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H. S. SOMMERS, JR

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SOLID-STATE CHARGE CARRIER VALVE

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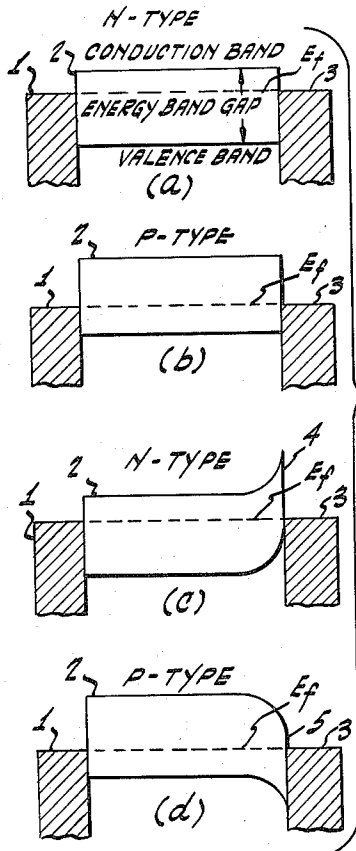


Fig. 1.

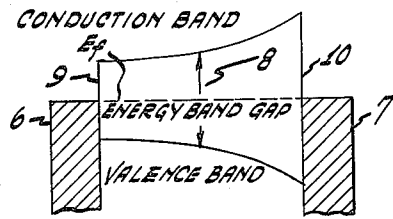


Fig. 2.

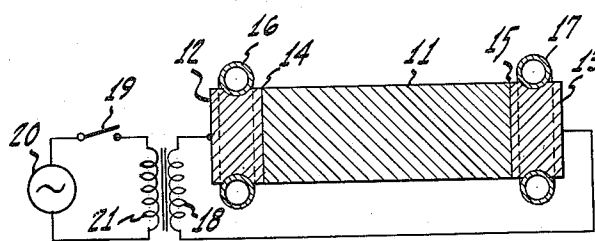


Fig. 3.

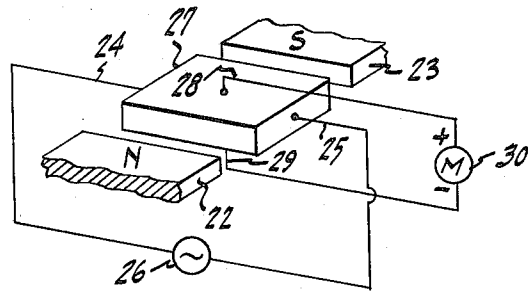


Fig. 4.

INVENTOR.
HENRY S. SOMMERS, JR.
BY *J. L. Whitaker*
ATTORNEY

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SOLID-STATE CHARGE CARRIER VALVE

Henry S. Sommers, Jr., Princeton, N.J., assignor to Radio Corporation of America, a corporation of Delaware

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This invention relates to improved solid-state devices and more particularly to an improved semiconductor device having a graded energy band gap for passing an alternating current by a unidirectional flow of charge carriers.

In the energy band theory of solids, several discrete levels of energy are postulated. An electron is raised in energy by moving from a lower band or level to a higher one. The lowest band is designated the valence band or normally filled band. The highest band is called the conduction band or the normally empty band. Between these two bands exists an energy band gap referred to as the forbidden band or energy band gap region. For a metallic conductor such as copper, the filled band and conduction bands overlap with substantially no energy band gap existing. For typical semiconductors, the energy band gap may have a width of a fraction of an electron volt to 1 or 2 electron volts, this gap increasing in width until the materials are considered to behave as insulators. Thus at one end, semiconductors imperceptibly blend into metals, and at the other end blend into insulators. It has been found that in semiconductive materials such as germanium, silicon, and the like, imperfections or impurities present in the crystal structure result in either an excess of free electrons or a deficiency of such electrons being present. These excess free electrons act as negative charge carriers and are responsible for the conduction of electricity in the crystal. Where a deficiency of electrons exists because of electrons having been effectively ejected from the crystal structure, empty spaces are left behind in the crystal structure called "holes." These holes can be filled by the movement of electrons into them leaving behind other holes. Under the influence of an electric field the hole behaves essentially as an excess electron with a positive electronic charge. Thus it has been found extremely convenient and useful in solid-state theory to regard the conduction of electricity in the semiconductor crystal as being carried on by negative and positive electric charge carriers, namely electrons and holes. A crystalline semiconductor having a substantially equal number of electrons and holes is referred to as an intrinsic semiconductor. A semiconductor whose conductivity depends upon excess charge carriers is called an extrinsic semiconductor. Where the electrons are present in excess, the semiconductor is designated as N-type; for holes in excess, P-type.

