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Yajima et al.

[11] **3,744,000**

[45] **July 3, 1973**

[54] **VARIABLE RESISTOR**

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[73] Assignee: **Nippon Carbon Company Limited,** Tokyo, Japan

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[21] Appl. No.: **40,237**

[52] **U.S. Cl.** **338/150,** 338/112

[51] **Int. Cl.** **H01c 13/00**

[58] **Field of Search** 338/89, 90, 150, 338/152, 112

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Primary Examiner—T. H. Tubbesing
Attorney—Sughrue, Rothwell, Mion, Zinn and Macpeak

[57] **ABSTRACT**

This variable resistor uses a block cutout from pyrolytic graphite or its alloy whose electrical specific resistance in a crystal axis c is different from that in a crystal axis a. The block is provided at its diametrically opposite portions with a pair of contacts to form an electrical conductive passage therebetween.

An angle θ of the electrical conductive passage inclined from the crystal axis a is made changeable to vary the resistance value across the pair of contacts.

1 Claim, 17 Drawing Figures

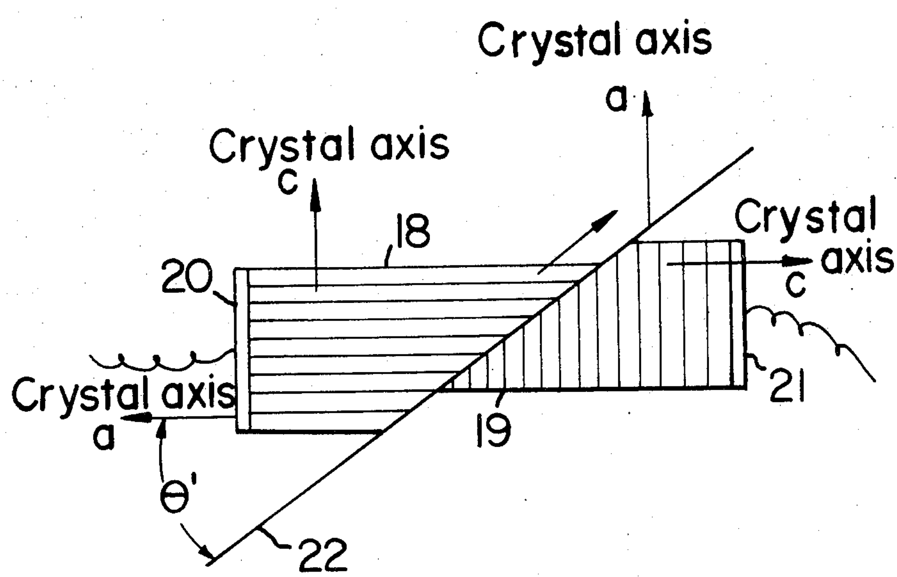


FIG. 1

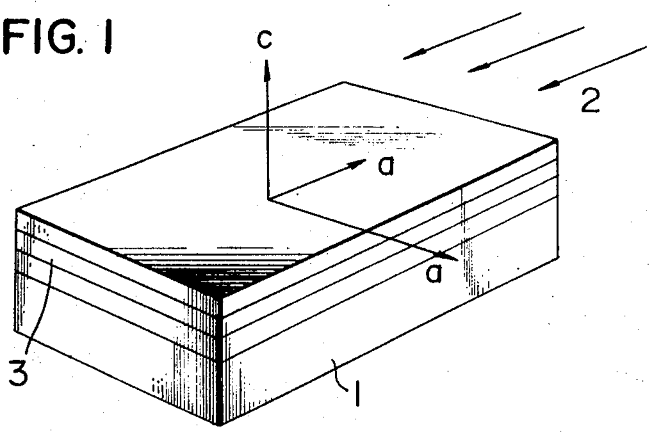


FIG. 2

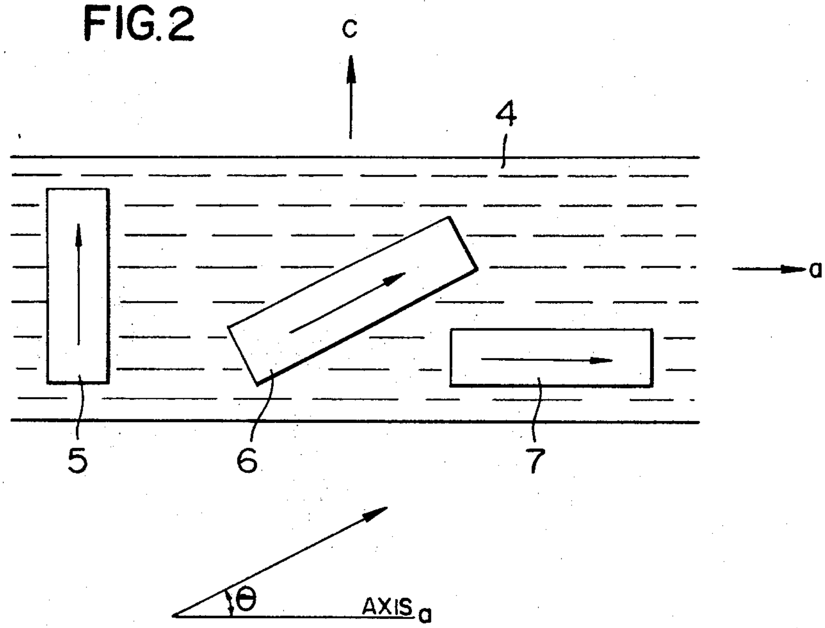


FIG.3

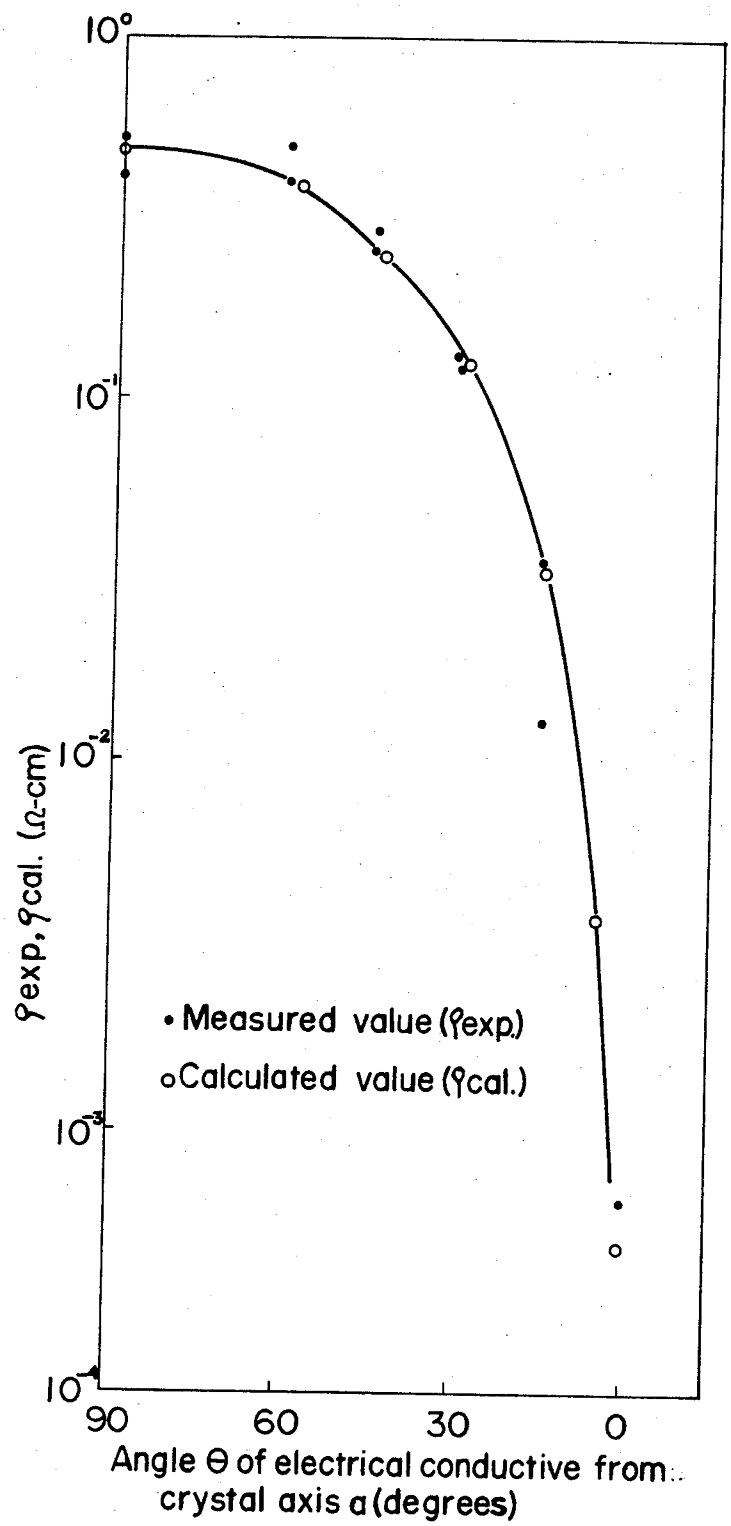

10°
10⁻¹
10⁻²
10⁻³
10⁻⁴
ρexp, ρcal. (Ω-cm)
• Measured value (ρexp.)
○ Calculated value (ρcal.)
90
60
30
0
Angle Θ of electrical conductive from crystal axis a (degrees)

