ELECTRONICS IN INDUSTRY

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Fig. 95.

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Fig. 111.

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Fig. 110.

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I

THE DEVELOPMENT OF THE SCIENCE OF ELECTRONICS

THIS book has been written with the intention of presenting a general understanding of some of the more recent developments in the field of industrial electronics. In order to present as full a picture as possible, it has been necessary to deal, in some detail, with the components and basic circuits that together form the more complex circuitry of electronic systems. Unfortunately, the field of electronics, as it exists today, is so vast that, even when limited to its industrial applications, it will not allow for complete coverage within the confines of a single volume. Many applications must therefore be omitted, and much theoretical detail condensed, in order to present as accurate an overall picture as is possible.

The aura of mystery that appears to surround such recent developments as the electronic computer, the electronic control of machinery and the electronic control of process plants, is by no means impenetrable. Their design and operation may be the realm of the mathematician, the scientist and the engineer, but once analysed, and the function of each sub-unit or component part reduced to purely physical concepts, their complexity becomes less formidable, and their operation understandable to those without specialized knowledge.

The theory of semiconductor devices, transistors and their near relations, has been covered in some detail, because it is in the development of these devices, and the techniques associated with them, that a large measure of the future of the science of electronics will probably lie. The field is wide, and much research remains to be carried out, but semiconductor devices are fast replacing the conventional components used only a few years ago. Their economy in operation, their reliability and their assumed longevity has fired the imagination of many electronic equipment designers, while their small dimensions and ability to resist shock and vibration has proved them to be particularly suited for use in electronic control and transmission equipment in this 'space era'. The satellites that now orbit this earth, and transmit vital information back to earthbound scientists, draw the electrical power for their transmitters and other electronic systems from the sun. Solar cells, which convert the energy radiated by the sun into electrical energy, are themselves semiconductor devices. The transmitters, and all the complex electronic circuitry within the satellites, incorporate semiconductor devices in their many forms, and much of the ancillary ground equipment that tracks the satellites, receiving and recording the information transmitted by them, relies on semiconductor devices for its efficient operation.

The development of 'solid-state' electronics, that part of the science which deals with semiconductors, is still in its infancy. Teething troubles still exist and the science is not, as yet, fully understood. However, recent development trends indicate that many of the problems encountered earlier are being solved. The inability of earlier devices to operate under severe conditions of temperature, or to operate at high power ratings, predicted by many as proving the limiting factors in semiconductor applications, seems now to be well on the way to being overcome. New materials and new techniques have emerged with remarkable rapidity, so that where, only a few years ago, the best of these devices could operate at only a few watts, later development has brought about some, such as the silicon-controlled rectifier, which can operate at several hundred-thousand watts.

A great deal of research effort, in recent years, has been directed to the development of low-temperature techniques with semiconductors. At temperatures approaching absolute zero, the electrical properties of many materials change dramatically, allowing for the practice of completely different techniques. Electrical noise, one of the greatest problems that face electronic engineers and scientists, particularly those engaged in the field of communications, is generated by all matter. At extremely low temperatures, electrical noise is reduced or eliminated so that minute signals, such as those emanating from stars, can be amplified and studied, free from the interference caused by noise within the receivers and amplifiers themselves. Low-temperature operation of electronic devices thus opens great possibilities in the field of radio astronomy, a new branch of science that has developed rapidly in recent years.

The development of radio astronomy, and radio telephony via satellites, has helped to concentrate the efforts of some research teams on to the study of the applications of low-temperature solid-state devices operating at ultra-high frequencies in the microwave region. In America, experiments carried out with synthetic rubies have shown these to possess an extraordinary property when they are reduced to temperatures near absolute zero and subjected to the influence of a magnetic field. They will store energy at microwave frequencies by excitation and, if a minute signal is passed through a ruby that has been excited, it will cause this energy to be released and this will become considerably amplified. Synthetic rubies are remarkably free from noise, producing only the noise made by matter itself in heat vibrations. At temperatures near to absolute zero, even this small noise content of a ruby is silenced, and faint signals from stars, or signals reflected or relayed from orbiting satellites, can be clearly amplified.