In a metallic conductor alternating-current flow occurs by the periodic reversal in direction of a single charge carrier, namely, the electron. In a conventional crystalline semiconductor body, alternating current flow occurs by the periodic reversal in direction of a single charge carrier, also, namely: electrons for N-type and holes for P-type.

It is an object of this invention to provide a solid-state device for passing alternating current by a unidirectional flow of electric charge carriers.

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It is a further object of the invention to provide a Peltier heat pump operated by alternating current.

It is still a further object of the invention to provide a Hall effect meter directly responsive to an alternating voltage or current.

In the present invention, a solid-state device is provided which will pass a conventional alternating current, but this alternating current flowing through the solid-state body will have the unique property of a flow of charge carriers of changing polarity but of constant direction. Thus while this alternating current will pass through the solid-state body as a conventional alternating current, it will differ therefrom with respect to the presence therein of certain directionally dependent thermoelectric and magnetoelectric effects, particularly the Peltier effect and the Hall effect. The alternating current within the solid-state device of this invention will therefore resemble a direct current insofar as certain magnetic, thermal, or electric effects are concerned. Thus the Peltier and Hall effects mentioned are independent of the sign of the charge carrier but depend only upon the direction of flow of this charge carrier.

It is a feature of this invention that a solid-state device for passing alternating current by a unidirectional flow of electric charge carriers is provided by preparing a solid-state body, such as a suitable semiconductor or insulator, that has a graded energy band gap therein, this body being characterized by having a unidirectional barrier therein for preventing a flow of electric charge carriers thereacross into said body. More specifically, a body of substantially intrinsic semiconductive material is provided having a graded energy band gap, one surface of the body having a relatively low energy band gap forming an injecting contact with a conductive material, and a second surface of the body having a relatively high energy band gap forming a non-injecting contact with the body. Thereby electrons and holes can flow from the injecting contact into the body and freely flow from the body into the non-injecting contact. However, the non-injecting contact does not allow the flow of electrons or holes into the body, thereby providing a unidirectional flow of electric charge carriers through the semiconductor.

Other objects and features of this invention will be described in greater detail in the following description taken in conjunction with the appended drawing in which:

Fig. 1 is a schematic representation of prior art metal-semiconductor contacts for explaining the theory of this invention;

Fig. 2 is a schematic representation of a semiconductor having a graded energy band gap according to this invention;

Fig. 3 is a schematic representation of a Peltier heat pump according to this invention; and

Fig. 4 is a circuit arrangement of a direct reading Hall effect meter according to this invention.

Referring to Fig. 1, energy band diagrams are shown in which the energy of an electron in a crystal is plotted as an ordinate against the distance in the semiconductor between metallic elements in contact therewith as the abscissa. The enclosed area of the diagram between conductive elements 1 and 3 represents the forbidden energy band of the crystal. The crystal can have no free electrons having energies in this forbidden region. The energy difference between the upper and lower edges of the forbidden region is referred to as the band gap.

In Fig. 1a is shown a body of N-type semiconductive material positioned between two injecting conductive elements such as metallic conductors. The semiconductor body is represented only schematically, by the forbidden band or energy band gap. The dotted line throughout the diagrams represents the Fermi level, E_F . This is the

level at absolute zero temperature where statistically the available electrons fill all the energy levels below E_f while none of the energy levels above E_f is occupied. As may be noted, the Fermi level for N-type material is closer to the conduction band than to the valence band and is at the exact level of the conducting electrons in the metallic elements. Electrons in Fig. 1a may freely flow from conductor 1 to body 2, and therethrough to conductor 3. Similarly electrons may flow from conductor 3 to body 2 to conductor 1.

A corresponding body of P-type material is shown in Fig. 1b. Here the majority carries are holes and flow freely in either direction through the semiconductor body. The Fermi level E_f is located closer to the valence band.