FIG.4

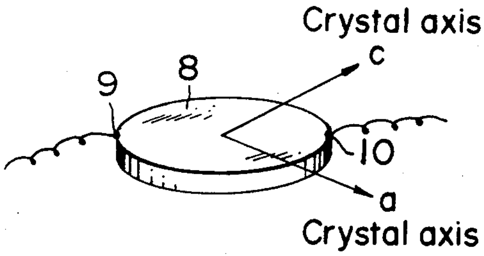


FIG.5a

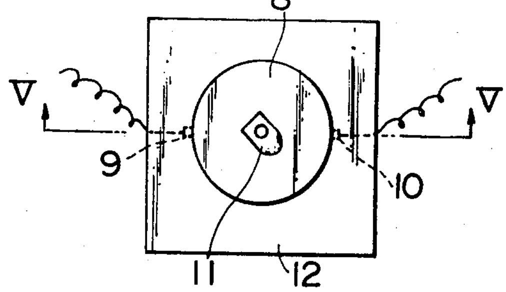


FIG.5b

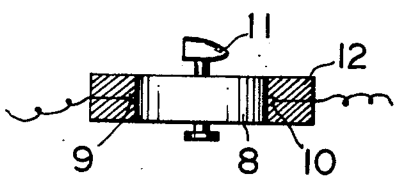


FIG.6a

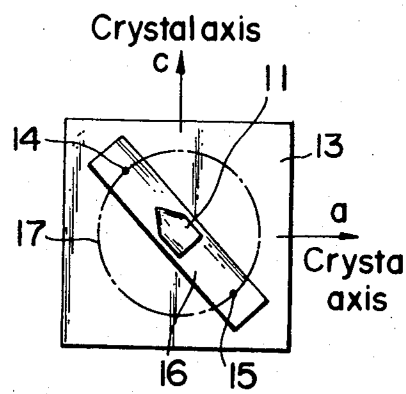


FIG.6b

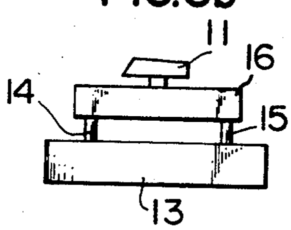


FIG.7

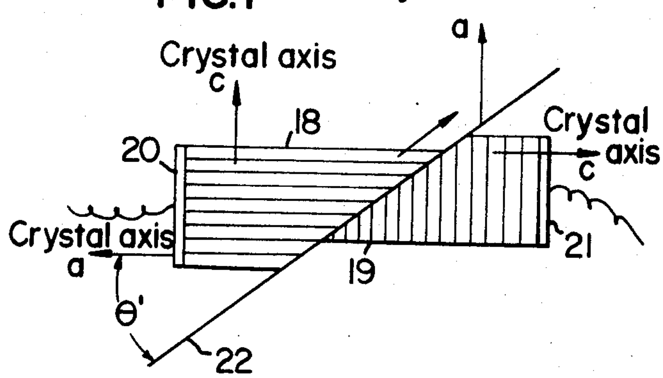


FIG.8a

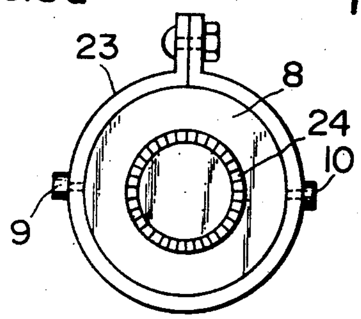


FIG.8b