In recent years, the rapid development of electronic techniques and equipment used in the microwave frequency range, greatly accelerated by wartime and post-war defence requirements for radar, has brought into being another new branch of electronic science. Microwave techniques have so far been mainly confined to the radar and communications fields. However, their use has already begun to spread into the field of industrial electronics, and there is every possibility that it will spread still further in time.

Since the circuit components and techniques used at microwave frequencies differ so very considerably from those encountered in many of the more established branches of electronics, and thereby form a complete study in themselves, their treatment in this book has been kept to a bare minimum. The main aim has been to illustrate the extent to which they differ, and, it is hoped, to create sufficient interest in the reader to encourage him to inquire more deeply into the subject through the medium of literature devoted entirely to microwave electronics.

In every age men have argued as to which of the inventions of their time will prove to be of the greatest benefit to mankind. Our present age is no exception. Atomic energy, the space vehicle and the electronic computer each have their advocates, yet it is difficult to argue about the future; nothing is certain but change, and prediction can be no more than speculation. There may be some further great discovery tomorrow that will make the three present contenders for superiority seem as old-fashioned as Stephenson's *Rocket.*

Scientific progress is a cumulative process; each new development aids and assists some others. The computer controls the atomic power-station. Atomic power increases the total power available to industry and thus speeds the production of other commodities. It will eventually power the space vehicles. The rocket and the satellite can be fired to greater and greater heights as power units are improved and the weight and space requirements of their electronic equipment are reduced owing to the development of solid-state devices. The vast, unwieldy machines that constitute the present generation of electronic computers may be replaced by pocket-sized machines in the future if the science of solid-state electronics develops as predicted. Scientific calculations, such as men could never achieve, lie within the power of the computer, and scientific progress is thus greatly accelerated. Split-second navigational calculation and control of space vehicles by computers allows for the attainment of greater and greater speeds, while still maintaining a reasonable level of safety. Each invention is individually important and each stands or falls by its own merit, but the benefits each will bestow on mankind, as history unfolds in the future, cannot be anticipated or predicted on individual merit alone. Each will enhance the roles of the others, and all will become integral parts of the whole involved pattern of scientific progress.

If the development of the science of electronics is traced back through history stage by stage, as a logical process, its roots will be found to extend far more deeply into the past than would at first be apparent. In its practical form, it may be considered to be less than three-quarters of a century old, but as a pure science it can be traced to much earlier times. It was perhaps with Alexander Fleming's invention of the electronic 'valve', which he patented in 1904, that the truly practical aspect of electronics came into being, and the theories that had been developed by earlier scientists began to be regarded as something more than the interesting results of laboratory experiments.

For many years, the practical applications of the science were confined to wireless telegraphy, developed by such pioneers as Marconi. Then, in 1922, the 2LO broadcasting station began its wireless broadcast service, and many more people awoke to the realization that this new science really had a very practical application.

In less than half a century, the applications of electronics have developed from the 'wireless' stage to become vital instruments for control, calculation and the exchange of information, in many cases approaching the efficiency of their human inventors and, in some, surpassing it. It is difficult now to find a field of human endeavour, whether it be in manufacture, commerce, transport, communication, medicine, science or in war, that has not been greatly influenced, and its efficiency enhanced, by electronic techniques in some form. Whether the age in which we now live will be recorded as the atomic age, the age in which inter-planetary exploration began, or the electronic age, only history will tell. One thing is certain, however, and that is whichever of the sciences does achieve the distinction, it will only have done so by the assistance of the others, whether by direct means or by virtue of the fact that each has accelerated the development of the others.

Although the study of electronics really started with men who conducted research and exercised their imaginations for purely scientific reasons, and who carried out their investigations without any real view to commercializing the results, the story of electronics, as it directly affects the ordinary man, began when Alexander Fleming saw the commercial possibilities in the device which he named the 'valve'.