As an alternating current is applied to conductors 1 and 3 in Figs. 1a and 1b, the following will be observed. For Fig. 1a, when electrons flow from left to right, conventional current flow will be from right to left. Reversal of the direction of current will reverse the direction of flow of the electrons. In Fig. 1b, carrier flow directed from left to right will correspond to current flow directed from left to right inasmuch as the holes are positive charge carriers. Upon reversal of the alternating current, the current flow direction and carrier flow direction will both change together. Thus in both Figs. 1a and 1b the alternating current will be carried by carriers whose direction of flow will periodically change as the direction of current transport changes. Inasmuch as a flow of conventional direct current in one direction corresponds to a flow of electrons in the opposite direction, in Fig. 1a current flow and carrier flow will be in opposite directions; in Fig. 1b, current flow and carrier flow will correspond in direction, inasmuch as the carriers flowing in Fig. 1b are positive charge carriers.

In Fig. 1c is shown an N-type body of semiconductive material having a rectifying barrier 4 at the right end thereof. In this body electrons can move from conductor 1 to body 2 and conductor 3 but are effectively blocked from moving in the opposite direction because of barrier 4. Thus only a unidirectional flow can occur through the semiconductor body. For negative charge carriers, i.e., for electrons, the carrier flow direction is from left to right and the current flow direction is from right to left.

In Fig. 1d is shown a corresponding barrier arrangement for a P-type material. Here the holes can flow from left to right but are prevented by barrier 5 from flowing from right to left. Thus only unidirectional flow can occur through the semiconductor body of Fig. 1d, with both the carrier flow direction and the current flow direction being from left to right.

If an alternating current is applied to the semiconductor bodies shown in Figs. 1c and 1d, on the positive cycle of the current, there will be no flow of current in the body of Fig. 1c because of barrier 4; holes will flow from left to right in Fig. 1d. On the negative cycle of the current, electrons will flow from left to right in Fig. 1c; i.e., current will flow from right to left. There will be no flow of current in the body of Fig. 1d because of barrier 5.

In Fig. 2 is shown a band energy diagram for a solid-state device according to this invention for passing an alternating current by a unidirectional flow of electric charge carriers. The solid-state body used in the practice of this invention has a graded energy band gap. Thus the energy band gap of the material adjacent conductive element 6 may be a fraction of an electron volt, whereas the energy band gap adjacent conductive element 7 may exceed this by anything from a fraction of a volt to several electron volts. The semiconductive material used for body 8 is preferably intrinsic, that is, a substantially equal number of negative and positive electric charge carriers are present in the body. This is shown by the location of the Fermi level E_f approximately equidistant from the valence band and the conduction band. Depending on the sign or polarity of the voltage, either elec-

trons or holes can flow from conductive element 6 into body 8 across contact 9, which therefore constitutes an injecting contact for both electrons and holes. The direction of injection, as is common terminology in this art, is considered as being from the metal to the semiconductor body. Contact 10 is a non-injecting contact, that is, neither electrons nor holes can flow from conductive element 7 into the semiconductor body 8. Electrons and holes, of course, can readily flow from the semiconductor body 8 to conductive element 7. Thus each electric charge carrier can flow only in the forward direction, that is, from left to right on the diagram shown, but not in the reverse direction. This means that for one polarity of applied voltage, electrons will flow from left to right or, effectively, current will be flowing from right to left through the semiconductor body. When the polarity is reversed, holes will now flow in the semiconductor body again from left to right corresponding to a flow of current through the body from left to right. As a result, an alternating current will be passed by the semiconductor body, but the flow of charge carriers within the body will be unidirectional, namely, only from left to right. Thus, in a conventional semiconductor body of a given conductivity type, N or P, the direction of carrier flow reverses with the current but the sign of the carrier is unchanged; in this device, the sign of the carrier reverses with the current but the direction of carrier transport in the semiconductor body does not reverse, but is unidirectional.