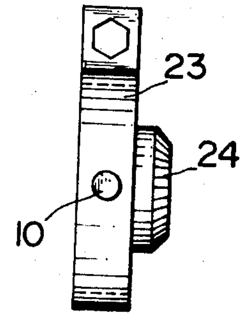


FIG.8c

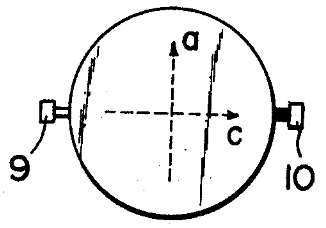


FIG.9

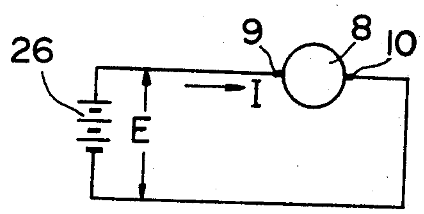


FIG.10

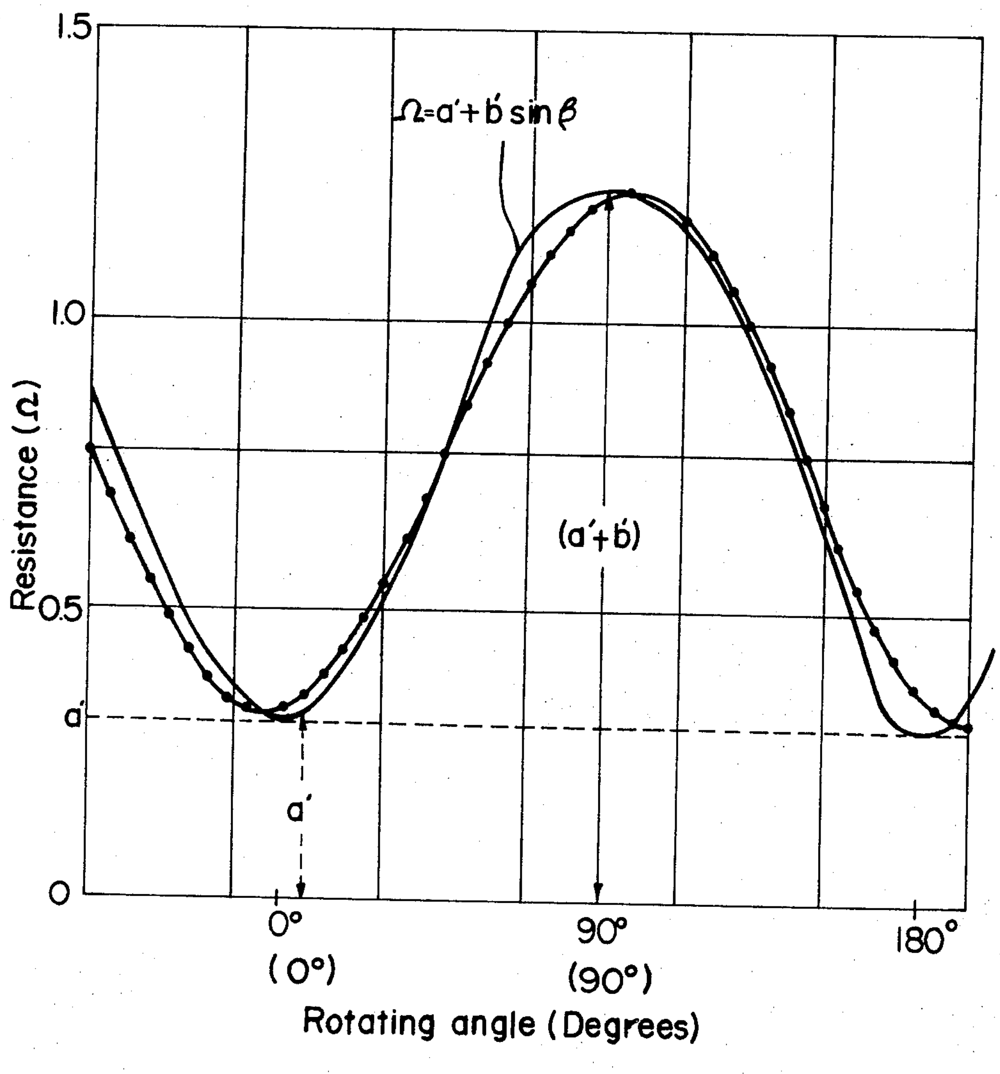

1.5
Ω=a'+b' sin β
1.0
Resistance (Ω)
0.5
a'
(a'+b')
a'
0
0°
(0°)
90°
(90°)
180°
Rotating angle (Degrees)

FIG.11

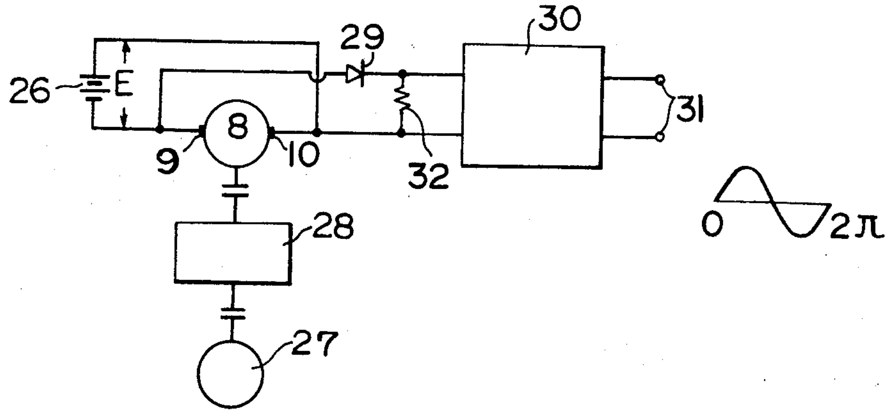
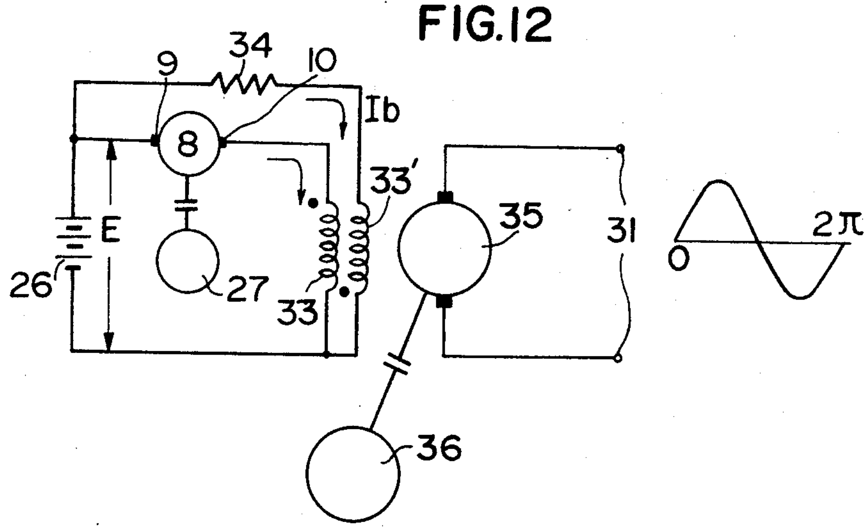


