June 20, 1961 H. WELKER ET AL 2,989,715

VARIABLE ELECTRIC RESISTANCE DEVICE

Filed Sept. 9, 1958

FIG. 1

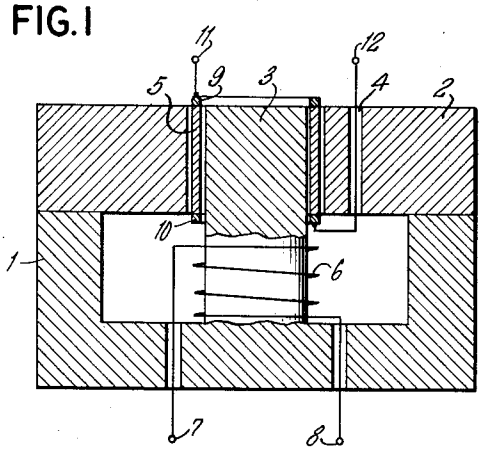
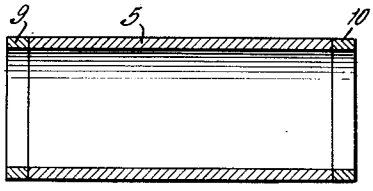


FIG. 2



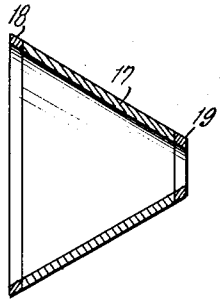
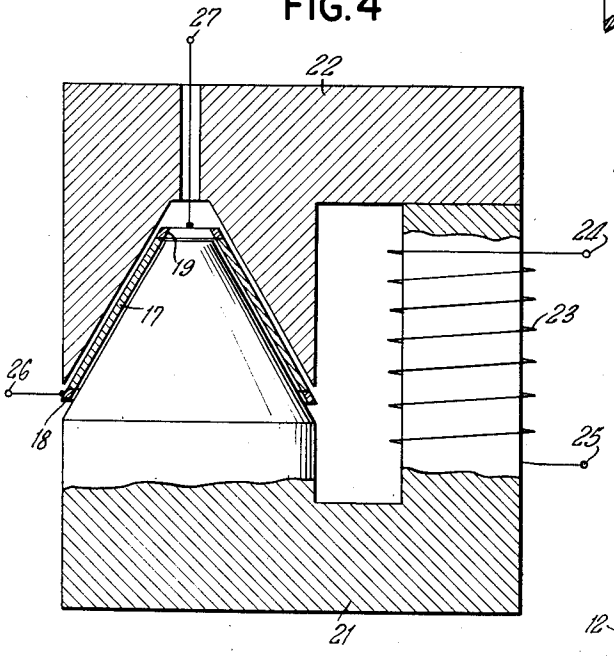


FIG. 3

FIG. 4



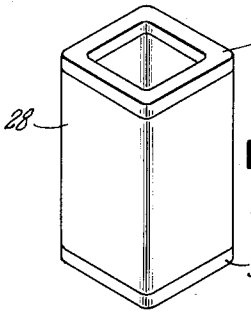


FIG. 5

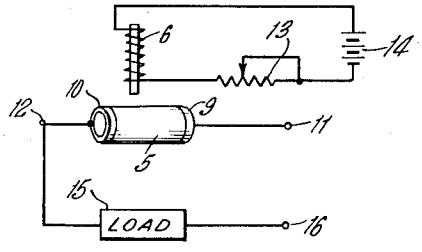


FIG. 6

United States Patent Office 2,989,715 Patented June 20, 1961

2,989,715

VARIABLE ELECTRIC RESISTANCE DEVICE

Heinrich Welker, Erlangen, and Herbert Weiss, Nurnberg, Germany, assignors to Siemens-Schuckertwerke Aktiengesellschaft, Berlin-Siemensstadt, Germany

Filed Sept. 9, 1958, Ser. No. 760,002
6 Claims. (Cl. 338—32)

Our invention relates to variable electric resistance devices of the type utilizing the effect of a variable or controllable magnetic field upon the ohmic resistance of a body formed of semiconducting substance. Electric devices of this type are disclosed and claimed in our copending application Serial No. 470,092, filed November 14, 1954, now U.S. Patent No. 2,894,234; and it is an object of our present invention to improve such devices toward better adaptability to various voltage and current requirements.

