July 22, 1952 A. J. AHEARN 2,604,596

BOMBARDMENT INDUCED CONDUCTIVITY IN SOLID INSULATORS

Filed Aug. 14, 1948

FIG. 1

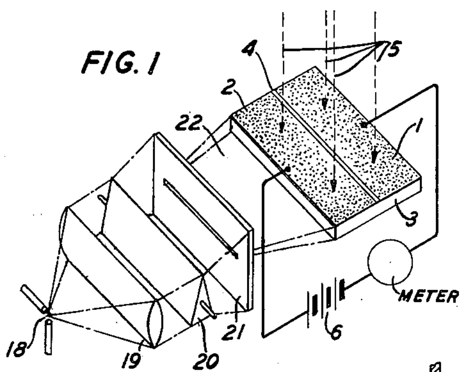


FIG. 2

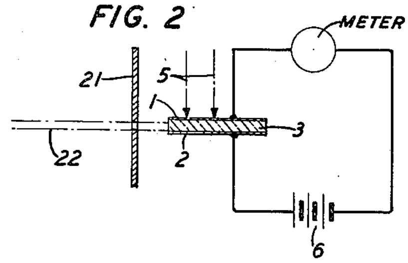


FIG. 3

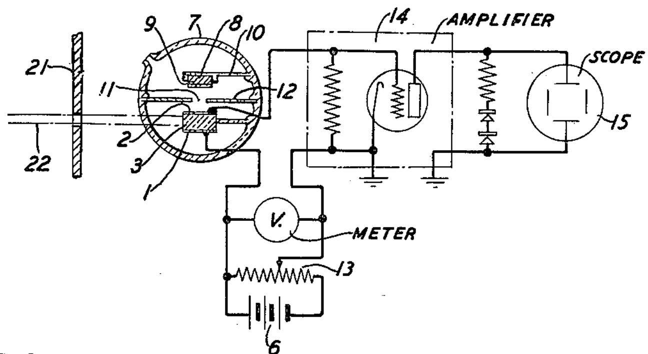


FIG. 4

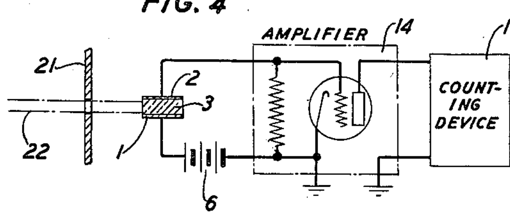
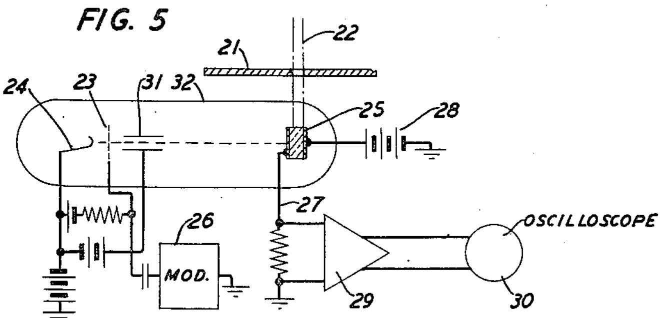


FIG. 5



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BOMBARDMENT INDUCED CONDUCTIVITY IN SOLID INSULATORS

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11 Claims. (Cl. 250—83.3)

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This invention relates to bombardment induced conductivity in solid insulators and to applications thereof in the electrical arts, and is an improvement over the invention of D. E. Wooldridge, Serial No. 747,888, filed May 14, 1947, now Patent 2,537,388 issued January 9, 1951. The improvement consists in the irradiation by light of the solid insulator in question while the insulator is being bombarded in accordance with the Wooldridge principle; and results in increased current and the reduction of polarization effects. To the extent that the invention aims at substantially the same result as by the use of a certain McKay improvement of the Wooldridge invention, it may be thought of as an alternative or additive to that invention as disclosed in K. G. McKay, Serial No. 789,667 filed December 4, 1947, now Patent 2,543,039 issued February 27, 1951, relating to the use of an alternating voltage, instead of a direct voltage, impressed on the solid insulator.