FIG.12



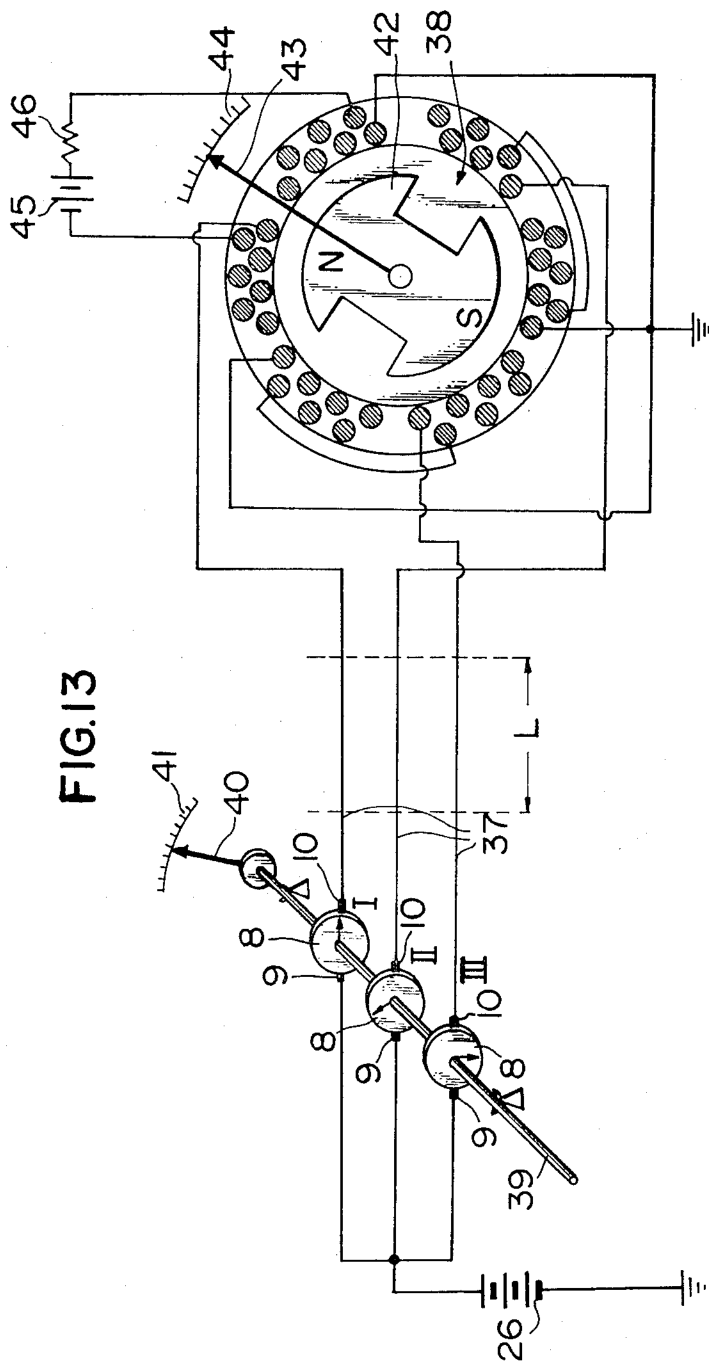


FIG. 13

VARIABLE RESISTOR

This invention relates to variable resistors for use in electrical circuits and more particularly to variable resistors comprising a block cutout from pyrolytic graphite or its alloy whose electrical specific resistance in a crystal axis c is different from that in a crystal axis a.

Variable resistors heretofore proposed directly utilize a resistance value of a material having specific resistances or adjust a distance across two contacts engaged with the material or utilize variation of the resistance value of the material caused by the pressure applied thereto or make use of a combination of resistors each having a given resistance value.

The above mentioned well known variable resistors have disadvantages that a range of variable resistance values is narrow, that it is difficult to make them small in size, excellent temperature or frequency characteristic cannot be obtained, and that the resistance value could not continuously be varied.

It is an object of the invention to provide a variable resistor which is capable of obviating all of the above mentioned disadvantages.

It is another object of the invention to provide such a variable resistor which makes use of difference of electrical specific resistances of a block cut out from pyrolytic graphite or its alloy in the direction of crystal axes *a* and *c*.

It is yet another object of the invention to provide such a variable resistor which can operate continuously without generating destructive heat in any of its parts.

It is a further object of the invention to provide such a variable resistor which can be used for measuring the frequency characteristic of an automatic control apparatus.

It is another object of the invention to provide such a variable resistor which can be used with electric energy sources which do not have reliable frequency regulation, such as a motor generator drive by an induction motor.

It is a still further object of the invention to provide such a variable resistor which can be used for indicating angles rotated in synchronism at points remotely separated one from the other.

These and other desirable objects are attained, according to the invention, by a variable resistor which comprises a block cutout from pyrolytic graphite or its alloy in a plane including crystal axes c and a thereof and a pair of contacts arranged diametrically opposite one another and engaged with said block to form an electrical conductive passage therebetween.

According to another important feature of the invention, an angle θ of said electrical conductive passage inclined from said crystal axis a is made changeable to vary the resistance value across said pair of contacts.

