

Feb. 9, 1960

G. SICHLING ET AL

2,924,633

IGNITION SYSTEM FOR INTERNAL COMBUSTION ENGINES

Filed March 25, 1955

2 Sheets-Sheet 1

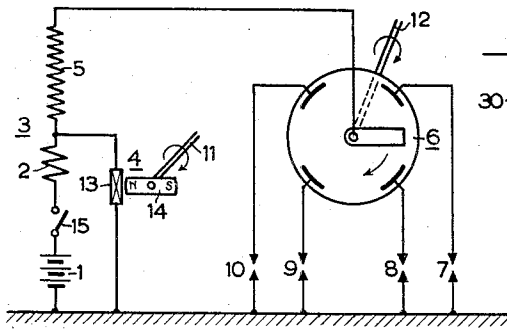


Fig. 1

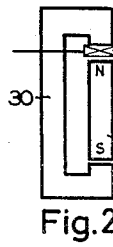


Fig. 2

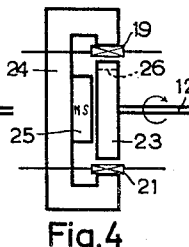


Fig. 4

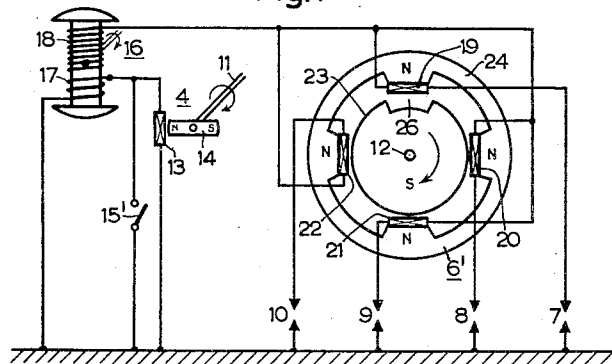


Fig. 3

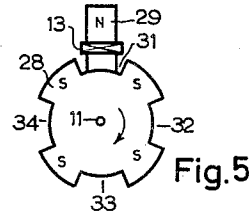


Fig. 5

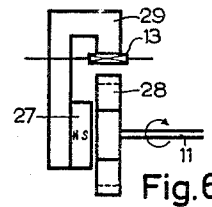


Fig. 6

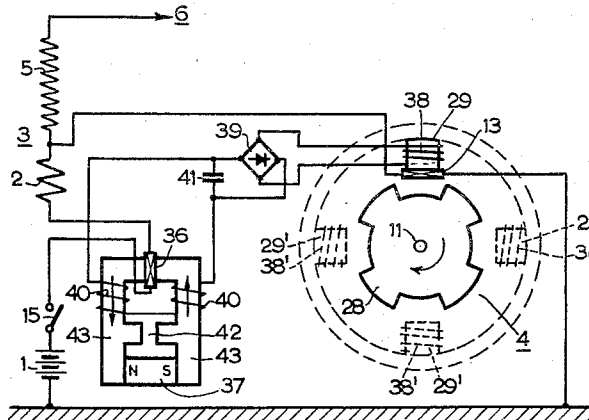


Fig. 7

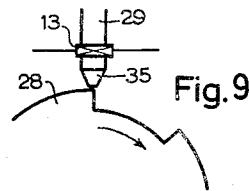


Fig. 9

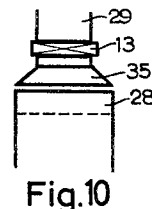


Fig. 10

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2 Sheets-Sheet 2

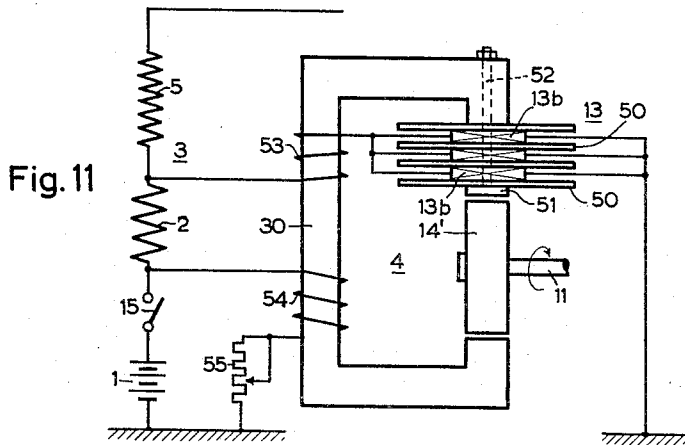


Fig. 11

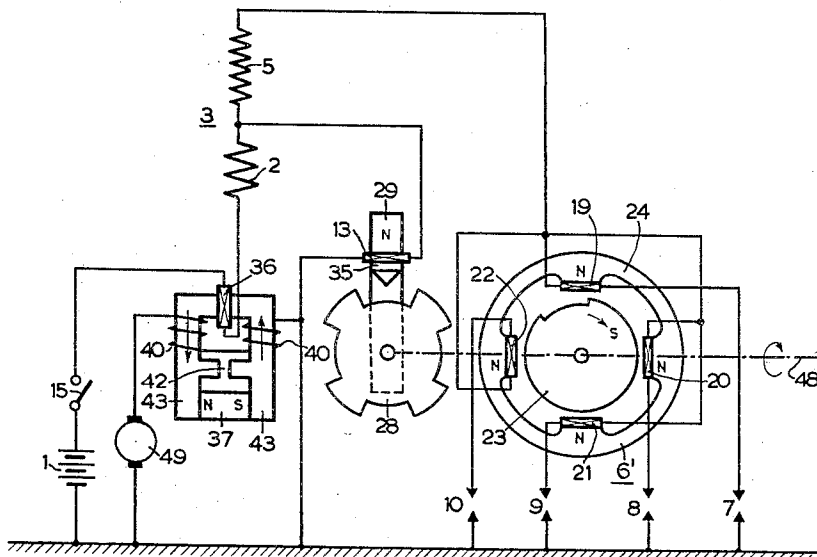


Fig. 8

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IGNITION SYSTEM FOR INTERNAL COMBUSTION ENGINES

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Application March 25, 1955, Serial No. 496,718

Claims priority, application Germany March 27, 1954

39 Claims. (Cl. 123—148)

Our invention relates to electric ignition systems for internal combustion engines. In such systems, the electric spark, as a rule, is produced either by battery ignition or by magneto ignition. The former takes electric power from a storage battery, while the power in magneto ignition is generated by a rotating inductor. Both types have in common that the primary circuit of an ignition coil is periodically interrupted at the ignition moments to produce in the secondary winding of the coil a surge of high ignition voltage. Engines with several cylinders are equipped with a distributor which is connected between the ignition coil and the spark plugs of the respective cylinders and which directs the ignition voltage in the required sequence to the individual spark gaps. The interruption of the primary circuit is usually effected by a cam-controlled breaker to which a capacitor is connected in parallel. The switching frequency of such a breaker is very high. For instance at an engine speed of 3000 r.p.m., the primary ignition current of four-cylinder four-cycle engines must be opened and closed 6000 times per minute and must each time control a current of a few amperes. The breakers, therefore, are subjected to extremely great switching duty and, despite modern advances, have retained the basic disadvantages inherent in mechanical circuit breakers. That is, the ignition breakers are affected by mechanical wear and are sensitive to ingress of dirt, particularly grease. For similar reasons the contact points of the distributor often suffer excessive wear and are subject to trouble due to dirt.