Applicant has discovered that in a diamond in which current pulses are induced by alpha particle bombardment while there is an electrical potential across the diamond, more pulses are large enough to be observed when light is directed into the diamond than when it is in the dark. While the effect which this light has upon the process may not be entirely understood applicant believes it to be the following at least in part. When a current pulse is induced in the diamond, the carriers of charge, electrons and "holes," proceed toward the respective external electrodes at a certain speed. Some of these become trapped at imperfections in the diamond lattice structure and are lost from the stream of current. At the same time these trapped carriers cause a polarization which impedes the passage of other similar carriers, and makes their trapping more probable. The result is that the current is rapidly reduced to a very low value before all the carriers can cross the diamond. When now light is directed into the diamond it has the effect of releasing a large fraction of the trapped carriers soon after they have become trapped, so that these released carriers can contribute to the current in the normal way again and so that the polarization of the diamond does not build up to so high a value as in the dark.

The efficacy of applicant's light irradiation principle to reduce or avoid polarization effects is therefore reflected in an increased current response under given conditions of field strength and energy of bombardment. The invention may be thought of as providing with quite different

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means an end result similar to that of McKay. The McKay invention provides a procedure whereby the direction of flow of current is reversed so often that strong polarization can not build up while in applicant's invention polarization tends to be destroyed as rapidly as it is built up. While applicant has achieved success with his method by using alpha particle bombardment of diamond, he has every reason to think that like effects would attend bombardment by other types of charged particles, such protons, electrons and beta particles. In fact, in this, as in other respects, the invention is quite comparable to the above Wooldridge-McKay alternatives so that the choice of incident radiation or bombardment may range as widely as to include X-rays, gamma rays, and other short-wave electromagnetic radiations. Because of this versatility the term "radiation" will be used in this specification to include these various types of bombardment, by particles or by waves. For like reasons the choice of solid insulator is as wide as the instances of said Wooldridge and McKay inventions and as enunciated in their patents as above; although applicant's work has been largely with diamond, which, by its special characteristics, relatively to other crystal forms, as pointed in said applications, typically and well illustrates the operation of the bombardment induced conductivity principle. Likewise, the field of practical utility of applicant's invention is the same as, or comparable with, those of said Wooldridge and McKay inventions, some of which will be given special consideration in the detailed description that follows.

Preliminarily to an explanation of the polarization phenomena which brought this invention into being and which suggest the objects and features of the invention, it is in order to orient the subject of the invention and provide a necessary minimum of background for it. For further elaboration, the Wooldridge and McKay specifications may be referred to.

The phenomenon of bombardment induced conductivity in solid insulators is an instance of valve action. Correspondingly as the vacuum tube is made conducting under the influence of electrical means (control grid potential) independently of the voltage applied between the electrodes, in the present invention a normally insulating solid material is made conducting by the incidence of radiation under control of conditions specific to said radiation (bombardment) rather than to the electric field induced by the electrodes bounding said solid insulator as in other instances of the flow of electricity in conducting media. Each unit of this radiation (note that in the usual practical case it would be a bombardment of charged particles), depending on its energy, can remove a number of valence electrons from their bonds in the material of said solid insulator in such a way that, as multipled by the number of units of radiation, and by the chain reaction consequent on the initial action, render the solid insulator temporarily conducting.

The bombarding particles (here, and hereafter in this specification, for simplicity and convenience only, the action of the invention will be visualized in terms of bombarding charged particles) penetrate the insulator, causing a disruptive separation of the positive and negative charges specific to the atoms which are affected thereby. These charges are drawn towards the electrodes which induce the field in which the insulator is contained, by the potential therebetween. This motion of charges constitutes a conduction current, which may be suitable amplified and measured by conventional apparatus. When in this way a charged particle bombardment removes a valence electron from its bonds in an insulating target, producing a deficiency of one electron in the atomic structure immediately affected, this localized electron deficiency is called a "hole." Under an applied electric field the arrangement of electrons is changed, and the location of any given hole is similarly changed. As a consequence, the hole may be conveniently regarded as a positive particle which is free to move under the influence of the field; similarly the electron freed from the bond in question constitutes a negative particle likewise free to move under the influence of the field.

If there is no applied field, any free electron or a positive hole moves in virtue of thermal agitation and consequently has a completely random motion. Under an applied electric field, there is a directional motion superposed upon the random one. The order of mobility of the electrons in diamond is about 150 centimeters per second for a field of one volt per centimeter. (F. Seitz, Physical Review 73, 549, 1948.) The mobility of the electrons is affected by the number of "traps," that is, by the presence of foreign atoms or imperfections in the crystal. If an electron gets into a trap, it takes a greater or less amount of time to get out, depending upon the thermal energy required. If the time which a free electron spends moving in the crystal before being trapped is, on the average, less than the transit time, many of the electrons freed by the bombarding particle will effectively move only part of the distance through the crystal and thus will not actually be collected on the electrode. Although this movement of charge through part of the crystal will contribute to the total observable conduction current, the contribution will be less than if the electron had been collected on an electrode. Similar considerations concerning mobility and trapping also apply to conduction by positive holes. In order to minimize the number of effective traps in a given target, so as to realize a substantial conductive current, the length of path in the target, between the electrodes, should be made as small as possible. Also, because of the effect of the fields of the trapped charges in the target, on the corresponding free electrons, which tends to counter balance the pull of the superposed field from the electrodes, said field should exceed a threshold value dependent on the precise conditions; that is, the potentials between said electrodes should exceed a certain threshold value.