These features of the invention are described in greater detail in the following description of certain embodiments.

This description refers to the accompanying drawings, in which:

FIG. **1** is a perspective view of a substrate and pyrolytic graphite or its alloy layers deposited from vapor phase thereon;

FIG. **2** is an explanatory view showing samples cutout from pyrolytic graphite or its alloy in directions inclined from its crystal axis a by different angles θ;

FIG. **3** is a graph showing a relation of angles θ of an electrical conductive passage from a crystal axis a to measured and calculated values of specific resistance of the samples shown in FIG. **2**;

FIG. **4** is a perspective view of one embodiment of a variable resistor according to the invention;

FIG. **5***a* is a plan view of another embodiment of a variable resistor according to the invention;

FIG. **5***b* is a section on line V—V of FIG. **5***a;*

FIG. **6***a* is a plan view of a further embodiment of a variable resistor according to the invention;

FIG. **6***b* is a front elevation of FIG. **6***a;*

FIG. **7** is a vertical section through another embodiment of a variable resistor according to the invention;

FIG. **8***a* is a front elevation of a manually adjustable resistor according to the invention;

FIG. **8***b* is its side elevation;

FIG. **8***c* is a front elevation of a disc-shaped block with contacts adapted to be used for the resistor shown in FIGS. **8***a* and **8***b;*

FIG. **9***a* is a circuit diagram provided with a variable resistor according to the invention and for generating an oscillating current;

FIG. **10** is curves showing relations of rotating angles of the variable resistor shown in FIG. **9***a* to measured and calculated resistances thereof;

FIG. **11** is another circuit diagram provided with a variable resistor according to the invention and for measuring the frequency characteristic of an automatic control apparatus;

FIG. **12** is a further circuit diagram provided with a variable resistor according to the invention and for generating a very low frequency voltage from a motor generator drive by an induction motor; and

FIG. **13** is a still further circuit diagram provided with three variable resistors according to the invention and for synchronuously indicating rotating angles of two rotary members remotely separated on from the other.

Referring now to FIG. **1** there is shown a rectangle-shaped substrate **1** consisting essentially of graphite. The substrate **1** is heated in a gaseous atmosphere **2** consisting of a carbon compound such as propane, methane, carbon tetrachloride at a high temperature. The gaseous atmosphere is thus thermally decomposed to produce carbon which is then deposited from the vapor phase on the surface of the substrate **1** and grown into pyrolytic graphite layers **3**. In the present instance the gaseous atmosphere **2** is introduced onto the surface of the substrate **1** in the form of streams as shown by arrows.

The above mentioned gaseous atmosphere added with an element to be alloyed with graphite such, for example, as a silicon tetrachloride ($SiCl_4$) gas containing silicon to be alloyed with graphite may be introduced onto the surface of the substrate **1** to deposit from the vapor phase thereon a pyrolytic graphite alloy layers **3**.

The pyrolytic graphite or its alloy layers **3** thus deposited from the vapor phase have a crystal axis *c* in a direction perpendicular to the surface of the substrate **1** and hence a crystal axis a thereof is in parallel with the surface of the substrate **1**.

Physical properties in the direction of the crystal axis a of the pyrolytic graphite or its alloy layers **3** thus obtained are considerably different from those in the direction of the crystal axis *c* thereof, as shown in the following Table 1.

TABLE 1

Physical Properties	Direction of Crystal Axis a	Direction of Crystal Axis c
Compressive Strength kg/cm^2	600	2,500
Shore Hardness	40	100
Electrical Specific Resistance $10^{-5}\Omega$-cm	40	50,000
Heat Conductivity Cal/cm-sec-°C	1.3	0.03
Oxidizing Velocity in Air at 700°C mg/cm^2min	2×10^{-1}	6×10^{-2}

The results shown in the above Table 1 were obtained by measuring the physical properties of the pyrolytic graphite layers 3 produced at 2,400° C.

Experimental tests have yielded the surprising result that the difference of the above mentioned properties in the crystal axes a and c becomes further increased when the pyrolytic graphite layers 3 obtained are heat treated at about 3,000° C, and that any other physical or chemical treatments subjected to the pyrolytic graphite layers 3 during or after the growth thereof can still further increase the above mentioned difference.

Experimental tests have also shown that the pyrolytic graphite has a ratio of the electrical specific resistance in the direction of crystal axis *a* to that in the direction of crystal axis *c* of about 1:1,000, while the pyrolytic graphite alloy containing silicon, for example, has the above mentioned ratio of about 1:10,000.

As above mentioned, one of the objects of the invention is to provide such a variable resistor which makes use of the above mentioned difference of electrical specific resistances in the directions of crystal axes a and c and which is capable of varying the specific resistance over a very wide range in a continuous manner without generating destructive heat in any of its parts.

Briefly summarizing the advantages of the improved variable resistor of the invention, it may be said to provide the following benefits.

1. Various resistance values can be obtained over a considerably wide range in a continuous manner without generating destructive heat in any of its parts;
2. Small in volume and compact in construction;
3. Mechanical strength is large and stable in handling;
4. Simple in construction and positive in operation without any troubles;
5. Temperature characteristic is excellent;
6. Frequency characteristic is also excellent; and
7. Temporary large current flow does not cause any breakage.