Various semiconductive materials may be used in the practice of this invention to form materials having a graded or non-uniform energy band gap. Pseudobinary alloys, i.e., mixed binary alloys, of the group III-V elements of the periodic table are considered suitable for this purpose. Particularly desirable are those combinations of elements that are miscible over a wide range of proportions and whose crystal lattice constants do not differ to a considerable extent. Thereby, few strains are produced in the resultant mixed crystal. The term "mixed crystal," as used herein, includes both monocrystalline and polycrystalline solid solutions. One such preferred material consists of a crystalline substance made up of gallium phosphide and gallium arsenide with a gradually changing ratio of arsenic to phosphorus. If the formula of this crystalline compound is considered as $\text{Ga}(\text{As}_y\text{P}_{1-y})$, then the value of y may vary from zero to one. For $y=1$, which would correspond to gallium arsenide, the forbidden band energy is approximately 0.9 electron volt. This would correspond to the low band gap portion shown as barrier 9 in Fig. 2. For $y=0$, corresponding to gallium phosphide, the band energy gap has a value of 2.24 electron volts. This would correspond to barrier 10 in Fig. 2. The system gallium arsenide-gallium phosphide, which forms a series of uniform mixed crystals over the entire range from $y=0$ to $y=1$, has been described in an article by O. G. Folberth entitled "Mixed Crystals of the III-V Elements" which appeared in *Zeitschrift für Naturforschung*, vol. 10a, No. 6, pp. 502-503 (1955). Reference may be made thereto for further details as to the properties of these mixed-crystal compounds. Also described therein is the mixed crystal of the pseudobinary alloy indium phosphide-indium arsenide, which also can be used to form a graded energy gap material useful in the practice of this invention. While these compounds are particularly preferred, other single-phase mixed crystals, both monocrystalline and polycrystalline, are also contemplated for the practice of this invention, such as silicon-germanium and bismuth selenide-bismuth telluride. Also, mixed crystals of suitable ternary alloys may be used. One such contemplated system is copper indium selenide and copper indium telluride ($\text{CuInSe}-\text{CuInTe}$). Also, inasmuch as the specific energy values for the band gap regions used in the practice of this invention are not critical per se, but a difference in energy between band gap regions is desired, it is seen that this in-

vention is applicable to various solid-state materials other than semiconductors, such as those ordinarily classed as insulators, which have relatively wide band gap regions. Thus materials such as cadmium sulfide-cadmium selenide and cadmium sulfide-zinc sulfide are also contemplated.

Various methods may be used for preparing the mixed crystals of this invention. For purposes of illustration, the preparation of the system indium arsenide-indium phosphide will be described, although this invention is clearly not limited thereto. A mixture consisting of 0.3 mole (43.5 grams) of indium phosphide and 0.1 mole (18.9 grams) of indium arsenide is heated in a quartz or graphite crucible to a temperature above 1070° C., the melting point of the indium phosphide. At this temperature the entire mass is molten. Then using the Kyropoulos or Czochralski crystal-pulling technique, and employing a single-crystal seed of indium phosphide, a mixed single crystal is gradually grown from the melt. Inasmuch as the high-melting component of the mixture, indium phosphide (M.P. 1070° C.), is present in molar excess compared with the lower melting component, indium arsenide (M.P. 936° C.), the first portion growing from the melt and attached to the seed will be rich in indium phosphide. Thus although the indium phosphide is present in the liquidus phase in a 3:1 molar excess, the crystal in the solidus phase at a corresponding temperature to the liquidus phase will have a much higher proportion of indium phosphide present. As the mixed crystal is grown and the temperature gradually lowered, the proportion of the indium phosphide present in the solidus phase will gradually decrease, with consequent increasing proportions of indium arsenide being present in the grown crystal. Thereby a crystal having a gradually diminishing concentration of indium phosphide in relation to indium arsenide will be grown. While for purposes of this invention it is generally preferred that this mixed crystal be monocrystalline, the use of twinned material or polycrystalline material is also contemplated.

An alternative method of growing a mixed crystal having a graded or non-uniform energy band gap employs a semiconductor alloying technique. A pellet of indium arsenide may be placed upon one surface of a block of indium phosphide, and the entire assemblage is maintained at a temperature intermediate the melting points of the two binary components, for example at 1000° C. At this temperature all the indium arsenide is molten, whereas the indium phosphide remains as a solid. The indium arsenide pellet at this temperature alloys into the indium phosphide block. The indium phosphide block is gradually cooled starting at the surface remote from the one on which the pellet of indium arsenide was originally placed. Because of the liquidus-solidus curve of the phase diagram, it is seen that the first portions to cool will be rich in indium phosphide, and gradually the concentration of indium phosphide will diminish until the pellet consisting of pure indium arsenide will be frozen.

In place of the alloying technique, a vapor diffusion method may be used. Thus phosphorus vapor may be diffused into indium arsenide to obtain a graded energy band gap indium phosphide-indium arsenide mixed crystal.