It is an object of our invention to devise an electric ignition device that fundamentally obviates the above-mentioned deficiencies inherent in mechanical contact breakers.

To this end, and in accordance with a feature of our invention, we substitute one or more of the switching devices in a spark ignition system by controllable semiconducting resistors, and we vary the resistance of the semiconductor member periodically to produce the required surge of high voltage in the secondary circuit of the system.

According to a more specific feature of our invention, we eliminate the periodic circuit breaker in the primary circuit of the ignition system and replace it by a semiconductor device of mechanically controllable resistance. The term "semiconductor" has a well defined meaning in the art. For example, the term is defined in Transistors: Theory and Applications by Coblenz and Owens, McGraw-Hill, 1955, p. 50-51, as follows: Semiconductors have a conductivity in the range between conductors and insulators and have an energy gap of the order of one electron volt. In the case of conductors there is no forbidden band or energy gap. In the case of insulators the energy gap is very large, perhaps as high as 15 electron volts.

According to another feature of our invention, we eliminate in the secondary high-voltage circuit of the ignition system, the distributor and substitute therefor

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a group of sequentially controlled semiconductor members.

When thus using a current controlling semiconductor device in the primary ignition circuit and also a current distributing semiconductor device in the secondary ignition circuit, all electric components of the ignition system are formed of static components which are rugged in use, require no attendance and have a virtually unlimited time of useful life.

According to another feature of our invention, in conjunction with any of those mentioned above, the semiconductor members in the ignition system are of the magnetically controllable type. The control of these semiconductor devices from large to small resistance and vice versa can be effected in a simple manner by subjecting them periodically to a magnetic field. To this end, and in accordance with a further feature of our invention, we provide the device with magnetic circuit means, preferably a permanent magnet, and move the magnetic structure or part thereof relative to the semiconductor member at the desired ignition frequency thus causing the semiconductor member to abruptly increase and decrease its resistance with the effect of opening or closing the ignition circuit. The movement required for operating the permanent magnet or other part of the magnetic control circuit is preferably derived from the crankshaft of the internal combustion engine. A rotating movement of the magnetic control part is preferable, although a translatory control movement may also be used.

Particularly suitable for ignition apparatus according to the invention are symmetrically conducting and magnetically controllable semiconductors of high carrier mobility, that is semiconductor substances whose carrier mobility is at least 6000 cm.²/volt sec., and also asymmetrically conducting semiconductors of the magnetic barrier type.

Among the semiconductors of high carrier mobility are those consisting of a binary compound of any one of the elements boron, aluminum, gallium, indium in the third group (subgroup B) of the periodic system with any one of the elements nitrogen, phosphorus, arsenic, antimony in the fifth periodic group (subgroup B). Semiconductors of this type, having a resistance controllable by the variation of an applied magnetic field, are described in the copending applications Serial No. 275,785, filed March 10, 1952 and Serial No. 391,647, filed November 12, 1953, both assigned to the assignee of the present invention.

Semiconductors of the magnetic barrier type, of which intrinsically conducting and surface-treated germanium is preferably applicable, are likewise characterized by a relatively low electric resistance which, by applying a magnetic field of a certain direction and of sufficient strength, can be increased to a very high value in only one direction of current conduction. The high asymmetrical resistance of these semiconductors can be wholly or partially eliminated by an additionally applied electric field or by radiation of a given direction. Semiconducting resistors exhibiting the magnetic barrier-layer effect are described in the copending applications Serial No. 297,788 filed July 8, 1952, now Patent No. 2,736,858 granted Feb. 28, 1956, Serial No. 462,516 filed October 15, 1954; and Serial No. 495,007 filed March 17, 1955, now Patent No. 2,869,001 granted Jan. 13, 1959, all assigned to the assignee of the present invention.

The foregoing and more specific objects, advantages and features of the invention will be apparent from the following description of the embodiments exemplified by the drawings in which:

Fig. 1 is a schematic circuit diagram of an ignition system for a four-cylinder engine operating with battery

ignition and equipped with a semiconductor device in the primary circuit of the ignition coil.

Fig. 2 shows schematically and more in detail the semiconductor device of the same ignition system.

Fig. 3 is the circuit diagram of an ignition system for a four-cylinder engine operating with magneto ignition and equipped in the primary circuit with a semiconductor device according to Fig. 2 and in the secondary circuit with a semiconductor device operating as a distributor.

Fig. 4 is a side elevation of the distributing device according to Fig. 3.

Figs. 5 and 6 show schematically an axial view and a side view of a modified form of a semiconductor-type ignition breaker for the primary circuit of a system as exemplified in Figs. 1 and 3.

Fig. 7 is the circuit diagram of a third embodiment of an ignition system, only the primary circuit being shown.

Fig. 8 illustrates schematically a complete ignition apparatus for a vehicle engine.

Figs. 9 and 10 illustrate respective modifications of an ignition control device applicable in the primary circuit; and

Fig. 11 shows schematically a further embodiment of a semiconductor device for use in the primary ignition circuit.

The battery ignition system shown in Fig. 1 is designed for a four-cycle engine. As usual, a storage battery 1 is connected in series with the primary winding 2 of an ignition coil 3 and in series with an interrupter 4. The secondary winding 5 of the ignition coil 3 is connected to the rotating contact of a distributor switch 6 which sequentially connects the secondary winding 5 with the individual spark gaps 7, 8, 9, 10 of the four spark plugs. The two driving shafts 11 and 12 of the interrupter 4 and of the distributor 6 are driven from the crankshaft of the engine at the required transmission ratio in the usual manner.

According to the invention, the interrupter device 4 operates without mechanical interrupter contacts. Instead, the device has a magnetically controllable semiconducting resistor 13 connected in the circuit of the primary winding 2. The semiconductor member 13 has normally a low resistance to the flow of current. At the ignition moment, however, the resistance is abruptly raised to a high value. This is done by subjecting the semiconductor member 13 to the field of a magnet 14. As a result, the flow of current through the primary winding 2 is suddenly reduced to a slight residual value and a high voltage surge is induced in the secondary winding 5. This voltage surge produces the igniting arc at the one spark gap then connected with the secondary winding 5 through the distributor 6.