In order to appreciate fully the work of Fleming, it is necessary to study at least part of the sequence of scientific discoveries and observations that lead up to his very successful series of experiments carried out between the years 1889 and 1896.

Sixteen years before Fleming began his experiments, F. Guthrie had observed that when a metal ball was heated to dull red heat, and was placed close to a negatively-charged electroscope, the electroscope lost its charge. He continued his experiments, using a positively-charged electroscope, to find that this was unaffected by the hot metal ball. Further experiments showed that a metal ball heated to a higher temperature would cause both a negatively- and a positively-charged electroscope to become discharged.

From these experiments, Guthrie drew the conclusion that metals at dull red heat emitted positively-charged carriers of electricity, whereas, at higher temperatures, they would emit both positively- and negatively-charged carriers.

In 1874, the electron was first suggested by Stoney as a hypothesis, though he was unable to establish its magnitude in any way. This was to be established in later years by J. J. Thomson, whose experiments developed from observations made by Crookes, around the year 1880, on the effects of electric discharges in gases.

Between the years 1882 and 1889, two Germans made an extensive study of the conducting properties of gases near heated solids and flames. These men, Elster and Geitel by name, experimented with a two-electrode tube. This device consisted of an electrically-heated filament, of metal or carbon, sealed inside a bulb together with a cold metal plate. The metal plate was fixed directly above the filament, and leads from it and the filament were brought out through the glass.

The results of the Elster and Geitel experiments showed that the two scientists had discovered one very important property of their two-electrode tube: namely that it would conduct electricity in one direction only. In other words, it was a rectifier. However, they were interested in their work from a purely scientific point of view, and do not appear to have been at all concerned with the commercial applications of their discovery.

Working in America in 1883, and apparently without any knowledge of the work of Guthrie, Elster or Geitel, Thomas A. Edison made an extremely important discovery. Edison, the inventor of the incandescent carbon-filament lamp, was having trouble with his brain-children. Some of them were developing 'hot-spots'. The filaments were diminishing in cross-section at certain points, and the heat at these points was increasing considerably. When this happened to a lamp, its life was considerably shortened, and the inside of the glass bulb became blackened by particles of carbon. He had observed that the carbon particles were projected in straight lines from the hot-spots to the glass, and set about trying to provide a remedy.

One experiment that Edison carried out, in his efforts to prevent the emission of carbon from filament to glass, took the form of the addition of a cold metal plate to the internal structure of a lamp. This plate was fitted between the legs of the horseshoe-shaped filament. A wire lead, connected to the plate, was brought out through the glass bulb.

In connecting a galvanometer between the plate lead and the ends of the filament, he found that a current flowed between the plate and the positive end of the filament, but that no current flowed when the galvanometer was connected between the plate and the negative end of the filament. Edison realized that, in the first case, the current that flowed through the galvanometer must also be flowing across the vacuous space between the plate and the filament. He realized also that current flowed only when the plate was positive with respect to the main body of the filament, that is, when it was connected to the positive end of the filament, as illustrated in Fig. 1 (b). This phenomenon became known as the 'Edison effect'.

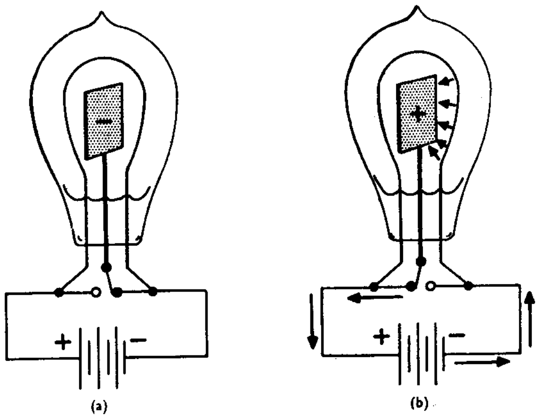

Fig. 1.