Consistently with the above and with further considerations to be recited later in this statement of invention, the primary object of this invention is to increase the bombardment induced conductivity response in solid insulators over that obtained by the prototype Wooldridge invention.

A subsidiary object of the invention, suggested by the principal factor which tends to limit the response in the prototype invention, is to eliminate or avoid the phenomenon of polarization or the like in bombardment induced conductivity applications.

As in accordance with the invention, the polarization is eliminated or avoided by irradiation of the solid insulator in question while subjected to the radiation or bombardment which tends to induce electric conductivity therein in the presence of an electric field. Applicant has bombarded diamond crystals with alpha particles emanating from polonium which is also called radium F, with eminently satisfactory results. Although a considerable degree of selection was necessary the test results were completely stable, repeatable and unambiguous. As has been expressed before the invention is useful in every application of the bombardment induced conductivity principle which has so far been suggested, and particularly as suggested in the above Wooldridge and McKay specifications. The following is adduced not only to indicate applicant's reasons for relating his results to the phenomenon of polarization but to teach the public how to operate his invention by a resumé of his own essential procedure.

When a suitable diamond (for example) with appropriate electrodes across which a sufficiently high voltage was applied, was bombarded with alpha particles from polonium, conductivity pulses were observed each of which was specific to an individual alpha particle. When the direction of the applied field was reversed the direction of the pulses was also reversed. When the voltage was reduced to zero, the pulses were observed for a short time, in general opposite in direction to those that occurred when the voltage was applied. Quite clearly these pulses were "space charge" pulses due to a polarization of the diamond medium, set up by the trapping of electrons or positive holes (depending on the direction of the applied field) before they have traveled completely through the diamond to the electrode. In general, in the absence of light, with a given rate of bombardment by radiation of a given quality (e. g. alpha particles from polonium) the pulse rate at first rises rapidly with increasing applied voltage and then approaches a limiting value i. e. the pulse rate approaches voltage saturation. The term "voltage saturation," as here used, is obviously analogous to the term as used in electronics to describe the situation where there is more than enough voltage to attract to the anode all of the electrons available at the surface of the cathode.

As is experimentally observed, the build up of a given amount of polarization at voltages well below the voltage saturation region should decrease the pulse rate by an amount governed by the decrease in the resultant electric field in the diamond. However the same amount of polarization decreases the pulse rate in the neighborhood of voltage saturation by a relatively smaller amount. Similarly the effect of the light in increasing the pulse rate is greater at low voltages than is the case at voltages which approach saturation.

This phenomenon of polarization in diamond and the like solid insulators appropriate to bombardment induced conductivity is a serious limiting factor in the practice of the bombardment induced conductivity principle since, in ordinary cases, the choice of voltage to insure voltage saturation at all times would not be consistent with the optimum voltage as determined by other considerations. This matter of a proper choice of voltage (that is, proper choice of field intensity) and the related matter of the proper choice of insulator thickness, is treated in the above McKay application.

The efficacy of the use of irradiation of the crystal insulator, as in accordance with the invention, is evident from the following resumé of applicant's experiments, which will be better appreciated and understood after a reading of the illustrative disclosures of apparatus that was used or might have been used.

A diamond (for example) was mounted in an evacuated bell jar with a potential of about 200 volts applied between very thin electrodes on opposite major faces and one entire face was subjected to intense alpha particle bombardment from polonium. It is known that this bombardment could be incident on one of the electrode faces, or any other face of the diamond, and not necessarily in such a way that the motion of the incident radiation is in the direction of the voltage field. Under these conditions the alpha bombardment induced conductivity response (the number of pulses and the height of the pulses) decreased markedly in the course of a minute or so from the initial value, when the voltage was first applied. The test was repeated while the diamond was illuminated with light from an ordinary tungsten lamp. The response, as above measured, was markedly greater than for the previous test after the onset of polarization. The high response persisted as long as the diamond was illuminated but dropped back to the low value determined by polarization in the course of several seconds after the light was turned off. The response was comparable with that initially observed when the voltage was applied, without the illumination, at which time polarization had not had time to become effective, this indicating that the result of the illumination was an effective anti-polarization means, although of course there might be other phenomena coexistent with this.