Since for producing the voltage surge in the secondary winding 5 it is only essential to produce a given amount of sudden current change in the primary winding 2, it is not necessary to fully interrupt the primary circuit. By correspondingly rating the components of this circuit the same current change can also be obtained if the resistance value of the semiconductor member 13 is merely raised to a high finite value which still permits the flow of a certain residual current.

This periodic change in resistance can simply be effected by having the engine-driven shaft 11 rotate a permanent magnet 14 which passes by the semiconductor 13 at the desired ignition moment. However, for avoiding wasteful stray of magnetic flux, an iron yoke or core structure, as shown at 30 in Fig. 2, is preferably provided. This structure is preferably built up of iron laminations of high magnetic permeability. It has two pole faces which form a large gap for accommodating the rotating magnet 14. The semiconductor member 13 is mounted on one pole face.

As mentioned above, there are two preferred ways of obtaining the magnetically responsive change in semi-

conductor resistance. According to one way, the semiconductor member 13 consists of a symmetrically conducting material of high carrier mobility. Substances having a mobility above 6000, preferably above 10,000 cm.²/volt sec., afford the desired effect in cooperation with magnetic fields of up to 10,000 gauss as obtainable with commercially available permanent magnets such as those of the type known under the trade name Alnico (precipitation hardened alloys of aluminum, nickel and cobalt); in contrast, semiconductors of lower carrier mobilities do not exhibit a sufficient magnetic response of their resistance with such changes in magnetic field strengths as are feasible with the available permanent magnets or electromagnets.

The symmetrically conducting semiconductor member may be formed as a monocrystal of any of the above-mentioned binary compounds. We prefer using indium arsenide or indium antimonide both having a carrier mobility above 20,000 cm.²/volt sec. The semiconductor member may have a flat and elongated prismatic shape. The current supply leads are connected to the semiconductor body, for instance by soldering, preferably at the short ends of the elongated body; and the body is preferably so arranged that its current-traversed length extends transverse to the travel direction of rotation of the magnet. As a result, the magnet passes quickly by the semiconductor body so that the change in resistance is especially abrupt.

The semiconductor body is given a size as required by the voltage and resistance conditions of a primary circuit. For example, when operating with a 6-volt battery, the normal resistance of the semiconductor member may be rated to be in the order of 2 ohms. By virtue of the magnetic action the conductance can be abruptly reduced to approximately $\frac{1}{40}$ or less of its normal value if very high magnetic field strengths are used.

The second preferred way of producing the abrupt change in resistance is to give the semiconductor member asymmetrical conductance by providing for occurrence of a magnetic barrier layer. The substance used for the semiconductor body may also consist of the above mentioned compounds. However, the carrier mobility need not be as high as for symmetrical semiconductors because the desired control effect is due to appearance and disappearance of barrier action. For that reason, the semiconductor material may consist of germanium having a carrier mobility of not more than about 3000 cm.²/volt sec. The magnetic barrier effect is best obtained with intrinsic semiconductors, preferably intrinsic germanium. That is, the barrier effect is most conspicuous with semiconductors whose electron concentration is in the same order of magnitude as the hole concentration. The barrier effect is brought about either by giving the semiconductor member a special surface treatment, or a particular geometric shape, or both, as is described in detail in the above mentioned applications Serial No. 462,516 and Serial No. 495,007. For example, in order to obtain the magnetic barrier effect in a semiconductor device according to Figs. 1 and 2, the semiconductor member 13 is made of intrinsically conducting germanium. One of those two surfaces of the semiconductor crystal that extend parallel to the current flow direction and parallel to the plane of illustration in Fig. 2, is given high surface recombination by grinding and polishing that surface to a mirror finish. The other surface parallel to the current flow and parallel to the plane of illustration in Fig. 2 is given low surface recombination by etching. This is done by anodically treating the surface in an electrolytic bath. Suitable as such a bath in the case of germanium is diluted caustic soda with some addition of hydrogen peroxide.

In such a semiconductor member, the electron-hole pairs become crowded near the surface of high recombination so that a carrier-depleted zone, namely the magnetic barrier layer, is formed in the zone of low recom-

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ination. This effect has the result that the semiconductor has high resistance to current flow in one direction and low resistance in the other direction, depending upon the polarity of the applied magnetic field. The rectifying action can be reversed by reversing the magnetic field polarity. This barrier effect is increased by giving the high-recombination surface a larger area than the low-recombination surface or reducing the latter surface to zero as described in the above-mentioned application Serial No. 495,007; but this need not herein be further described because the particular design of the magnetic-barrier device is not essential to the present invention proper.

As mentioned, the semiconductor member is dimensioned in accordance with the required resistance and power value. For instance, if a semiconductor with a magnetic barrier layer is used, it may be given a resistance range of about 0.1 to 8 ohms, 1 to 80 ohms, or 10 to 800 ohms. For controlling high power values, it may be necessary to subdivide the member into a number of individual crystals and to provide them with cooling fins (50 in Fig. 11) described in a later place.

If the semiconductor member 13 is symmetrically conductive and of high carrier mobility as explained above, then the primary circuit of the ignition coil is interrupted twice for each full rotation of a magnet 14. This is because the magnetically responsive change in resistance in such a semiconductor is independent of the direction of the controlling magnetic field. On the other hand, if a semiconductor with a magnetic barrier layer is used, then only one interruption occurs per rotation because, depending upon the orientation of the magnet 14 relative to the current-flow direction in the semiconductor 13, only the north pole or only the south pole of the magnet will cause an increase in resistance. If the magnet 14 is given a cross-shaped design, then four interruptions per rotation will occur if a symmetrically conductive semiconductor of high carrier mobility is used, while in the case of a magnetic barrier semiconductor two interruptions per rotation are produced, assuming that each two opposite poles of the cross-shaped magnet have the same polarity.

In Fig. 1, the conventional ignition switch is denoted by 15. This switch may be located in the ignition lock and must be closed when starting the engine.

The ignition system according to Fig. 3 is also designed for a four-cylinder engine but operates with magneto ignition. An inductor 16 rotates in the field of a magnet structure (not illustrated) and is composed of a primary winding 17 and a secondary winding 18 which serve similar functions as the two windings of the ignition coil 3 shown in Fig. 1. The circuit of the primary winding 17 comprises the same interrupting device 4 as described above with reference to Figs. 1 and 2. The ignition switch in Fig. 3 is denoted by 15' and in this case is connected parallel to the semiconductor member 13 of the interrupter device 4. The ignition switch 15' is normally closed and must be opened for placing the system in operative condition. The operation of the ignition system is essentially the same as that of the system in Fig. 1, the resistance of member 13 being suddenly increased to a maximum value at the moment when the permanent magnet 14 passes by the member to then induce a current pulse in the inductor 16. The semiconductor member 13 is of the magnetic barrier type and has normally a low resistance and the polarity of connection required for blocking the current flow by the barrier effect when the magnet pole of the proper polarity passes by the member, as explained above.