Preece, in England, made a series of quantitative measurements of the Edison effect in the years 1884 and 1885, and came to a number of important conclusions. He discovered that the effect remained uninfluenced by the type of metal used for the plate, that the distance between plate and filament greatly influenced the flow of current between them and also that both the filament temperature and the potential difference between plate and filament greatly influenced the current flow. He found that an increase in current flow could be brought about by: reducing the distance between plate and filament, raising the filament temperature or raising the positive charge of the plate with respect to the filament.

Working upon much the same lines as Preece, W. Hittorf showed that current could be passed through a vacuum with only a small potential difference between plate and filament, provided the latter were incandescent.

E. Goldstein, experimenting with gas-discharge tubes fitted with carbon or platinum cathodes, found that tubes with the normal cold cathode, and which had gas pressure within them so low that even high voltages would not cause a measurable discharge, would pass a current at quite low voltages if the cathode were heated.

J. A. Fleming, who was well aware of the work carried out by both Edison and Preece, conducted a further series of experiments on the Edison effect. These he carried out at the University of London between the years 1889 and 1896.

Although the unilateral conducting property of the incandescent lamp fitted with a cold plate was comparatively well known at the time that Fleming began his experiments on it, nobody appeared to have recognized the commercial value of the device. Consequently it was Fleming who took out a patent for it in Britain in 1904, and in America and Germany in 1905. Fleming alone seems to have appreciated the true value of this rectifying device as a detector of high-frequency oscillations in wireless telegraphy. The 'Fleming valve', like the lamps used by Edison in his experiments, consisted of an electrically-heated filament and a cold plate, or anode, sealed into an evacuated bulb. Figure 2 shows a circuit in which a Fleming valve was used to detect radio signals.

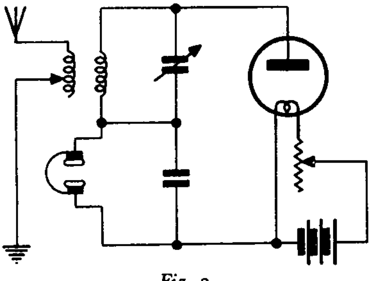

Fig. 2.

It is interesting to note that Fleming named his device a 'valve' because it allowed current to flow in only one direction: a property which is analogous to the action of a non-return air valve. The name 'valve' has remained with us in Britain, whereas in America most of the devices, which we refer to by the generic name 'valve', are referred to as 'tubes'. The word 'plate', on the other hand, is still used in America, whereas we, in Britain, generally refer to this electrode as the 'anode'. The second electrode of the Fleming valve, the filament, is generally termed the 'cathode' nowadays, both here and in America, though this, in a modern valve, generally refers to a separate electrode which is heated by a filament. However, in valves which do not possess a cathode separated from the heater, that is in valves in which the filament emits electrons, as did the filament in the Fleming valve, the filament itself is generally referred to as the cathode.

If necessity is truly the mother of invention, then scientific development is its father. So often in history arguments grow, and persist over the years, about the identity of the true originator of a theory or the inventor of a new device. This happens because scientific development reaches a state in which a particular invention becomes possible, or scientific knowledge reaches a level permitting the birth of a new theory. Necessity demands the birth of the new theory or invention and scientific development makes it possible. It is not surprising then that several men, all thinking along the same lines, should reach the same conclusions almost simultaneously, and that each should subsequently be acclaimed as the originator. So it was with the discovery of the electron as a particle in 1897. This discovery was made by Weichert in January, Kaufman in July and J. J. Thomson in October of that year. Thomson went further and calculated the ratio of the charge of an electron to its mass, finding this to be so large that the particle is able to move almost without inertia through an electric field.

Gradually, with the application of great scientific minds such as that of Maxwell, the atomic theory evolved, failing at times when faced with physical phenomena, but making steady progress despite and because of differences of opinion. In 1900, Planck applied the existing theories to energy as well as matter, and developed his quantum theory. In 1905 Einstein published his work on the theory of relativity.

The practical as well as the theoretical side of the science of electronics was developing at the same time and, in 1907, an American, Lee de Forest, discovered a new use for the vacuum valve. By interposing a third electrode between the filament and the anode, he developed a valve which could be used for amplification.