The theory of polarization in this art is taught in greater detail than would be justified in the present specification, in the above Wooldridge and McKay specifications. It has been treated very briefly, and in general, above. The theory as related to the irradiation of the solid insulator by a light may, it is submitted, be accurately stated as follows.

With an applied voltage the alpha (for example) bombardment induced conductivity response decays with time because the polarization which is built up by the trapped charges (electrons or positive holes) reduces the applied field. The illumination increases the response during the period that would otherwise be characterized by decay by eliminating or diminishing this polarization. The action effects the release of the electrons or positive holes from their traps.

According to the modern band theory of solids, an electrical insulator like diamond can become conducting, as in bombardment induced conductivity, only when electrons are given at least enough energy to jump across a region of forbidden energy values in the energy spectrum. According to the literature, this forbidden region in diamond is about seven electron volts wide. The alpha particle and electron bombardment induced conductivity experiments, including those employing illumination and alternating potentials across the electrode are consistent with this theory because they indicate that the electrons in these conductivity pulses have received ten or more electron volts of energy.

In the neighborhood of crystal imperfections, however, the theory predicts allowed energy levels in this normally forbidden region. These levels constitute electron traps. When electrons in conductivity pulses fall into these traps, they set up a space charge, that is, the diamond or the like becomes polarized. Depending on the nature and degree of the crystal imperfection, these electron traps may be shallow or relatively deep. That is, the electron trap energy levels may be just below the top of the forbidden energy region or they may be relatively far below the top.

In the illumination experiments all wavelengths shorter than 3000 A. U. were excluded by glass. In other words, the energy of the light quanta which increased the bombardment induced conductivity response was not greater than about four electron volts. These light quanta would, therefore, have enough energy to remove electrons from traps which were at most four electron volts deep. It is believed that light of shorter wavelength might be effective in increasing the bombardment induced conductivity response with respect to electrons which are trapped in deeper traps. Reference is made for background in this general field to "Color Centers in Alkali Halide Crystals" by F. Seitz, Reviews of Modern Physics, volume 18, Number 3, pages 384–408, July 1946.

Other objects and teachings of the invention are derivable from the detailed description hereinafter following, with reference to the accompanying drawings in which:

Figs. 1 and 2 illustrate two preferred methods of applying the necessary electric fields to the surfaces or parts of surfaces of the insulators in question, with relation to the incidence of the bombarding particles or radiation, while also being irradiated with light, Fig. 1 also showing diagrammatically a somewhat elaborated form of lighting system that has been used in practice, and Fig. 2 showing what might be the same lighting system in an even more diagrammatic form;

Fig. 3 illustrates a system of the invention for indicating the presence of conductivity in an insulator which is affected by the bombardment of charged particles while, as per the invention, irradiated by light;

Fig. 4 illustrates a system similar to that of Fig. 3 for indicating the presence of bombardment induced conductivity in an insulator, here specifically an apparatus for actually counting the incident charged particles, not restricted to a particular type of source of bombarding particles; and

Fig. 5 illustrates the application of the bombardment induced conductivity principle of the invention to a complete amplifier organization.

It should be understood, in what follows, that, with respect to applicant's invention, similarly as its prototypes, the incident radiations may almost impartially be made up of various common types of charged particles although applicant's work has been mainly with alpha particles, which are positively charged particles. Other types of charged particles here applicable include ordinary electrons as emanate from the cathodes of the usual electronic devices, beta particles, which are essentially high speed electrons, and other kinds of radiation which may be analyzed in terms of the charged particles on which their constitution may be postulated. Similarly as a charged particle of a conventional type, as alhpa,beta or electron particles, of sufficient energy can remove a valence electron from its bonds as taught herein and in the McKay and Wooldridge patents, so also units (photons) of electromagnetic radiation, as in X-rays and gamma rays (that is, generally electromagnetic radiation exclusive of Hertzian, infra-red, visible or ultraviolet light, all of which are low energy electromagnetic waves) may possess sufficient energy to cause the removal of valence electrons from their bonds in such a way that the solid insulator is rendered temporarily conducting. Alpha and beta particles usually, and as contemplated by the present disclosure, emanate from radioactive material. It should also be understood that circuits or systems for evidencing the fact of bombardment induced conductivity, as in accordance with the invention, do not differ in concept depending on whether the ultimate result is a graphical showing of the conductivity, as on an oscillograph screen, or a response in a device for obtaining a quantitative measure of the incidence of the beam of radiation. This is true although certain figures of the drawings are so differentiated in order to indicate such choice of means in the interest of special considerations. As has already been intimated, there is likewise a wide choice of solid insulator, as taught in the prototype specification, although applicant's work has largely concerned diamond.

