeters, said impurities being fully ionizable into ions and electronic carriers in a concentration independent of the temperature of operation and where the scattering of these electronic carriers by crystal lattice vibrations and by impurities results in a mobility of these carriers which is substantially independent of temperature, a source of voltage potential for producing conduction in said crystal material, low ohmic electrode connections attached to spaced portions of said crystal and leads attached to said low ohmic connections and said voltage source whereby said potential is applied to said circuit, which is operable in a temperature range including room temperature where impurities in said semiconductive material are fully ionized into ions and electronic carriers and where the scattering of these electronic carriers by crystal lattice vibrations and by impurities results in a mobility of these carriers which is substantially independent of temperature whereby said circuit is temperature independent.

2. An electrical resistor characterized by a single crystal semiconducting body selected from the group consisting of germanium and silicon, two ohmic electrodes attached to said body, the electrical conductivity of said body arising from impurity atoms selected from the group consisting of phosphorus, antimony or arsenic in said body which are essentially homogeneously distributed through said body, the electrical resistor operated in a temperature range where said impurities are fully ionized into ions and electronic carriers in a concentration independent of the temperature of operation and where the scattering of these electronic carriers by the crystal lattice vibrations and by impurities results in a mobility of these carriers which is substantially independent of temperature whereby an electrical resistor of essentially zero temperature dependence is achieved.

3. An electrical resistor characterized by a single crystal semiconducting body, two ohmic electrodes attached to said body, the electrical conductivity of said body arising from impurity atoms in said body which are essentially homogeneously distributed through said body in a concentration of greater than 10^{14} per cubic centimeter, the electrical resistor operable in a temperature range including room temperature where said impurities are fully ionized into ions and electronic carriers in a concentration independent of the temperature of operation and where the scattering of these electronic carriers by crystal lattice vibrations and by impurities results in a mobility of these carriers which is substantially independent of temperature whereby an electrical resistor of essentially zero temperature dependence is achieved.

4. An electrical resistor characterized by a single crys-

tal body of germanium, two ohmic electrodes attached to said body, the electrical conductivity of said body arising from impurity atoms selected from the group consisting of phosphorous, antimony and arsenic essentially homogeneously distributed through said body in a concentration of at least 10^{14} cubic centimeter, the electrical resistor operable at a temperature range including room temperature where said impurities are fully ionized into ions and electronic carriers, the impurities being present in the germanium in a concentration of greater than 10^{14} per cubic centimeter and where the scattering of the electronic carriers by the crystal lattice vibrations and by impurities results in a mobility inde-

pendent of temperature and greater than 200 square centimeters per volt second whereby an electrical resistor of zero temperature dependence is achieved.

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