The most preferable magnetically controllable resistance devices among those disclosed in said copending application have the shape of a flat disc of semiconductor substance provided with a peripheral contact electrode and a central electrode. Such devices are well suitable for many control, regulating, and protective purposes but they afford optimum efficacy only at relatively low ohmic resistance values, which limits their use in practice to relatively low voltages and relatively high currents. It is therefore another, more specific object of the present invention to devise variable resistance devices, based upon the same principle of resistance change in response to changes of a magnetic field acting upon the resistance material, that are not so limited but can be given any desired resistance value and can be used to advantage for any desired voltages and currents within a very much wider, virtually unlimited range.

Another object of our invention is to provide a magnetic-field responsive resistance device which is insensitive to sudden surges of abnormally high overvoltage or greatly excessive current and hence is eminently suitable for protection of more sensitive electric components such as transistors, discharge tubes, circuit breakers or measuring instruments.

To achieve these objects and advantages, or those mentioned hereinbelow, we provide the variable electric resistance device with magnet field means, preferably an electromagnet of variable or controllable excitation, and dispose in the magnet field a resistance member formed of a hollow, tubular body of semiconductor substance with two electrodes or terminal contacts attached at its respective axial ends, the orientation of the tubular body relative the magnetic field being such that the field, or a predominant component thereof, passes transversely through the walls of the tubular body. Therefore, the ferromagnetic core structure of the field means is given a tubular field gap and the tubular semiconductor resistance body is coaxially located in the gap.

When the tubular resistance member is traversed by electric current passing through the terminal contacts and the magnetic field has zero intensity, the current flow lines in the resistor extend substantially straight from one to the other terminal contact, and the resistance is a minimum. When the magnetic field is effective, for instance by exciting the electromagnet producing it, the current flow lines are diverted and lengthened so that they extend substantially helically through the tubular semiconductor body, thus increasing the effective ohmic resistance in dependence upon the intensity of the magnetic field.

The invention will be further explained with reference to the embodiments of devices according to the invention illustrated by way of example on the accompanying drawing in which:

FIG. 1 shows schematically an axial section of a resistance device containing a cylindrical semiconductor resistance member separately illustrated by the sectional view of FIG. 2; FIG. 3 is a sectional view of a conical resistance member, and FIG. 4 illustrates in section a resistance device incorporating the resistance member of FIG. 3. FIG. 5 shows in perspective a hollow prismatic resistance member also suitable in devices according to the invention, and FIG. 6 shows schematically a circuit diagram illustrating one of the ways in which a device according to the invention may be used.

The variable resistance device illustrated in FIGS. 1 and 2 comprises a cup-shaped core structure of ferromagnetic material such as laminated iron and has a pole portion 2 which covers the cup space, and a central core portion 3 which forms an annular, tube-shaped field gap 4 together with the pole portion 2. Located in the tubular gap is a resistance member composed of a resistance body 5 of semiconductor substance and two metal electrodes 9, 10 serving as current supply terminals which are fused or soldered to the semiconductor body. The semiconductor body 5 may consist of indium antimonide or any of the other semiconductor substances mentioned below. The terminal electrodes 9 and 10 may both consist of indium metal, or tin, or indium-tin alloys, although other metals known for use as contacts or semiconductor bodies are likewise applicable.

The resistance member is hollow-cylindrical and extends in coaxial relation to the core portion 3. The resistance member is insulated from the core 3 as well as from the pole portion 2. A magnetizing coil 6 is disposed on the core portion 3 within the cup space of the structure and is connected with terminals 7, 8. The electrodes 9, 10 are connected with respective terminals 11 and 12. When the field coil 6 is excited by passing current therethrough, the magnetic field induced in the core structure and passing through the gap 4 extends transverse to the walls of the tubular semiconductor body 5.

One of the applicable ways of using such a device is exemplified by the circuit diagram of FIG. 6 in which the device of FIGS. 1 and 2 is shown only schematically. When the field coil 6 is excited through a controllable resistor 13 from a suitable current source 14, the semiconductor member 5 varies its resistance thus controlling the current passing through a load 15 from a power source to which the load terminal 16 and the resistor terminal 11 are attached.

As explained above, the change in resistance is due to the fact that the current flow lines which, when the magnetic field is zero i.e. when coil 6 is not excited, pass straight between the electrodes 9 and 10, become diverted so that they pass helically from one to the other electrode, the reason for this behavior being fully explained in the above-mentioned co-pending application Serial No. 470,092.

It will be understood that the same resistance-varying effect is attained when the magnetic field is varied in any other suitable way. For example, the core structure may consist of, or may comprise as its core portion, a permanent magnet, and the change in field strength, acting upon the semiconducting resistance body, may be effected by longitudinally displacing the resistance member in the field gap.