The foregoing generalization also applies to the particular electrode systems and Figs. 1 and 2 illustrate two kinds of electrode systems that may be almost impartially used in any of the systems described or to be described in this specification, although a particular choice may be urged by practical considerations. These two systems differ in the nature of the coupling of the electrodes to the solid dielectric substance on which they are superposed. In Fig. 1 the two electrodes are mounted in a side-by-side presentation on the same surface of the diamond in question and, therefore, so that the conduction current flows chiefly near its bombarded surface; whereas in Fig. 2 the electrodes are mounted on opposed surfaces of the diamond so that the conduction current represents a phenomenon existing throughout its mass. The word "diamond" is here used only as illustrating a practical alternative among the many solid dielectrics that are available. For reasons of expediency only it will be assumed, unless otherwise stated, that diamond is used in the organizations of the other figures.

Similarly as in the McKay invention identified in the statement of the invention herein, and similarly as in the Wooldridge invention also there identified, the solid insulator material may be chosen on the following basis: It should have a high insulating characteristic so as to be most amenable, without ambiguity, to the conditions

imposed by the type of phenomena being treated. To this end, and for other reasons as well which are not fully known at this time, the insulator should have preferably not only good insulating qualities but also should be preferably of a single crystal type with a high degree of chemical purity and freedom from inelastic strain or other crystal defects. These considerations commend the use of diamond, quartz, zinc sulfide, the alkali halides (including potassium chloride and potassium bromide), magnesium oxide, calcium fluoride, sodium nitrate, topaz, sliver chloride, orthoclase, beryl, calcite, apatite, selenite, tourmaline, emeralds, extremely pure silicon carbide, and stibnite. Several of these substances, notably diamond, zinc, sulphide, magnesium oxide, silicon carbide, and stibnite, have been used in the basic studies of bombardment induced conductivity and there is every good reason to think that the feature of using an alternating voltage field, attributable to applicant, is applicable to each of them.

Referring to Fig. 1 more specifically, two conducting metal film electrodes **1** and **2** are mounted on one surface of insulator **3**. The gap **4** separating the electrodes is relatively small and various widths from .001 to .008 inch have been successfully used in bombardment induced conductivity tests. These electrodes may be prepared by dividing the diamond surface roughly in half by stretching a wire of appropriate diameter across and in close contact with the surface and then evaporating a conducting metal layer, in vacuum, onto said surface. This layer can be made so thin as to be semitransparent, provided that its electrical resistance is so low as not to affect its electrical performance unfavorably. The shadow cast by the wire provides a gap when the wire is removed. This gap would have constant width and represented a uniformly high resistance thereacross at any point.

The charged particles (of course comprehending radiation generally as pointed out in the statement of invention) are assumed to conform to a ray or beam indicated generally by reference number **5**, which beam is incident on the diamond surface. Of course the beam tends to be most effective where it is incident on the diamond surface at the gap but, depending on the type of charged particles, the electrodes would not necessarily impose a substantial barrier; however, the electrode system of Fig. 1 requires that the bombarding particles strike the gap or very closely adjacent thereto. Later numbered figures will show, more specifically and in detail, organizations including the elements which are here shown to a large extent diagrammatically. The angle of incidence has not been observed to be critical.

A moderate direct voltage applied between these electrodes by source **6** produced a relatively high electric field in the top surface layers of the diamond near the gap and the resultant induced conductivity pulses observed in the indicating means, which is diagrammatically indicated as a meter, pass only across these surface layers. In the statement of invention above, certain quantitative values, or their criteria, have been indicated, this applying not only to this figure but to the other figures as well.