Figs. 3 and 4 also illustrate an embodiment of an ignition distributor operating with magnetically controllable semiconducting resistors. Four semiconducting resistor members 19, 20, 21, 22 are connected in series with the respective spark gaps 7, 8, 9, 10. The semiconductor members are connected to the secondary winding 18 of

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the inductor 16 and are equally spaced about the shaft 12 of the distributor device 6'. The device has a magnetic field structure which comprises a rotating control part 23 mounted on the distributor shaft 12 to rotate together therewith. During rotation of a part 23 of a magnetic circuit, the magnetic flux through the individual semiconductor members is abruptly varied in the required sequence, and the conductance of the semiconductors 19 to 22 is temporarily raised to a high value so that the spark gaps 7 to 10 are in effect sequentially connected with the winding 18 at the proper ignition moments.

In order to normally secure a high electric resistance of the semiconductor members 19 to 22 to normally prevent the flow of current, these members are located between respective four pole shoes of a cup-shaped yoke structure 24 of magnetic material and the disc-shaped magnetic bridging part 23. The magnetic flux is produced by a stationary permanent magnet 25 which has a relatively large pole face located opposite the rotatable part 23 at such a slight distance therefrom that the magnetic reluctance in the air gap is only slight. The recess 26 at the periphery of 23 has the effect of successively interrupting the magnetic flux through the semiconductor members 19 to 23, thus establishing in effect an individual connection of each spark gap with the secondary winding 18 at a time. An ignition distributor 6' of the type shown in Figs. 3 and 4 may also be used instead of the distributor 6 in an ignition system according to Fig. 1.

Figs. 5 and 6 relate to a modification of the interrupter 4 in systems according to Figs. 1 and 3. It is assumed that the interrupter device is to rotate at $\frac{1}{2}$ of the engine revolving speed and is to be used for a four-cylinder four-cycle engine, requiring four interruptions of equal time spacing during each revolution of the engine. Similar to the distributor 6' in Figs. 3 and 4, a magnetic flux in the device according to Figs. 5 and 6 issues from an axially located permanent magnet 27 which has a large pole face located opposite a disc-shaped magnetic bridging member 28 with an only slight air-gap spacing. The bridging member 28 rotates with the drive shaft 11 of the interrupter. The semiconductor member 13 is mounted on the pole face of a stationary pole piece 29 which forms part of a field structure magnetically connected with the other pole of the permanent magnet 27. The disc-shaped member 28 has four recesses 31 to 34 uniformly distributed over its periphery. The recesses interrupt the magnetic flux through the semiconductor member 13, thus passing each time a current pulse through the primary winding of the ignition coil. The primary circuit is, in effect, interrupted whenever one of the lobes of part 28 is located opposite the semiconductor member.

It is not necessary in a system according to Fig. 1 to have the primary winding 2 continuously traversed by current during the entire interval between the individual ignition moments. That is, the generation of the secondary voltage surge requires having the primary winding 2 traversed by current only for such an interval of time prior to the ignition moment that the winding is magnetically charged to the maximum value at that moment. Consequently, the peripheral length of the recesses 31 to 34 need be only large enough to make certain that, at the highest possible revolving speed of the engine, the field of the primary winding 2 (Fig. 1) is fully built up as soon as one of the lobes of part 28 enters into the range immediately below the semiconductor member 13, this instantaneous position being shown in Fig. 5.

The continuous current consumption of battery ignition systems is relatively large. For that reason, it is often desired, particularly for unattended engines, to prevent the flow of continuous current when the engine stands still and if the ignition switch 15 is left closed and the interrupter 4 has accidentally reached standstill in its circuit-closing position. To this end, and in accordance with another feature of the invention, a semiconductor member

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is connected in series with the ignition switch 15 and is placed under the blocking influence of a constant magnet field, for instance of a permanent magnet, to prevent the flow of current in the primary circuit until the blocking field is eliminated by a speed-responsive counter bias. For providing such a bias, a part of the interrupter device 4 which during running of the engine is subjected to an alternating or pulsating magnetic field may be provided with a winding which energizes, through rectifiers and if desired through smoothing means, a releasing coil for obviating the blocking magnetic field. As a result, the primary ignition circuit is automatically opened when the revolving speed of the engine drops below a given minimum value and is closed again when during starting of the engine this minimum speed is exceeded. This relieves the loading of the starter battery and prevents damage if one neglects to open the ignition switch 15.

The ignition system illustrated in Fig. 7 is equipped with an automatic current blocking device embodying the above-mentioned features. The primary ignition circuit corresponds to that of Fig. 1 and comprises an interrupter 4 whose design and operation are essentially similar to the interrupter of Figs. 5, 6. The secondary circuit is only partly illustrated in Fig. 7; it may be in accordance with Fig. 1 or Fig. 3. A magnetically controllable semiconductor member 36 is connected in series with the ignition switch 15 and is disposed between the pole faces of two magnetic yoke structures 43 which are joined with a permanent magnet 37 so that the field flux issuing from this magnet is effective in the semiconductor member 36. As a result, the semiconductor member 36 normally has a high resistance and substantially prevents the flow of current from battery 1 through the primary winding 2 of the ignition coil 3. The pole piece 29 of the magnetic circuit in the interrupter device 4 differs from that shown in Figs. 4 and 5 by carrying a winding 38. This winding is connected through a full-wave rectifier 39 to windings 40 on the yoke structures 43 of the blocking device. If desired, a smoothing capacitor 41 may be connected parallel to the output terminals of rectifier 39 as is shown in Fig. 7.

As long as the engine is in operation or during starting of the engine, the movable bridge member 28 of the interrupter device 4 travels by the pole piece 29 and induces in its windings 38 a current which produces in the windings 40 a counter-acting bias field. This bias field displaces the magnetic flux from the semiconductor element 36 to an air gap 42 located in a magnetic shunt path across the semiconductor member. As a result, the semiconductor member 36 has low resistance only as long as the engine revolves at a speed above a given minimum. This permits current to flow through the primary winding 2 of the ignition coil 3.

In order to amplify the current applied to the counter-magnetizing windings 40, the interrupter 4 may be provided with one or more pole pieces 29' in addition to the above described pole piece 29, each pole piece 29' being provided with a winding 38'. By connecting the windings 38' in series or parallel with the winding 38, a correspondingly increased current or voltage is supplied to the windings 40. However, as shown in Fig. 8, the current for the counter-magnetizing windings 40 may also be supplied from another current source, preferably the electric generator of a vehicle engine, which supplies voltage only when the engine operates above a given minimum speed.