In its position between the anode and the filament, or cathode, this third electrode, which was made in the form of a wire mesh, or grid, was favourably placed to exercise electrostatic control over the flow of electrons through the vacuum.

The de Forest valve, which its inventor named the 'audion', was used only for the amplification of audio frequencies in the early stages of its development but, later, it was used as a radio-frequency amplifier.

In the audion, or 'triode' as it is now called, the current flow between cathode and anode is controlled by the potential difference between the cathode and the grid. Variations in this potential difference cause corresponding differences in the cathode-anode current. This action is accompanied by little or no current flow in the grid, so that power in the anode circuit can be controlled with little or no expenditure of power in the grid circuit. The grid of a triode is, therefore, known as the 'control grid'.

In later experiments with the triode, it was found that, if power were tapped from the anode circuit, and fed back to the grid, regeneration resulted, and improved amplification was brought about. Further experiments with regenerative amplifiers brought to light the fact that, if sufficient power were fed back, the circuit would enter a state of self-oscillation, and the introduction of suitable tuned circuits enabled the frequency of the oscillations to be determined. Thus the oscillator, an electronic generator of alternating currents, came into being.

The discovery of the use of the three-electrode vacuum valve as an oscillator has been credited to several men, both in America and in Britain. However, the patent that was filed in 1913 held the name of Alexander Meissner as the inventor.

Atomic theory again took a step forward in 1911 when Rutherford proposed a different conception of the structure of the atom. He visualized it as consisting mainly of space, with the greater part of its mass concentrated in a single positively-charged nucleus. Electrons, he suggested, revolved around the central nucleus, just as planets revolve around the sun in a solar system; each is held in a state of equilibrium by its own centrifugal force acting in opposition to the attraction of the nucleus. In 1913 Bohr applied Planck's quantum theory to Rutherford's conception of atomic structure, and the foundations of modern atomic theory were firmly laid.

II

VALVES

Emission of electrons

The free electrons in metals are held within the bounds of the material by surface restraint. Only when an electron attains a given velocity can it break these bounds. Under normal conditions this seldom happens, but under certain conditions, which include that of raised temperature, the distribution of the velocities of free electrons becomes changed to such an extent that some will possess velocities sufficient to carry them through the surface restraint and outside the metal itself, and electron emission takes place.

Since every electron emitted from a body constitutes a minute negative charge, the space outside the body becomes negatively charged, the strength of that charge being the sum of the charges of all the electrons emitted. At the same time, the body itself is loosing a minute negative charge for each electron emitted. Consequently the body becomes positively charged to the same degree that the space around it has become negatively charged.

Under these conditions, a cloud of electrons exists outside the body, the density of the cloud decreasing with increased distance from the body. Thus when an electron is emitted from the body and enters the space charge of the electron cloud, it becomes affected by two forces: one, the repellent force of the negative space charge, and the other, the attractive force of the positively-charged body. Both these forces tend to urge each emitted electron back to the body. Electrons do, in fact, return to the body from which they were emitted, and, at any given temperature, a state of equilibrium is reached when the number of electrons emitted in a given space of time is equal to the number returning to the body in the same time. For any given metal there is a definite rate of electron emission at every temperature level.

As Edison discovered during his experiments with incandescent lamps, an external, positively-charged field, placed in close proximity to an emitting body, will attract electrons from the space-charge around the body. Further, if the external field is of sufficient strength to draw off all the electrons being emitted at a given temperature, a certain saturation current, per unit area of the body, will be reached. When this point has been reached, any increase in the positive charge of the external field will leave the electron flow unaffected. The flow can then only be increased by still further raising the temperature of the body, and thus increasing the rate of electron emission.

The high-vacuum diode valve

The modern diode valve, which takes a variety of forms in its many applications, is basically the same as the original Fleming valve, being a two-electrode device. The modern version, however, does not necessarily have a filament as a cathode, though some still do. Later developments in valve design brought about the indirectly-heated cathode, and this is more commonly in use nowadays.