Among the above, the first mentioned advantage that various resistance values can be obtained over a considerably wide range in a continuous manner without generating destructive heat in any of its parts could not be obtained by the conventional variable resistors heretofore proposed.

In FIG. 2 a sample 5 is cutout from pyrolytic graphite 4 in a direction perpendicular to its crystal axis a, a sample 6 is cutout in a direction inclined from the crystal axis a by an angle θ and a sample 7 is cutout in a direction parallel with the crystal axis *a*.

The pyrolytic graphite 4 is produced by thermally decomposing a propane gas at 2,000° C and depositing carbon thus obtained from the vapor phase on the surface of a graphite substrate.

An electrical conductive passage of each of the samples 5, 6 and 7 which is inclined from the crystal axis a by different angles is shown by an arrow in FIG. 2.

Then, the specific resistance across each electrical conductive passage of the samples 5, 6 and 7 is measured with the aid of four probes method whose standard resistance is 0.01Ω and current carrying capacity is 0.3A. The measured values $\rho_{exp.}$ thus obtained are shown by small dots in FIG. 3.

Now, the specific resistance ρ_θ of the sample 6 whose electrical conductive passage is inclined from the crystal axis a by an angle θ is given by the equation

$$\rho_\theta = \rho_c \sin^2\theta + \rho_a \cos^2\theta \ldots \quad (1)$$

where ρ_c is the specific resistance of the sample 5 whose electrical conductive passage is perpendicular to the crystal axis *a* and ρ_a is the specific resistance of the sample 7 whose electrical conductive passage is in parallel with the crystal axis *a*.

Then, the specific resistance ρ_θ is calculated with the aid of the equation (1). The calculated values ρ_{cal} thus obtained are shown by small circles in FIG. 3.

As seen from FIG. 3, the calculated values ρ_{cal} are substantially equal to the measured values ρ_{exp}. This fact is very important in case of designing the variable resistor according to the invention.

A variable resistor shown in FIG. 4 comprises a disc-shaped block 8 cutout from pyrolytic graphite or its alloy in a plane including crystal axes *c* and *a* and a pair of contacts 9 and 10 arranged diametrically opposite one another and secured to the periphery of the block 8 to form an electrical conductive passage therebetween.

The resistance value across the contacts 9 and 10 is determined by the electrical conductive passage inclined from the crystal axis *a*. In the present instance, this resistance value is constant and the variable resistor shown in FIG. 4 constitutes a fixed resistor.

A number of disc-shaped blocks 8 whose electrical conductive passages are inclined from the crystal axis a by the same or different angles and hence having the same or different resistance values may be connected in series and/or parallel each other, thereby changing the shape of the curve shown in FIG. 3.

When the block 8 is rotatably mounted in a base plate 12, it is possible to rotate the block 8 by means of a knob 11 secured thereto as shown in FIGS. 5*a* and 5*b* and vary the resistance value across the contacts 9 and 10 over a wide range in a continuous manner without generating destructive heat in any of its parts.

In this case, the contacts 9 and 10 are replaced by brushes.

The contacts or brushes 9 and 10 may be made of metals such as silver, copper or any other electrical conductive metals and of non-metals such as carbon, graphite or any other electrical conductive non-metal.

FIGS. 6*a* and 6*b* show another embodiment of the variable resistor according to the invention. In the present instance, a square-shaped block 13 is cutout from pyrolytic graphite or its alloy in a plane including crystal axes c and a and a pair of contacts 14 and 15 arranged diametrically opposite one another and secured to the lower surface of a rotatable member 16 having a knob 11 are made in slidably contact with the block 13. In the present example, it is also possible to rotate the member 16 by means of the knob 11 along a circular locus 17 on the block 12 and hence vary the resistance value across the contacts 14 and 15 over a wide range in a continuous manner.

In another embodiment shown in FIG. 7, provision is made of a set of two blocks 18 and 19 each cutout from pyrolytic graphite or its alloy in a plane including crystal axes *c* and *a* as shown in FIG. 7. The two blocks slidably engaged each other at a plane 22 intersecting the crystal axis *c* of each block. A pair of contacts 20 and 21 secured to that periphery of each block at the end opposite to the sliding plane 22 form an electrical conductive passage across the contacts 20 and 21. In the present instance, the resistance value across the contacts 20 and 21 may be varied by displacing either one or both of the blocks 18 and 19 along the intersecting plane 22 or by changing positions of the contacts 20 and 21 secured to the blocks 18 and 19, respectively.

Because the material used is pyrolytic graphite, the resistance along axis *c* is very high relative to the resistance along axis *a*. The resistance from contact 20 to plane 22 may therefore be considered negligible with respect to the resistance from plane 22 to contact 21. As block 19 moves along plane 22 it can be seen that the average distance between the portion of block 19 contacting block 18 and contact 21 increases, thereby increasing the resistance between contact 20 and contact 21. θ' can be selected so that movement of block 19 along axis 22 will cause a large or small change in resistance in accordance with the intended use of the device. Furthermore, pyrolitic graphite materials serve as a lubricant to enhance the sliding of the blocks along axis 22.