The blocking device illustrated in Fig. 7 or Fig. 8 may also serve for limiting the primary ignition current at high revolving speeds. For this purpose the semiconductor element 36 is made of a magnetically controllable semiconductor of symmetrical conductance and high carrier mobility whose resistance depends only upon the strength but not on the polarity of the controlling magnetic field. Since the voltage impressed upon windings 40 increases with the engine speed, the magnetic flux traversing the semiconductor member gradually changes toward reversed

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polarity, whereafter the resistance of member 36 gradually increases with the engine speed.

While reference is made in the foregoing to the provision of permanent magnets in the semiconductor control devices of the primary and secondary ignition circuits, it will be obvious that the controlling magnetic flux for the semiconductors may also be produced by electromagnets (see Fig. 11). The excitation winding of such an electromagnet may be energized from the storage battery or generator of a vehicle and may be located, for instance, in Fig. 6 on the part 27 which in this case consists of magnetic material of high permeability.

The complete ignition apparatus illustrated in Fig. 8 is designed for a four-cycle four-cylinder engine on a vehicle. The ignition system has an ignition coil 3 in a primary circuit similar to that explained with reference to Figs. 1 and 7. The primary circuit comprises an interrupting device as shown in Figs. 5 and 6. This device is equipped with a pole piece 35 described below with reference to Figs. 9 and 10. The distributor 6' in the secondary ignition circuit is in accordance with Figs. 3, 4. The rotor 23 of the distributor and the rotor 28 of the interrupter are mounted on a common shaft 48 driven from the crankshaft of the engine in proportion to the engine speed. At the proper moments the interrupting device produces a voltage surge which is directed by the distributor to the proper spark gap. The magnet system of the interrupter or of the distributor or of both may be angularly adjustable in order to set the device to the correct timing.

The primary circuit is further equipped with a blocking device as described above with reference to Fig. 7, except that this device has its control coils 40 energized from the generator 49 of the engine. Since this generator is in operation and provides a sufficient voltage only when the engine is running, the blocking device controls its semiconductor member 36 to prevent the flow of appreciable current from the battery 1 if the engine is at standstill and if it has been neglected to open the ignition switch 15.

Furthermore, the magnetic control circuit may also be designed in such a manner that the magnetic flux variation in the semiconductor member to be controlled is brought about by a movable or rotatable magnetic bridging structure which acts to periodically displace the magnetic lines of force onto a shunt path. According to another modification, the individual semiconductor members are placed into a constant magnetic field, and this field is temporarily obviated in the semiconductor by a counter-magnetization produced, for instance, by a rotating bias magnet or by a portion of a second magnetic circuit of opposed polarity. It is further not obligatory for the invention to use the construction shown in Figs. 4 and 6 for the energizing permanent magnet. That is any other movable or stationary part of the magnetic control circuit may be designed as a permanent magnet. Since semiconductors of the magnetic barrier type exhibit a large change in resistance only with a given direction of the controlling magnetic field, and since such semiconductor members when subjected to a magnetic field of the opposite polarity may even show some reduction of their normal resistance, the magnetic control circuit for such semiconductor members may be designed to reverse the polarity of the controlling magnetic field at the ignition moment in order to secure a further reduction of the effective semiconductor resistance. This is readily possible by applying an alternate polarity to the individual sectors or teeth of the rotating part of the magnetic control circuit.

For producing a strong spark at the spark plugs it is desirable to have the resistance increase of the semiconductor member 13 in Fig. 1 or Fig. 3 occur as rapidly as possible. It is preferable, therefore, to take care of increasing the rate of change of the controlling magnet

field. To this end, the modification shown in Figs. 8, 9 and 10 has a magnetically conducting pole piece 35 inserted between the semiconductor member 13 and the movable magnetic control part 28. The pole piece 35 tapers toward the rotating part 28 and forms a knife-type edge which faces the rotating part 28 and extends transverse to its direction of rotation. In order to secure at the entrance place of the magnetic lines of force about the same iron cross section as at the place adjacent to the semiconductor member 13, the knife-edge is preferably widened as shown in Fig. 10. However, for increasing the rate of change of the magnetic control flux, it is often sufficient to give the semiconductor member 13 an elongated shape, such as the shape of a flat and elongated prism, and to arrange the member so that its greatest length extends transverse to the travel direction of the flux-controlling part of the magnetic circuit. If desired, the semiconductor member may be subdivided into individual rods or strips, which are arranged one behind the other and transverse to the travel direction of the magnetic control part. The individual semiconductor members are electrically interconnected in series of parallel relation depending upon the electric requirements. Field forcing means for reducing the transition interval within which the semiconductor member varies between maximum and minimum resistance are also applicable. Such means are described in the copending application Serial No. 491,983, filed March 3, 1955, U.S. Patent 2,843,763, issued July 15, 1958, assigned to the assignee of the present invention. These field forcing means consist preferably of a feedback coupling of the electric circuit being controlled with the controlling magnetic field or with a magnetic field which produces in the semiconductor member a flip-flop resistance characteristic. The various means described in the last-mentioned copending application for reducing the electric transition losses during the switching interval of the semiconductor member are likewise applicable.

The above-mentioned features for increasing the rate of resistance change and reducing the transitory losses in the semiconductor member are exemplified by the embodiment illustrated in Fig. 11.

Fig. 11 shows a primary ignition circuit similar to that described above with reference to Figs. 1 and 2. The interrupter device 4 has a semiconductor member 13 composed of a number of individual crystals 13b of flat and elongated shape. These crystals are located one above the other with their longitudinal direction transverse to the rotational direction of the magnetic control part 14. The semiconductor crystals 13b are further provided with intermediate cooling fins 50. These fins consist of iron and are insulated from the crystals just as in all illustrated embodiments the body of the semiconductor member is electrically insulated from the adjacent magnetic structure. The crystals 13b and fins 50 are fastened to the magnetic structure 30 by means of a pole plate 51 and of a bolt 52.

According to Fig. 11 the primary ignition circuit includes a feed back winding 53 on the core structure 30. The rotating control part 14' of the magnetic circuit in this embodiment consists of highly permeable material, and the core structure 30 is provided with an energizing winding 54 to provide the magnetic flux. The winding 54 is energized from the battery 1 through a resistor 55.