On the organization as above, which is the same as the correspondingly identified organization of the prototype Wooldridge application, there is superposed the suborganization of the invention, here constituted by a source **18** of polychromatic light, the condensing lens 19 which is used to parallelize the beam for passage through the prism 20, which may be rotatable as shown so as to play the resultant beam over the aperture plate 21. The eventual beam 22 emerging from the aperture is incident on the diamond. Of course the exposure should include that portion of the diamond through which the conduction pulses pass. In Fig. 1 strictly as shown this would assume that some of the light penetrates the diamond to the vicinity of the slot 4. Should it be desired to increase the incidence of the light on that portion it would be a simple matter to angle the diamond so as to provide direct exposure of the electrode surface to the light. Like considerations apply to Fig. 2 to be described were elements 19, 20, and 21 of said Fig. 1 to be used with the diamond of this Fig. 2, as they might well be. The source 18 is described, and diagrammatically shown, as a polychromatic source only because of the related showing of lens, prism, and aperture plates, the whole suggesting a means for choosing light of a given wavelength by this combination of means, since the aperture will pass only a selected portion of the incident beam, selected according to a desired portion of the frequency spectrum of the light beam, as determined by the angular position of the prism 20. It should be understood, that although there may be a differentiation as to the depth of the traps affected by the light and depending on the particular frequency of the light waves involved, the use of light generally without discrimination as to frequency would, in the ordinary case, probably be reasonably effective in preventing the polarization which inhibits the bombardment induced conductivity.

If the light is used without such discrimination it would not have to be condensed, neither would the beam have to have any particular configuration or affect a limited portion of the diamond surface. In fact, applicant has found his invention effective when the light is suffused over the whole diamond organization. It should also be understood that although, in the subsequently numbered figures, the expedient of the invention is represented merely by a light beam and an aperture plate, the elaborate organization of Fig. 1 as to the invention should be equally well understood to be applicable thereto. In fact the aperture plate might be dispensed with so as to indicate the nature of the invention merely by a teaching of a beam of light incident on the diamond.

Fig. 2 presents the second type of electrode placement. Here the electrodes 1 and 2 are placed on opposite sides of the diamond 3. A typical diamond specimen for this purpose might be about one-quarter inch in either principal dimension and about .020 inch thick. Thus a potential difference of 100 volts from direct voltage source 6, across these electrodes, will produce a uniform electric field of about 2000 volts per centimeter throughout the body of the diamond. In this type of electrode placement some of the induced conductivity pulses, observed in the meter or other indicating device shown, pass completely through the body of the diamond as distinguished from the Fig. 1 placement in which the pulses pass only in the region of the front surface. Similarly as in Fig. 1, the polarization within the diamond which, as explained in the statement of invention, tends to accompany the achievement of bombardment induced conductivity where a direct voltage field is used, is eliminated or prevented by irradiation of the diamond by light represented by the beam 22 passing through the aperture in the aperture plate 21 and incident on the diamond in such a way as to provide a substantial penetration thereof.

In Fig. 3, illustrating a practical embodiment of a system operating according to the principles enunciated with respect to Figs. 1 and 2, like elements are again designated by like reference numerals. The diamond 3 is coated with metallic electrodes 1 and 2 as in Fig. 2. The whole is mounted in an evacuated receptacle 7. The charged particle source 8, first assumed as the source of alpha particles, may consist of a silver sheet 9 on which is deposited a layer of radium sulphate having a given density of radium atoms (in a typical instance, 12 micrograms of radium per square inch). Of course other sources of alpha particle emanation are well known in the art and may impartially be used in the Fig. 3 organization. In fact that organization may well be used to explore the possibilities as to new sources of said emanations. The reference numeral 10 indicates diagrammatically a support for the silver sheet. In the prior art there are adequate teachings of mountings similar to this and the other elements here disclosed in an evacuated container. Other facilities, likewise taught by the prior art, could be used to advantage, such as a magnetic control means to determine the particular direction of incidence of the particles on the diamond, or even to adjust the position of the alpha particle source in apposition to the aperture 11 in diaphragm-like element 12, for further determining and limiting the precise coaction of the beam of charged particles and the diamond. The particular means of the invention for irradiating the diamond with a light beam is disclosed similarly as in Fig. 2.

The same illustration is applicable to the use of a beta particle source and in this instance the element 9 could have the form of a piece of glass on which a minute quantity of artificially radioactive strontium had been deposited. The same teaching extends, of course, to other sources of charged particles or electromagnetic radiation such as gamma or X-rays.

To suit the teachings of this Fig. 3, which discloses, outside of the light irradiation means of the invention, a more elaborate and complete organization than that of Figs. 1 and 2, the potentiometer 13 may be used as shown to determine a desired fractional part of the voltage of the primary source 6, the voltage impressed therefrom being indicated by the voltmeter V. Of course in the specific instance of Fig. 3, the bombarding particles penetrate the exposed upper electrode before affecting the diamond, this of course not representing a significant departure from the alternative in which the diamond is directly bombarded, providing this electrode be sufficiently thin. The detecting circuit may comprise amplifier 14 and cathode-ray oscilloscope or the like 15, both showing diagrammatically, to suggest the comparatively impartial choice of specific means to achieve these functions.