The technique of controlled gradient freezing may also be used to obtain a graded energy band gap material. While this technique may be used for obtaining monocrystalline material, it is particularly suitable where polycrystalline material is desired. A mixture consisting of indium phosphide and indium arsenide in essentially the same molar proportions as previously employed for the crystal-pulling method is placed in a graphite or quartz crucible or other suitable container and maintained above the freezing point of the high-melting component, indium phosphide. The crucible is then very gradually cooled from the bottom up until the entire melt is frozen. It will be found that the resulting melt is highly segregated, with the portions toward the base of the crucible being

rich in indium phosphide and the upper surface portions rich in indium arsenide. The gradient freezing method is also particularly applicable where it is desired to obtain a crystal having a controlled geometry.

While the foregoing methods are particularly suitable for pseudobinary mixtures whose phase diagram has a continuous liquidus-solidus curve, the methods described may also be used where a eutectic point appears in the phase diagram. With such substances the mixed crystal is preferably grown over the portion of the phase diagram curve where only the two phases solidus and liquidus are present, thereby avoiding the mixed phase regions of the phase diagram.

In general, it is convenient and preferred that the solid-state material used in the practice of this invention have its energy band gap graded in a uniform manner. However, this is not essential to the practice of this invention as the primary requirement thereof is the presence of at least two regions within the semiconductor body having differing energy band gaps. Thus non-homogeneous mixed crystals may be used. It will be further understood that these differing energy band gap regions need not extend throughout the entire body of the semiconductor material but need be present only in portions of the surface to which electrodes can be conveniently attached by conventional or other techniques to give the desired injecting and non-injecting contacts. Suitable metallic contacts may be made to the materials described by first etching the semiconductor surfaces to be treated and then plating metallic contacts thereon. Desired leads are then conveniently soldered to the metallic plating. For example, a mixed crystal of the gallium arsenide-gallium phosphide or bismuth selenide-bismuth telluride type may be treated with a suitable etchant such as diluted aqua regia and then immersed in a conventional nickel cyanide or other suitable nickel plating bath, such as an electrodeless nickel plating bath; or a layer of copper may be plated onto the treated surface from a conventional copper cyanide plating bath. The ordinary lead-tin soft solder of commerce may be used for attaching suitable leads to the plated surfaces.

In Fig. 3 is illustrated the utilization of the device of this invention as a Peltier heat pump. The Peltier effect is a well-known thermoelectric phenomenon, namely, one in which the passage of a current across a thermoelectric junction results in a change in temperature occurring at the junction due either to an absorption or release of heat. The magnitude of the effect varies, particularly depending upon the nature of the materials used for the contact. Where the contact is established between a metal and a semiconductor, the flow of electric charge carriers from the metal to the semiconductor will result in a cooling occurring at the junction inasmuch as, according to solid-state theory, energy must be supplied to transfer the electric charge carrier from the conduction band of the conductive element to the appropriate band level of the semiconductor body. This energy is supplied by the metal, which then shows a temperature drop. When the electric charge carriers pass from the semiconductor body to the conductive element, this fall of the electron from a higher energy level to a lower energy level is given off in the form of heat, and a rise in temperature of the metal results. It is thus seen that the Peltier effect depends only upon the direction of flow of the electric charge carriers and is completely independent of the polarity of the charge carriers. Thus an electron or a hole will behave in the same manner as far as the Peltier effect is concerned, the effect being solely dependent upon the direction of flow of the electric charge carriers and independent of its polarity. Until comparatively recently, the Peltier effect was only of theoretical interest because Joule heat, i.e., i^2R losses, tended to markedly overshadow it. However, Peltier junctions have now become of considerable importance for use in electronic refrigeration and air-conditioning, and con-

siderable work has recently been done along these lines. In an article by O'Brien, Wallace and Landecker entitled "Cascading of Peltier Couples for Thermoelectric Cooling," which appeared in the *Journal of Applied Physics*, vol. 27, No. 7, pp. 820-23 (July 1956), is described the theory involved and its application with respect to standard refrigeration techniques.