Generally, the operation of the interrupter device according to Fig. 11 is the same as that of the interrupter device described above, except that the feedback winding 53 and the cooling action of the semiconductor assembly increase the abruptness of the current pulse and hence the steepness of the ignition voltage. When the rotating control structure 14' reaches a position at which the semiconductor assembly commences to reduce its resistance so that current starts flowing through the primary winding 2 of the ignition coil and through the feedback winding 53, the winding imposes upon the magnetic

circuit an additional magnetization acting on the semiconductor resistance in the same sense as the movable control structure. This increases the rate of current change and thus also the feedback effect. As a result, the resistance drops with extreme rapidity to the lowest value dependent upon the resistance conditions in the primary ignition circuit. The overall effect of such a device is to operate with a flip-flop characteristic. That is as soon as the control structure 14' passes beyond a given position, the resistance of the semiconductor assembly is suddenly triggered down from a high maximum to the minimum value.

This effect is augmented by the increased rapidity with which the waste heat in the semiconductor assembly is dissipated through the cooling fins 50. It is, therefore, of advantage to expose the fins to cooling air supplied, for instance, by the fan under the hood of a vehicle.

It will be apparent from the foregoing to those skilled in the art that the invention permits of a great variety of modifications and combinations of the individual system components and hence may be embodied in apparatus other than those specifically illustrated and described, without departing from the essential features of the invention and within the scope of the claims annexed hereto:

We claim:

1. Ignition apparatus for internal combustion engines, comprising a plurality of spark gaps, an ignition coil having a low-voltage primary circuit and having a high-voltage secondary circuit, periodic current control means connected with said primary circuit for producing voltage surges in said secondary circuit, a distributor having parallel branches connecting said secondary circuit with said respective spark gaps and having semiconductor members of magnetically controllable resistance connected in said respective branches, said distributor having magnetic control means for sequentially controlling said semiconductor members to reduce their respective resistances to thereby sequentially distribute said voltage surges to said spark gaps.

2. Ignition apparatus for internal combustion engines, comprising a plurality of spark gaps, an ignition coil having a low-voltage primary circuit and a high-voltage secondary circuit, a control device having a semiconductor member of magnetically controllable resistance connected with said primary circuit and having magnetic control means for periodically varying the resistance of said semiconductor member to produce high-voltage surges in said secondary circuit, a distributor having parallel branches connecting said secondary circuit with said respective spark gaps and having semiconductor members of magnetically controllable resistance connected in said respective branches, said distributor having magnetic control means for sequentially controlling said semiconductor members to reduce their respective resistances to thereby sequentially distribute said voltage surges to said spark gaps.

3. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having a semiconductor member connected in said circuit and having magnetic field means in whose field said semiconductor member is disposed, said field means having rotatable structure for periodically varying said field to control the resistance of said member, whereby voltage surges are applied to said spark gap means.

4. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having a semiconductor member connected in said circuit, said device having a magnetic field structure forming a pole face and having a gap adjacent to said pole face, said semiconductor member being located on said pole face within said gap, rotating means forming a part of said magnetic field structure, a body in said

gap attached to the semiconductor member, said body having a shape tapering from said member toward said part in the plane of rotation of said part but widening from said member toward said part in a direction transverse to said plane so that said member has an edge facing said part and extending transverse to said plane over a length larger than that of said semiconductor member.

5. An ignition apparatus for internal combustion engines having a battery and an engine-speed responsive voltage source, the combination of an ignition circuit connected to said battery to be energized therefrom, a magnetically responsive semiconductor member connected in said circuit in series with said battery and having a normally high resistance to prevent flow of current from said battery, a magnetic field control device having a field in which said semiconductor member is located, which field normally produces said high resistance in said member, said control device having field control means connected to said engine-responsive voltage source for reducing the resistance of said member to permit flow of current when the engine speed exceeds a given minimum value.

6. An ignition apparatus for internal combustion engines having a battery and an engine-speed responsive voltage source, the combination of an ignition circuit connected to said battery to be energized therefrom, a magnetically responsive semiconductor member connected in said circuit in series with said battery and having a normally high resistance to prevent flow of current from said battery, a magnetic control device comprising a structure including a permanent magnet having a field in which said semiconductor member is located, said control device having a control winding disposed on said structure and magnetically opposed to said permanent magnet, said control winding being connected to said voltage source for reducing the resistance of said member to permit flow of current when the engine speed exceeds a given minimum value.

7. An ignition apparatus according to claim 2, said distributor having a winding in inductive relation to said magnetic control means for generating in said winding a voltage only when the engine is running, a current blocking device having another magnetically responsive semiconductor member of normally high resistance connected in said primary circuit in series with said ignition coil, said blocking device having a field in which said latter semiconductor member is located and being connected to said voltage source for reducing the resistance of said member to permit flow of current when the engine speed exceeds a given minimum value.

8. Ignition apparatus for internal combustion engines, comprising spark-gap means, an inductance coil having a low-voltage primary circuit and having a high-voltage secondary circuit connected to said spark-gap means, a control device having a semiconductor crystal member of magnetically controllable resistance connected with said primary circuit and having movable magnetic control means for varying the resistance of said semiconductor member to produce high-voltage surges in said secondary circuit, said control device including a magnetizable field structure forming a magnetic circuit which includes said movable control means and extends through said semiconductor member, and a feedback winding connected in said primary circuit in series with said member and poled in cumulative relation to the magnetic flux controlled by said movable control means.

9. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having a semiconductor crystal member of magnetically controllable resistance connected in said circuit and having rotary magnetic control means for periodically varying the resistance of said semiconductor

member, said magnetic control means being operatively connected to the engine to be responsive to the engine speed to apply periodic voltage surges to said spark-gap means, said semiconductor member being a symmetrically conductive semiconductor crystal having a carrier mobility above 6000 cm.²/volt second.

10. An ignition apparatus for internal combustion engines having an electric power source and an engine-speed responsive voltage source, the combination of an ignition circuit connected to said power source to be energized therefrom, a magnetically responsive semiconductor member connected in said circuit in series with said power source and having a normally high resistance to prevent flow of current from said power source, a magnetic control device comprising a structure including a rotary magnet having a field in which said semiconductor member is located to produce said normally high resistance of the semiconductor member, said control device having a control winding disposed on said structure and magnetically opposed to said magnet, said control winding being connected to said engine-speed responsive voltage source for reducing the resistance of said member to permit flow of current when the engine speed exceeds a given minimum value.

11. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having a semiconductor member connected in said circuit and having magnetic field means in whose field said semiconductor member is disposed, said field means having rotatable structure for periodically varying said field to control the resistance of said member, whereby voltage surges are applied to said spark-gap means, said semiconductor member being a symmetrically conductive semiconductor crystal having a carrier mobility above 6000 cm.²/volt second, said rotatable structure being operatively connected to the engine shaft, to be responsive to engine speed.

12. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having a semiconductor member connected in said circuit and having magnetic field means in whose field said semiconductor member is disposed, said field means having rotatable structure for periodically varying said field to control the resistance of said member, whereby voltage surges are applied to said spark-gap means, said semiconductor member being an asymmetrically conductive semiconductor crystal having a magnetic barrier layer.

13. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having a semiconductor crystal connected in said circuit and having magnetic field means in whose field said semiconductor member is disposed, said field means comprising permanent magnet means for producing said field and having magnetic structure rotatable relative to said semiconductor member for periodically varying said field to control the resistance of said member, whereby voltage surges are applied to said spark-gap means, said semiconductor member being an asymmetrically conductive semiconductor crystal having a magnetic barrier layer.

14. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit comprising induction coil means connected to said spark-gap means, and a semiconductor device having a semiconductor member connected in the current path in said circuit and having magnetic field means in whose field said semiconductor member is disposed, said field means having rotatable magnetic structure for periodically varying said field to control the resistance of said member, whereby voltage surges are applied to said spark-gap means; said semiconductor member being taken from the group consisting of binary compounds of an element of

the class consisting of boron, aluminum, and gallium, and indium with an element of the group consisting of nitrogen, phosphorus, arsenic, and antimony.

15. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit comprising induction coil means connected to said spark-gap means, and a semiconductor device having a semiconductor member connected in the current path in said circuit and having magnetic field means in whose field said semiconductor member is disposed, said field means having rotatable magnetic structure for periodically varying said field to control the resistance of said member, whereby voltage surges are applied to said spark-gap means, said semiconductor member being an asymmetrically conducting semiconductor of the magnetic barrier type comprising intrinsically conducting germanium.

16. The invention defined in claim 4, the first periodic magnetic control means including a magnet rotatably mounted adjacent the semiconductor member of the control device which member is subjected to the field of said magnet to vary the resistance of the member, as aforesaid, said magnetic control means being responsive to the engine speed to periodically produce said high-voltage surges in the secondary circuit.

17. The apparatus defined in claim 1, the magnetic control means being operatively connected to respond to engine speed to apply said voltage surges to said spark-gap means in the required sequential relation.

18. The apparatus defined in claim 2, the magnetic control means being operatively connected to respond to engine speed to apply said voltage surges to said spark-gap means in the required timed relation.

19. An apparatus for controlling an electric circuit in dependence upon a magnetic field, comprising means for obtaining sequential electric pulses, said means comprising a rotatably mounted magnetic field means providing a plurality of circumferentially mutually displaced magnetic field poles, a semiconductor crystal member disposed adjacent said field means, across an air gap, so as to be subjected to the flux from said field poles sequentially, electric connections to said crystal for passing an electric current through said crystal transversely to the magnetic flux in the crystal, and an electric circuit to be controlled, the latter circuit including said member as a resistive element in the current path therein so as to be responsive to change in resistance of said member due to said magnetic field.

20. An apparatus for controlling an electric circuit in dependence upon a magnetic field, comprising means for obtaining sequential electric pulses, said means comprising a rotatably mounted magnetic field means providing a plurality of circumferentially mutually displaced magnetic field poles, a semiconductor crystal member disposed adjacent said field means, across an air gap, so as to be subjected to the flux from said field poles sequentially, electric connections to said crystal for passing an electric current through said crystal transversely to the magnetic flux in the crystal, and an electric circuit to be controlled, the latter circuit including said member as a resistive element in the current path therein so as to be responsive to change in resistance of said member due to said magnetic field, the semiconductor having a carrier mobility of at least 6,000 cm.²/volt second.

21. A system for producing voltage surges comprising inductively linked low voltage primary and high voltage secondary circuit means, means for electrically energizing the primary circuit means, a rotatably mounted magnetic field means providing a plurality of circumferentially mutually displaced magnetic field poles, a semiconductor crystal member disposed in the flux path across an air gap so as to be subjected to the flux from said field poles sequentially, the primary circuit means including electric connections for passing an electric current through said member transversely to the magnetic flux in the member,

whereby voltage surges are produced in said secondary circuit means.

22. A system for producing voltage surges comprising inductively linked low voltage primary and high voltage secondary circuit means, means for electrically energizing the primary circuit means, a rotatably mounted magnetic field means providing a plurality of circumferentially mutually displaced magnetic field poles, a semiconductor crystal member disposed in the flux path across an air gap so as to be subjected to the flux from said field poles sequentially, the primary circuit means including electric connections for passing an electric current through said member transversely to the magnetic flux in the member, whereby voltage surges are produced in said secondary circuit means, and spark-gap means connected in said secondary circuit means.

23. A system for producing voltage surges comprising inductively linked low voltage primary and high voltage secondary circuit means, means for electrically energizing the primary circuit means, a rotatably mounted magnetic field means providing a plurality of circumferentially mutually displaced magnetic field poles, a semiconductor crystal member disposed in the flux path across an air gap so as to be subjected to the flux from said field poles sequentially, the primary circuit means including electric connections for passing an electric current through said member transversely to the magnetic flux in the member, whereby voltage surges are produced in said secondary circuit means, the semiconductor having a carrier mobility of at least 6,000 cm.²/volt second.

24. A spark-gap system for producing sequential voltage surges across the gap, comprising a low voltage primary coil circuit, means for energizing said primary coil circuit, and a high voltage secondary coil circuit inductively linked with the primary coil circuit, a semiconductor single crystal of magnetically controllable resistance connected in the current path in said primary coil circuit, and magnetic control means for sequentially varying the magnetic flux in said crystal to sequentially vary the resistance of said crystal to produce said voltage surges across the gap in the secondary circuit, said magnetic control means including a magnetic element, said magnetic element and said crystal being mounted for relative rotary displacement with respect to each other, to periodically and abruptly alter the magnetic flux passing through said semiconductor.

25. The apparatus defined in claim 24, the semiconductor being an indium arsenide monocrystal having a carrier mobility above 6000 cm.²/volt second.

26. The apparatus defined in claim 24, the semiconductor being an indium antimonide monocrystal having a carrier mobility above 6000 cm.²/volt second.

27. A system for producing voltage surges, comprising inductively linked low voltage primary and high voltage secondary circuit means, means for electrically energizing said primary circuit means, a semiconductor crystal of magnetically controllable resistance connected in the current path in said primary circuit, and magnetic control means for varying the magnetic field in said crystal to vary its resistance, to produce said voltage surges in the secondary circuit means, said magnetic control means including a magnetic element, said magnetic element and said crystal being mounted for relative rotary displacement with respect to each other, to periodically and abruptly alter the magnetic flux passing through said semiconductor.

28. A system for producing voltage surges, comprising inductively linked low voltage primary and high voltage secondary circuit means, means for energizing said primary circuit means, a semiconductor crystal of magnetically controllable resistance connected in the current path in said primary circuit, and magnetic control means for varying the magnetic field in said crystal to vary its resistance, to produce said voltage surges in the

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secondary circuit means, said magnetic control means comprising a rotary multi-magnetic poled member.