It is not a rigid requirement that the container be evacuated. In fact a rough vacuum is produced merely to eliminate small induced conductivity pulses caused by ionization of the air produced by the charged particles in their transit to the diamond. These small affects may alternatively, or in cooperation with the use of a vacuum, be largely eliminated by mounting the particle source as close as practicable to the diamond, this therefore requiring that the diamond 3, source 8 and diaphragm 12 all be very closely interspaced.

Fig. 4 emphasizes the embodiment of the invention as a counter, alternatively, for example, to the well-known Geiger counter. Similar elements are similarly designated as in Fig. 3, the essential difference being the using of the counting device 16 in place of the oscilloscope 15 of Fig. 3, it being recognized that the prior art provides impulse (pulse) counters of a large variety and scope and having a greater facility for counting purposes than the oscilloscope of Fig. 3, although, as has been explained, it may be used quantitatively both to measure the intensity of any given pulse and the number of such pulses. A potential of the order of 200 or 300 volts may be applied across the diamond crystal. Of course a solid insulator other than a diamond crystal, within the spirit of the invention, may be used. The diamond crystal and electrode structure may be made to occupy a space each of whose dimensions is less than one-quarter of an inch. When this structure has been exposed to the desired source of radiation, the particles from which are to be counted, the resultant current pulses which flow through the diamond each time a charged particle penetrates it are amplified as shown and the signals thus produced are counted by the device 16 which may be adjusted so that only pulses of a given amplitude or greater are inspected for counting purposes. The expedient of the invention, involving the irradiation of the diamond by light, in order to prevent or eliminate polarization effects, is taught by the same means as is illustrated in connection with the earlier numbered figures.

Fig. 5 illustrates an amplifier organization of the invention, therefore employing irradiation by light of the solid insulator, which here is a diamond with an evaporated gold electrode on either face as the diamond is presented to the bombarding electrons. This suborganization comprising the diamond and its immediately associated circuits and structures is a part of an organization altogether constituting an amplifier which may be considered as applicant's version of the prototype amplifier disclosed in Figs. 6 and 7 of the above Wooldridge patent. This figure, also, is the same as Fig. 6 of the above McKay patent except for the use of the antipolarization means of the invention as compared with McKay's alternative means. McKay's Fig. 5 which discloses the vacuum tube and contents of the amplifier of the invention, in specific detail, is omitted from the present application for reasons of simplicity. It should be understood in advance that the signal wave, that is the wave to be amplified, and which is identified by reference number 26 and the legend Mod., may be sinusoidal, a square wave, or a wave of any other conformity. More particularly, having in mind a practical expedient, the organization may be an amplifier of pulse waves.

In Fig. 5 the vacuum tube closure member 32 is comparable with the closure member of a conventional vacuum tube. A vacuum tube is here necessary, as it was not in the earlier numbered figures which illustrates apparatus utilizing alpha and beta particles, because here the charged particles are electrons emanating from the usual cathode source as in conventional vacuum tubes. The reference numerals 23, 24 and 31 together indicate an electron gun of a type which is customary in vacuum tubes which generate and utilize a conformed cathode ray or beam. The gun conforms and directs the beam emanating from cathode 24 onto the solid insulator 25. An aperture-plate might well be used to further delimit the beam, as in the earlier numbered figures. The conditions affecting this solid insulator are similar to those as specific to the earlier disclosed circuits, the impingement of the electrons being reflected in amplified form as the bombardment induced current inherent in the operation. Polarization is prevented or eliminated, exactly as in the earlier disclosed circuits, by the similarly disclosed means which are identified by like reference numerals.

The particular electron gun in question, as specifically disclosed, conforms to conventional practice for such electron guns as used for a variety of purposes. The cathode 24 may be indirectly heated, as disclosed, or be of a filamentary type. The electron emanations are urged outwardly and concentrated by anode 31, beyond which the beam passes to the solid insulator, here again assumed to be a diamond crystal as disclosed. Electrode 23, which otherwise constitutes a conventional element of an electron gun is also the grid control element on which the signal waves to be amplified are impressed from modulator 26. By it a true density modulation of the electrons in the beam is achieved, as distinguished from the alternative arrangement of Fig. 6 of the prototype Wooldridge patent in which the modulation is achieved by playing a beam across the crystal so as to change the concentration of electrons incident on the crystal.