Heretofore, only a direct current has been considered feasible for obtaining a useful Peltier effect; thus passing an alternating current through cascaded junctions would merely result in an alternate heating and cooling of the same junctions with no net temperature change occurring. According to the present invention, however, and referring to Fig. 3, a semiconductor body 11 is selected that is useful as a thermoelectric element for use in a Peltier heat pump, for example, a graded or nonuniform bismuth selenide-bismuth telluride compound. This body 11 is connected to conductive elements 12 and 13, which may be of copper and which may be joined to the semiconductor body 11 by plating a metal on the semiconductor body and then a layer of solder as previously described. Thereby junctions or contacts 14 and 15 are formed with the graded energy band gap solid-state body 11, in circuit relation with the secondary of a transformer 18. Upon closing of switch 19, alternating voltage source 20 provides current flow to primary winding 21 of the transformer, and an alternating current is then induced in the semiconductor circuit. If it is assumed that the energy gap in semiconductor body 11 is graded from a low energy to a high energy gap in a left to right direction, junction 14 located between body 11 and conductive element 12 will be cooled, and junction 15 located between conductive element 13 and body 11 will be heated. Within the external metallic portion of the circuit, a conventional alternating current is flowing, but within the semiconductor body itself the alternating current is passing through this body by a unidirectional flow of charge carriers, assumed for purposes of illustration to be proceeding from left to right. Thus when element 12 is positively charged with respect to element 13, holes will flow through the semiconductive body from left to right. Upon reversal of the current, namely element 15 becoming negative with respect to element 13, electrons will flow from left to right. As pointed out, an alternating current will therefore be passed through semiconductor body 11 by a unidirectional flow of charge carriers whose polarity is periodically changing. Thus by the foregoing arrangement alternating current has been utilized to provide a Peltier heat pump action, whereas, with devices heretofore known, the only manner in which alternating current could be utilized for such a purpose would be by first rectifying it to a direct current.

In Fig. 4 is shown the utilization of this device for a direct-reading alternating-current or alternating-voltage meter using the Hall effect. The Hall effect finds particular utility in semiconductor measurements in determining the sign of electric charge carriers. This effect depends upon the development of a transverse electric potential gradient in a current-carrying conductor upon the application of a magnetic field thereto. The magnetic field is applied in a direction perpendicular to the direction of current flow. Magnets 22 and 23 may be used for providing the magnetic field. Current leads 24 and 25 are connected to the source of alternating current 26 that is to be measured and also to the semiconductor body 27. Conventional Hall electrodes 28 and 29, are connected to body 27 and also to a direct-current reading meter 30, for example, a conventional moving magnetic vane type. The semiconductor body 27 is assumed to have its energy band gap graded from a low to a high gap in a left to right direction. When the polarity of source 26 is such that lead 24 is positive with respect to lead 25, the charge carriers will be holes moving from left to right in the semiconductor body 27. These holes will be deflected upward by the magnetic field, thereby

making electrode 28 positive with respect to electrode 29. On reversal of source 26, that is lead 24 is negative with respect to lead 25, the current flow through body 27 will be carried by electrons, which will be deflected downward by the magnetic field. Again electrode 28 will be positive with respect to electrode 29. This means that an alternating current passing through body 27, which will be by a unidirectional flow of charge carriers, will give a direct-current Hall effect. This can conveniently be measured by a direct-current responsive device, such as meter 30 connected to electrodes 28 and 29. Thus, effectively, a full wave Hall-effect rectifier has been provided. Because body 27 has a graded energy band gap, its Hall effect differs from that obtained with a homogeneous semiconductor, one without a graded band gap, in two respects: first, the usual semiconductor body will reverse the sign of the Hall voltage with reversal in current; secondly, for a substantially intrinsic semiconductor, one having substantially equal hole and electron mobilities, the Hall effect will be zero for an alternating current. Thus, in a conventional homogeneous intrinsic semiconductor, a cancellation of the positive and negative Hall voltages will occur. In the device illustrated in Fig. 4, both negative and positive carriers give the same sign for the Hall effect. Thus effectively an alternating voltage or alternating current may be conveniently measured using a conventional direct current reading instrument without providing for any current rectification. This Hall-effect meter is particularly useful for measuring frequencies below those where the skin effect becomes important. The output provided will be substantially independent of the input frequency of the alternating current.

While I have described the above invention with respect to certain illustrative embodiments, it will be apparent that the devices described can be used for many other electrical, magnetic, optical and photo effects, in addition to the Peltier and Hall effects described, where the effect depends upon the direction of flow of the electric charge carrier and is independent of the sign of the carrier. It should be clearly understood that the specific description of preferred embodiments has been made only by way of example and not as a limitation to the scope of my invention as set forth in the objects thereof and in the accompanying claims.