29. A system for producing voltage surges, comprising inductively linked low voltage primary and high voltage secondary circuit means, means for energizing said primary circuit means, a semiconductor crystal of magnetically controllable resistance connected in the current path in said primary circuit, and magnetic control means for varying the magnetic field in said crystal to vary its resistance, to produce said voltage surges in the secondary circuit means, said magnetic control means comprising a rotary magnet having at least one recessed region on its peripheral surface, said peripheral surface moving adjacent said semiconductor crystal.

30. In an ignition apparatus for internal combustion engines, comprising spark-gap means and an ignition circuit connected to said spark-gap means, the improvement comprising a semiconductor device having a semiconductor crystal member of magnetically controllable resistance connected in said circuit and having magnetic control means for periodically varying the resistance of said semiconductor member, said magnetic control means comprising a rotatable magnetic field altering means operatively connected to the engine to be rotated in response to the engine speed to apply timed voltage surges to said spark-gap means, said magnetic control means further comprising a magnetic structure providing a plurality of pole faces, the semiconductor member and said rotatable magnetic field altering means being disposed between said pole faces for serial flow of magnetic flux through the semiconductor member and the rotatable magnetic field altering means.

31. In an ignition apparatus for internal combustion engines, comprising spark-gap means and an inductance coil having a low-voltage primary circuit and having a high-voltage secondary circuit connected to said spark-gap means, the improvement comprising a control device having an elongated semiconductor crystal member of magnetically controllable resistance connected with said primary circuit for lengthwise passage of current there-through and having magnetic control means for varying the resistance of said semiconductor member, the magnet control means comprising a rotatable magnet means operatively connected to the engine shaft, to be responsive to engine speed, to produce sequentially timed high-voltage surges in said secondary circuit, a magnetic yoke having a pole face disposed adjacent one face of said semiconductor member for producing in said semiconductor a magnetic field transverse to the flow of current therethrough, the rotatable magnet means being in the path of said field and having its direction of rotation transverse to the current direction of the semiconductor and being disposed near the opposite face of the semiconductor.

32. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having a semiconductor crystal member connected in said circuit and having a magnetic field structure in whose field said semiconductor member is disposed, said semiconductor member being asymmetrically conductive and having a magnetic barrier layer when said field has a given polarity relative to the current flow direction in said member, said field structure having field control means comprising a rotatably mounted magnetic means operatively connected for rotation responsive to engine speed for periodically varying the resistance of said member, whereby timed voltage surges are applied to said spark-gap means, said field structure further including a magnetic structure providing a plurality of pole faces, the semiconductor member and said rotatable magnetic means being disposed between the pole faces for serial flow of magnetic flux through the member and the rotatable magnetic means.

33. Ignition apparatus for internal combustion engines,

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comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having a semiconductor member connected in said circuit and having a magnetic field structure in whose field said semiconductor member is disposed, said member being symmetrically conductive and having a carrier mobility above 6000 cm.²/volt second, said field structure having field control means comprising a rotatably mounted magnetic means operatively connected for rotation responsive to engine speed for periodically varying said field to control the resistance of said member, whereby timed voltage surges are applied to said spark-gap means, said field structure further including a magnetic structure providing a plurality of pole faces, the semiconductor member and said rotatable magnetic means being disposed between the pole faces for serial flow of magnetic flux through the member and the rotatable magnetic means.

34. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having a semiconductor crystal member connected to said circuit, the device having magnetic field structure means in whose field said semiconductor member is disposed, said field structure having a magnetic structure displaceable relative to said member responsively to engine speed for periodically varying said field to control the resistance of said member, said semiconductor member having a flat and elongated shape and having its longest dimension transverse to the direction of relative displacement of said structure, whereby timed voltage surges are applied to said spark-gap means, said relative displacement being rotational.

35. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device comprising a semiconductor crystalline member connected in said circuit, a magnetic field structure including a rotary magnet in whose field said semiconductor member is disposed, said rotatable magnet being operatively connected for rotation correlatively to engine speed for periodically varying said field to control the resistance of said member, said semiconductor member having a flat and elongated shape and having its longest dimension transverse to the direction of movement of said structure, whereby sequentially timed voltage surges are applied to said spark-gap means, said semiconductor member comprising a plurality of flat partial members arranged one adjacent the other for serial passage of magnetic flux therethrough and being electrically interconnected in said circuit, and metallic heat dissipating means disposed intermediate and in contact with the partial members.

36. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having a semiconductor crystal member of magnetically controllable resistance connected in the current path in said circuit and having a rotary magnet for periodically varying the resistance of said semiconductor member, said magnet being operatively connected to the engine to be responsive to the engine speed to apply periodic voltage surges to said spark-gap means, said semiconductor member being an asymmetrically conductive semiconductor crystal having a magnetic barrier layer.

37. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit, comprising inductively linked primary and secondary circuit means, operatively connected to said spark-gap means, and a semiconductor device having a semiconductor crystal member connected in said primary circuit and having a magnetic field structure in whose field said semiconductor member is disposed, said field structure having magnetic field control means for periodically and abruptly varying said field to control the resistance

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of said member, whereby sequential voltage surges are applied to said spark-gap means, said control means comprising a rotary magnet operatively connected to the engine shaft to be responsive to engine speed.

38. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having an elongated semiconductor member connected in said circuit for lengthwise passage of current therein, said device having a magnetic field structure forming a pole face and having a gap adjacent to said pole face, said semiconductor member being located on said pole face within said gap, said field structure comprising a magnetic element rotatable in said gap for varying the magnetic field in said member, the plane of rotation being transverse to the current flow direction in the semiconductor, the rotatable magnet element having at least one recess in its peripheral surface to provide an abrupt decrease in flux passing through the semiconductor member, and a magnetically permeable body stationarily disposed between said member and said rotatable magnetic element and having a shape expanding from said member toward said rotatable magnetic element in a direction transverse to the plane of rotation of the element.

39. Ignition apparatus for internal combustion engines, comprising spark-gap means, an ignition circuit connected to said spark-gap means, and a semiconductor device having an elongated semiconductor member connected in said circuit for lengthwise passage of current therein, said device having a magnetic field structure

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forming a pole face and having a gap adjacent to said pole face, said semiconductor member being located on said pole face within said gap, said field structure comprising a magnetic element rotatable in said gap for varying the magnetic field in said member, the plane of rotation being transverse to the current flow direction in the semiconductor, the rotatable magnet element having at least one recess in its peripheral surface to provide an abrupt decrease in flux passing through the semiconductor member, and a magnetically permeable body stationarily disposed between said member and said rotatable magnetic element and having a shape expanding from said member toward said rotatable magnetic element in a direction transverse to the plane of rotation of the element, said magnetically permeable body having a knife-type edge facing said rotatable magnetic element and extending transverse to the rotational direction of said magnetic element.

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