Alternatively, the resistance value across the contacts 20 and 21 is made adjustable by varying the angle θ' of the intersecting plane 22 inclined from the crystal axis a of each of the blocks 18 and 19, respectively.

FIGS. 8*a*, 8*b* and 8*c* show a manually adjustable resistor whose disc-shaped block 8 is rotatably mounted in an insulative holder 23 and made adjustable with the aid of a knob 24.

In the present instance, the resistance value across the contacts 9 and 10 may be varied by rotating the knob 24 over a wide range in a continuous manner.

In a circuit arrangement shown in FIG. 9, a disc-shaped block 8 is rotatably inserted through brushes 9 and 10 in an electrical circuit including a direct current voltage supply source 26 whose voltage E is applied through the brushes 9 and 10 to the block 8.

When the direct current voltage supply source 26 supplies the direct current voltage E across the block 8 and the block 8 is rotated, current I flowing through the block 8 oscillates. The oscillations are given by the equation $(a+b \sin\alpha)$ A where a is the current flowing through the crystal axis *c* and $(a+b)$ the current flowing through the crystal axis *a*. Then, the resistance across the electrical conductive passage formed between the brushes 9 and 10 is measured and the results thus obtained are shown by a full line curve in FIG. 10, which is given by the equation $(a'+b' \sin\beta)\Omega$ where $a'\Omega$ is the resistance of the block 8 in the crystal axis *a* and $(a'+b')\Omega$ is the resistance of the block in the crystal axis *c*. The resistance calculated from the above equation is shown by small dots connected curve in FIG. 10. As seen from FIG. 10, these calculated resistance values are substantially equal to the measured resistance values.

In a circuit arrangement shown in FIG. 11, a disc-shaped block 8 is rotated at a constant low speed by means of an induction motor 27 through a reduction gear 28 and the brushes 9 and 10 are connected through a diode 29 and a direct current amplifier 30 to output terminals 31. 32 designates a shunt resistor. In the present instance, rotation of the block 8 at different low speeds by changing a gear ratio of the reduction gear 28 ensures a generation of any desired very low frequency voltage which can be used for measuring the frequency characteristic of an automatic control apparatus.

In another circuit arrangement shown in FIG. 12, a disc-shaped block 8 is rotated at a constant low speed by means of an induction motor 27 and the variable output current Ipg is supplied to an exciting winding 33, while a regulating resistor 34 and a regulating winding 33' connected in series are connected in parallel with the block 8 and the exciting winding 33. These exciting windings 33 and 33' are wound to produce magnetic fields opposite in polarities and serve to excite a generator 35 driven by a prime mover such as an induction motor 36. The motor generator drive shown in FIG. 12 does not have reliable frequency regulation. The above mentioned circuit arrangement, however, makes it possible to use a high power direct current generator for the purpose of regulating frequency in a reliable manner.

In a still further circuit arrangement shown in FIG. 13, provision is made of three disc-shaped blocks I, II and III whose crystal axes c are displaced one from the other by 120°, respectively. These blocks I, II and III are connected through the brushes 9 to three conductors 37 connected in common to a direct current voltage supply source 26 and through the brushes 10 to stator windings of a synchronous motor 38 which is located at a position remotely separated from the blocks I, II and III by a distance L. The blocks I, II and III are rotated by a driving shaft 39 having an indicating needle 40 associated with a dial scale 41. 42 designates a rotor of the synchronous motor 38 whose shaft is provided with an indicating needle 43 associated with a dial scale 44. 45 is a bias current supply source for supplying a bias current through a resistor 46 to the stator winding of the synchronous motor 38 for the purpose of annihilating the direct current component.

When the driving shaft 39 causes to rotate the blocks I, II and III and hence move the indicating needle 40 along the dial plate 41, the indicating needle 43 also moves along the dial plate 44. Thus, the circuit arrangement shown in FIG. 13 renders it possible to effect the same angular indications at points remotely separated one from the other.

The embodiments illustrated and described herein are illustrations only of the invention, and other embodiments will occur to those skilled in the art. No attempt has been made herein to go into all possible embodiment, but rather only to illustrate the principle of the invention and the best manner now known to practice it.

What is claimed is:

1. A variable resistor comprising a first and second block of pyrolytic graphite and silicon, each block having crystal axes *c* and *a*, crystal axis *c* defining the axis of maximum electrical resistivity and crystal axis a defining the axis of minimum electrical resistivity wherein the ratio of resistivity along axis *c* to the resistivity

along axis a is 10^4; said first block slidably engaging said second block in a plane at an angle θ' from axis a of said first block and at an angle $90°-\theta'$ from axis a of said second block; a first contact secured to the side of said first block opposite to the side which slidably engages said second block and a second contact secured to the side of said second block opposite to the side which slidably engages said first block; wherein the resistance between said first and second contacts is a function of the position of the first block with respect to the second block on their slidably engaging surfaces, and the resistance is changed by sliding said first block with respect to said second block along said slidably engaging surfaces.

* * * * *