The indirectly-heated cathode takes the form of an oxide-coated, cylindrical metal sleeve fitted over an insulated filament or heater. Electron emission takes place at the sleeve, and not from the actual heater itself as with directly-heated cathodes, the function of the heater being purely that of raising the temperature of the cathode cylinder.

There is considerable variation in the methods employed in the manufacture of indirectly-heated cathode cylinders but, in general, they consist of nickel or nickel alloy tubes which are coated with barium and strontium carbonates. Subjection to high temperatures then reduces the carbonates to oxides.

The development of the indirectly-heated cathode was prompted by the fact that when filamentary cathodes were heated by alternating currents, they had the effect of introducing a troublesome a.c. component in the anode currents of valves. This effect is far less pronounced when the cathode is indirectly heated, being brought about only by the very small alternating fields caused by the heater current. Further advantages of indirectly-heated cathodes lie in the fact that their entire surfaces are at one potential and that, when several valves are being used in one circuit, a single source of power is all that is required for the heaters, even if the cathodes are operating at different potentials.

High-voltage operation of oxide-coated cathodes tends to bring about the development of hot-spots on the emitting surface. Since it is not possible to use indirect heating with emitters made of tungsten or thoriated tungsten, most cathodes for high-voltage operation are still of the filamentary type.

Figure 3 (b) shows the construction of a typical high-vacuum diode valve, and 3 (a) the conventional symbol used in circuit diagrams for such a valve.

The current flow through a diode is dependent upon two factors: the rate at which electrons are being emitted at the cathode, and the potential difference between anode and cathode. The former is governed by the temperature at which the cathode is operating and, since this is maintained at a given level during normal valve operation, emission rate can be ignored as a valve current control. Thus, in normal

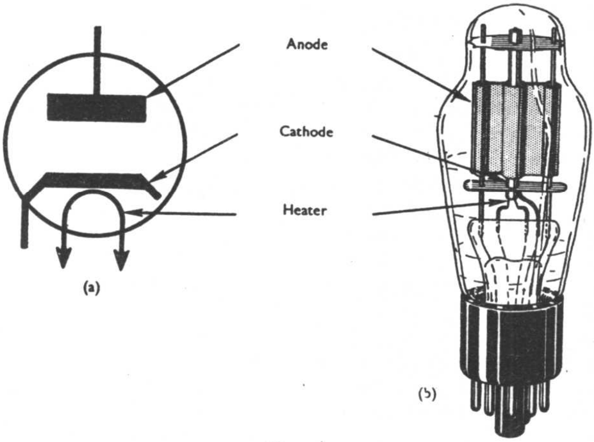

Fig. 3.

conditions of diode operation, it is the potential difference between anode and cathode that determines the level of current flow through the valve.

Once the cathode is heated, it begins to emit electrons, creating a negative space charge around itself, in the form of an electron cloud. This, as has already been stated, tends to repel emitted electrons and to drive them back to the cathode. With the anode at a negative potential with respect to the cathode, as illustrated in Fig. 4 (a), the negative electrostatic charge of the anode reinforces the negative charge of the electron cloud, and thus an increased repellent force is exerted on electrons being emitted from the cathode, tending to drive more of them back to re-enter the cathode.

With no potential difference between anode and cathode, only the negative charge of the electron cloud itself is influencing the electrons

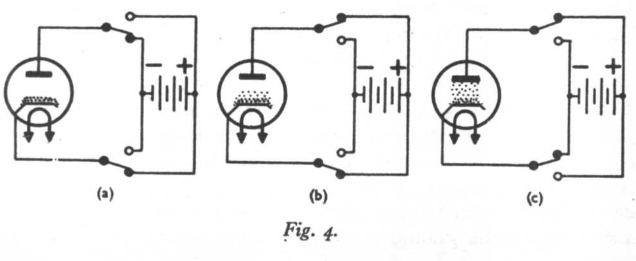

Fig. 4.