The shape and dimensions of the resistance member may also be modified in various respects. For example, while in FIGS. 1 and 2 the illustrated resistance member is of straight cylindrical shape, FIG. 3 shows a tubular member of frustoconical shape. According to FIG. 3 the semiconductor body 17 is provided with terminal electrodes 18 and 19, and according to FIG. 4 such a conical resistance member is inserted into a likewise conical field gap formed between the two portions 21 and 22 of a

magnetizable field structure which is excited by means of a magnetizing coil **23** connected to terminals **24, 25**, the electrodes **18** and **19** of the semiconducting resistor member being connected to respective terminals **26** and **27**.

It will be understood from FIG. 5 that the resistance member may also be given a substantially prismatic shape, the tubular main body **28** consisting of semiconducting substance and the terminal electrodes **29** and **30** of metal.

The above-described modifications will suffice to show that as far as the shape of the tubular body is concerned it is merely essential to give this body a generally annular cross section closed upon itself and to provide it with electrodes at the two axial ends thereof, the tubular resistance member being so oriented in the field of a magnetic field system that the field, or a predominant component thereof, extends transversely through the walls of the semiconductor body.

The above-mentioned compound, indium antimonide, is not the only semiconductor substance suitable for the purposes of the invention. In principle, the described phenomenon of a magnetically controllable electric resistance is also observed with elemental semiconductor substance such as germanium and with numerous semiconducting compounds such as mercury telluride (HgTe) and the semiconductor substances appertaining to the class generally called $A_{III}B_V$ compound which comprises all sixteen binary compounds formed of any one of the third-group elements boron, aluminum, gallium and indium with any one of the fifth-group elements nitrogen, phosphorus, arsenic and antimony. Semiconductor compounds having a carrier mobility of about 6,000 cm.²/volt second are generally preferable because of the limitation to which the magnetic field is subjected by saturation of the iron structure as is explained in the copending application Serial No. 470,092. From this viewpoint we have found indium antimonide (InSb) to afford best results in cases where voltages in the order of one to ten volts or more, and currents in the order of amperes are involved. However, for similar purposes, indium arsenide (InAs) or mixed crystals of indium arsenide and indium phosphide are likewise applicable. To compounds gallium arsenide (GaAs) and indium phosphide (InP) are less preferable when the resistance device is to have relatively low ohmic resistance, but they are well suitable where high-ohmic resistance is required. It will be noted that the semiconductor substances found by us to deserve preference for the purposes of the invention belong to the class of the $A_{III}B_V$ compounds.

The semiconductor substance may have extrinsic conductance, usually n-type, as exhibited by the high-purity semiconductor substances resulting from the production and processing methods generally known and used for materials now being employed as transistors, thermistors, and other diode and triode semiconductor devices for electrical purposes. In this respect reference may be had, for example, to Section 6, Preparation of Semiconductor Materials by H. F. Priest in Handbook of Semiconductor Electronics, edited by L. P. Hunter, McGraw-Hill Book Company, New York, 1956, or the following publications: Pearson and Tannenbaum, The Physical Review (U.S.A.), page 153, April 1, 1953; H. Weiss, Zeitschrift für Naturforschung, pages 463–469, August 1953; H. Welker, Zeitschrift für Naturforschung, pages 248–251, April 1953, and page 744 to page 749, of 1952; and Gremmelmaier et al., Zeitschrift für Naturforschung, page 333, May 1953.

The electrodes such as those denoted by **9** and **10** in FIG. 2, may be made of any suitable metal, as already explained above, it being understood that, as a rule, these electrodes are not required to form a barrier-layer on p-n junction with the resistance material. By using indium metal as electrode material, this metal may contain donor substance such as tellurium, selenium or sulphur atoms, although the presence of such beneficial impurities is not necessary.

The tubular resistance bodies can be made by casting the molten material in a mold. For such casting purposes a slightly conical design is preferable to a strictly cylindrical shape of the resistance body. The melting and casting of the previously purified material is preferably done in vacuum. The material in the finished resistance body may be polycrystalline or coarsely crystalline. It is not necessary to subsequently submit the body to zone melting for further purification or for producing a substantially monocrystalline texture, although such further processing may be applied if desired.