What is claimed is:

1. A solid-state device for passing alternating current by a unidirectional flow of electric charge carriers comprising a body of material selected from the group consisting of substantially intrinsic semiconductors and substantially intrinsic insulators, said body having an energy band gap which gradually diminishes from one surface toward the opposite surface thereof, an electrode providing a first contact to said body at said one surface and another electrode providing a second contact to said body at said opposite surface, said first contact being non-injecting of both electric charge carriers and being collecting of both electric charge carriers with substantially equal ease, and said second contact being injecting of both electric charge carriers with substantially equal ease.

2. A solid-state device for passing alternating current by a unidirectional flow of electric charge carriers comprising a body of material selected from the group consisting of substantially intrinsic semiconductors and substantially intrinsic insulators, said body having a first portion with a given energy band gap and a second portion with an energy band gap lower than the energy band gap of said first portion, and conductive means individually connected to said first and second portions, the connection to said first portion being non-injecting of both electric charge carriers and being collecting of both electric charge carriers with substantially equal ease, and the connection to said second portion being injecting of both electric charge carriers with substantially equal ease.

3. A solid-state device for passing alternating current by a unidirectional flow of electric charge carriers comprising a solid-state body selected from the group consisting of substantially intrinsic semiconductors and substantially intrinsic insulators, said body having a graded energy band gap, spaced apart first and second portions in said body having respectively low and high energy band gaps relative to each other, and first and second conductive means connected to said first and second portions, said first portion forming an injecting contact with said first conductive means whereby electrons and holes can flow from said first conductive means to said first portion, and said second portion forming a non-injecting contact with said second conductive means whereby electrons and holes can flow from said second portion to said second conductive means and are prevented by said non-injecting contact from flowing from said second conductive means to said second portion.

4. A solid-state device for passing alternating current by a unidirectional flow of electric charge carriers comprising a solid-state body selected from the group consisting of substantially intrinsic semiconductors and substantially intrinsic insulators, said body having a graded energy band gap, spaced apart first and second portions in said body having respectively low and high energy band gaps relative to each other, first and second conductive means connected to said first and second portions, said first portion forming an injecting contact with said first conductive means whereby electrons and holes can flow from said first conductive means to said first portion, and said second portion forming a non-injecting contact with said second conductive means whereby electrons and holes can flow from said second portion to said second conductive means and are prevented by said non-injecting contact from flowing from said second conductive means to said second portion, and a source of alternating current connected to said conductive means in circuit relation thereto, said alternating current passing through said body by a unidirectional flow of electric charge carriers.

5. A solid-state device for passing alternating current by a unidirectional flow of electric charge carriers comprising a body of semiconductive material of substantially intrinsic conductivity, a low energy band gap surface portion and a high energy band gap surface portion in said body, and a unidirectional barrier at said high energy band gap surface portion for preventing a flow of electric charge carriers thereacross into said body.

6. A solid-state device according to claim 5 wherein said body is selected from a graded energy band gap crystalline alloy having the formula $Ga(As_yP_{1-y})$ wherein y may vary from zero to one.

7. A Peltier heat pump comprising a solid-state body

selected from the group consisting of substantially intrinsic semiconductors and substantially intrinsic insulators, said body having a graded energy band gap, spaced-apart first and second portions in said body having respectively low and high energy band gaps relative to each other, first and second conductive means connected to said first and second portions whereby a flow of electric charge carriers from said first conductive means to said body produces a drop in temperature and a flow of electric charge carriers from said body to said second conductive means produces a rise in temperature, and a unidirectional barrier at said second portion of said body whereby electric charge carriers are prevented from flowing into said second portion from said second conductive means.

8. A heat pump according to claim 7 further including a source of alternating current connected in circuit relation to said body to provide a driving potential for charge carriers entering said body to cool it and for charge carriers leaving said body to heat it.

9. A Hall effect device comprising a solid-state body selected from the group consisting of substantially intrinsic semiconductors and substantially intrinsic insulators, said body having a graded energy band gap, spaced-apart first and second portions in said body having low and high energy band gaps relative to each other, first conductive means individually connected to said spaced-apart first and second portions of said body for establishing a flow of current therethrough, a unidirectional barrier at the high band gap portion of said body for preventing electric charge carriers from flowing from said conductive means connected thereto to said high band gap portion, means for establishing a magnetic field in a direction perpendicular to the flow of current through said body, and second conductive means connected to said body for conducting to an external means the direct current resulting when a source of alternating current is connected to said first conductive means.

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