It will be understood that various other electrodes, for focussing and accelerating electrons, may be associated with the anode 31 or supplement it as taught by the prior art, although these accessory elements are not absolutely necessary and, in interest of simplicity, are omitted from Fig. 5. The necessary electric field for the solid insulator is provided by the direct voltage source 28 and the electron bombardment induced conductivity in said insulator is reflected in a correspondingly varying current in lead 27, this current varying with the correspondingly varying number of electrons incident on the solid insulator as determined by the signal source 26. The current in lead 27 may be amplified by element 29 and indicated by oscilloscope or the like 30, similarly as in the earlier numbered figures. Of course other types of translating device than the oscilloscope disclosed may be used.

It should be understood that the amplifying action here concerned has no relationship to the amplifying action inherent in the conventional vacuum tube which the organization would somewhat resemble without the diamond crystal solid insulator. On the contrary, the amplifying action results from the inherent ability of the solid dielectric (diamond crystal) under the conditions imposed to become conductive when bombarded by the electrons. The impressed signal waves partake of this amplification, the eventual conductivity current reflecting, in amplified form, such signal waves. Perhaps this phenomenon would be utilized in the form of a light modulator, wherein the variations in the intensity of the light incident on the diamond result in bombardment conductivity which is modulated by the light intensity modulations.

While only a limited number of possible applications of the invention have been disclosed, it should again be emphasized that the scope of utility of the invention is essentially as wide as that of the utility of the bombardment induced conductivity principle in general. The following quantitative measurements on this light effect were made. The tungsten filament in a standard 21 C. P. (candle power) lamp was focussed onto the edge of a diamond as in Fig. 2 By means of limiting apertures, the intensity of the illumination could be varied. At approximately .001 C. P. the pulse rate under alpha bombardment was about 7000 per minute and rose rapidly with increasing intensity of illumination. At about .06 C. P. the pulse rate was approximately 23,000 per minute and further increase in input intensity gave no further increase in pulse rate, i. e. light saturation had been achieved.

What is claimed is:

1. The method applicable to a solid insulator which comprises, establishing an electrical field in the region of said insulator, impressing radiation exclusive of low energy electromagnetic waves on said insulator while affected by said field, while at the same time continuously irradiating said insulator with light, and utilizing the resultant induced electrical conductivity current which, at least in part, flows in said insulator.

2. The method applicable to a solid insulator which comprises, applying an electric field in the region of said insulator, bombarding said insulator with electrically charged particles while affected by said field, while at the same time continuously irradiating said insulator with light, and utilizing the resultant induced electrical conductivity current which, at least in part, flows in said insulator.

3. In the method applicable to a solid insulator which comprises, impressing radiation exclusive of low energy electromagnetic waves on said solid insulator while it is immersed in an electric field, the further steps, in the interest of antipolarization, of irradiating said solid insulator with light and utilizing the resultant induced conductivity current which, at least in part, flows in said insulator.

4. The method applicable to a diamond which comprises, impressing an electric field on said diamond from a voltage source connected to conducting electrodes or coatings on boundary surfaces of said diamond, impressing radiation exclusive of low energy electromagnetic waves on said diamond, irrespective of direction, while irradiating said diamond with light, also irrespective of direction, and utilizing the resultant induced conductivity current which traverses at least a portion of said diamond, in the circuit including said source.

5. The method recited in claim 4 in which the radiation comprises electrically negative particles.

6. The method recited in claim 4 in which radiation comprises alpha particles.

7. The method recited in claim 4 in which the radiation comprises beta particles.

8. In combination, an electrical insulator, means for applying an electric field across at least a portion of said insulator, means for impressing radiation exclusive of low energy electromagnetic waves on said insulator, means for irradiating with light at least a portion of said insulator affected by said field, and a current responsive means in circuit with said field impressing means for indicating the resultant bombardment induced current in said insulator.

9. The combination recited in claim 8 in which said field impressing means is adapted to impress a direct voltage field.

10. In combination, an electrical insulator, conductive coatings on relative opposed surfaces thereof, means for impressing an electric field across at least a portion of said insulator, using said coatings, means for bombarding said insulator with electrically charged particles, and a current responsive means in circuit with said field impressing means for indicating the resultant bombardment induced current in said insulator.

11. In combination, an electrically insulating crystal, two conducting electrodes applied to separated portions of the surface of said crystal, a circuit connecting said electrodes and including a source of voltage for impressing an electric field across the crystal and including a current responsive means, means for bombarding said crystal with electrically charged particles, and means for irradiating said crystal with light during said bombardment, said current responsive means being adapted to respond to current impulses corresponding individually to the incident corresponding charged particles.

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