One of the outstanding advantages of devices according to the invention as compared with those previously disclosed is the fact that by virtue of the tubular resistance body and the correspondingly designed field structure, the resistance of the device can be given virtually any desired value simply by correspondingly selecting its length, diameter and wall thickness. For that reason, such a device can be used for any desired voltage and current requirements. For example, when using a device according to FIGS. 1 and 2 with a resistance member consisting of indium antimonide and having an outer diameter of 1 centimeter, a wall thickness of 1 millimeter and an axial length of 5 centimeters, the device is capable of controlling currents up to approximately 10 amps. at a voltage up to approximately 10 volts along the resistance body. A resistance body of the same diameter and wall thickness but shorter length of course corresponds to a smaller voltage drop down to approximately one volt. The obtainable change in resistivity with indium antimonide having a conductivity of $\sigma=200$ is 1:40 with a magnetic field of up to 10,000 gauss. Indium antimonide of a conductivity $\sigma=800$ affords a change in resistivity of 1:30 at 10,000 gauss. Although the latter range of change in resistance is smaller than with indium antimonide of lower conductivity, a better constancy relative to changes in temperatures is obtained.

Another advantage of devices according to the invention is the fact that they are insensitive to sudden surges of excessive voltage or excessive current. For that reason, they are well suitable for the protection of other electrtic components of greater sensitivity such as transistors, switches, circuit breakers or measuring devices. For example, in a load circuit according to FIG. 6, the load **15** can be protected from such surges by connecting the circuit of excitation coil **6** with the load circuit so as to respond either to the current or the voltage of that circuit with the effect of causing any voltage or current surges to instantaneously increase the effective resistance of the semiconductor member for protection of the load.

In comparison with transistor and similar devices applicable for power control, devices according to the invention operate with any ratio of dimensions and any absolute value of these dimensions. For example, the extremely small spacing between the electrodes of a transistor need not be observed in devices according to the invention where the electrodes may be spaced from each other any desired distance required for obtaining given electric characteristics.

We claim:

1. A variable electric resistance device comprising magnet means having two pole portions of which one surrounds the other with radial clearance so as to form together therewith a tubular field gap, and a hollow tubular resistance member of extrinsic-type semiconductor substance disposed in said gap in coaxial relation thereto and having terminal electrodes mounted on opposite axial ends respectively, said substance having a minimum carrier mobility of about 6000 cm.²/volt second.

2. A variable electric resistance device comprising magnet means having two pole portions of which one surrounds the other with radial clearance so as to form together therewith a tubular field gap, and a hollow tubular resistance member disposed in said gap in coaxial rela-

tion thereto, said member having a tubular body of semiconductor substance selected from the group consisting of indium antimonide and indium arsenide, and metal contacts mounted on opposite axial ends respectively of said body.

3. A variable electric resistance device comprising magnet means having two pole portions of which one surrounds the other with radial clearance so as to form together therewith a cylindrical tubular field gap, and a hollow cylindrical resistance member of semiconducting compound substance coaxially mounted in said gap, said member having respective terminal contacts on both of its axial ends said compound having extrinsic conductance and a minimum carrier mobility of about 6000 cm.^{2}/volt second.

4. A variable electric resistance device comprising magnet means having a central conical pole piece and an interiorly conical outer pole piece, said outer pole piece concentrically surrounding said central pole piece with radial clearance and forming together therewith a conical tubular field gap, and a hollow conical resistance member of semi-conducting compound substance coaxially mounted in said gap, said member having respective terminal contacts on both of its axial ends said compound having extrinsic conductance and a minimum carrier mobility of about 6000 cm.^{2}/volt second.

5. A variable electric resistance device comprising an electromagnet having two pole portions of which one surrounds the other with radial clearance so as to form together therewith a tubular field gap and having an excitation coil for controlling the magnetic field in said gap, an electric resistance member having a hollow tubular body of semiconductor substance disposed in said tubular gap in coaxial relation thereto and terminal electrodes mounted on opposite axial ends of said body, whereby changes in excitation of said coil cause said member to change its resistance between said electrodes, said substance having a minimum carrier mobility of about 6000 cm.^{2}/volt second.

6. A variable electric resistance device comprising an electromagnet having two pole portions of which one surrounds the other with radial clearance so as to form together therewith a tubular field gap, an electric resistance member having a hollow tubular body consisting of $A_{III}B_V$ semiconductor compound and being disposed in said tubular gap in coaxial relation thereto, said member having respective terminal electrodes mounted on opposite axial ends of said body, whereby changes in excitation of said magnet cause said member to change its resistance between said electrodes said compound having extrinsic conductance and a minimum carrier mobility of about 6000 cm.^{2}/volt second.

References Cited in the file of this patent

UNITED STATES PATENTS

2,616,074	McCreary	Oct. 28, 1952
2,736,858	Welker	Feb. 28, 1956
2,752,434	Dunlap	June 26, 1956