This concluding article in the series continues with electromechanical output transducers, particle and radiation sensors, then follows with special purpose semiconductor devices.

CONCLUSION OF A NEW SERIES FOR THE BEGINNER

THIS

The servo uses a d.c. motor as an output transducer, which is coupled via a gearbox to a feedback potentiometer. As the diagram in Fig. 7.1c shows, a pinion gear on the gearbox shaft can convert the rotational motion of the motor spindle into a linear push-pull movement when so required.

The d.c. servo operates as follows. In the absence of an input signal the motor is stationary with zero volts at the amplifier output, and the potentiometer slider is half way along the resistance track. When a d.c. signal is applied to the comparator, it will be amplified to a level sufficient to cause the motor to rotate.

The potentiometer slider moves to a setting where the feedback signal has the same value as the input signal and is of opposite polarity, thus cancelling the input signal and switching the motor off.

Stepping Motor

Stepping motors are derived from synchronous motors of the type used in clock and timer mechanisms.

When connected to a special electronic switch circuit, the stepping motor can be speed-controlled in both directions, and will also offer a rotational output consisting of a series of angular steps. The stepping motor armature has permanent magnet poles—usually 12—and two field coils, see Fig. 7.1d.

If a single pulse is fed to one of the inputs of the electronic switch the armature will move $\frac{1}{12}$ of a revolution, but a fast train of pulses at the input will cause smooth rotation at a rate dependent on pulse repetition frequency. Thus, there can be complete control of motor speed and spindle positioning.

ELECTROMECHANICAL OUTPUT TRANSDUCERS

We are concerned here with devices that provide a mechanical force to push, pull, rotate, or accurately position some mechanical system in response to an electrical signal.

Solenoid

The solenoid in Fig. 7.1a is a straightforward example of a mechanical output transducer for pushing or pulling. A cylindrical plunger of ferrous material is drawn into the coil by the magnetic field arising from a current flowing in the wire turns. The force is only attractive and the plunger is returned to its original position by a spring when the current ceases to flow.

Electromagnet

Another simple type of transducer for supplying a mechanical force is the electromagnet with pivoted armature as in Fig. 7.1b. When a current flows through the coil, the core is magnetised and attracts the ferrous armature against the tension of a return spring.

Servomechanisms

A more sophisticated arrangement for accurate linear or rotational positioning is the d.c. proportional servo, so called because the output motion is proportional to the input signal. Applications include the remote panning of closed-circuit television cameras, rotating aerials, and radio control of models.

PARTICLE AND RADIATION SENSORS

Radioactive substances emit electromagnetic waves (gamma rays) and high speed atomic particles. Gamma radiation is equivalent to x-rays of high energy. There are several kinds of particle, such as the fast moving electron (beta particle) and the helium nucleus (alpha particle).

Silicon Alpha Detector

Alpha particles can be counted by specially constructed silicon diodes, and germanium diodes—with an extra layer of intrinsic semiconductor material inserted between the *n*- and *p*-type regions (*pin* diode)—will respond to gamma rays.

The silicon diode in Fig. 7.2a has a gold leaf window which offers little resistance to the passage of an alpha particle. When reverse biased, the diode emits a pulse as an alpha particle penetrates the window and causes ionisation of silicon atoms.

Geiger-Müller Tube

The Geiger-Müller tube (Fig. 7.2b) is an extremely sensitive detector of individual beta particles and gamma ray quanta. The tube is filled with an inert gas plus additives to ensure that an electrical discharge between the cylindrical and wire electrodes is quenched quickly.

ELECTROMECHANICAL OUTPUT TRANSDUCERS

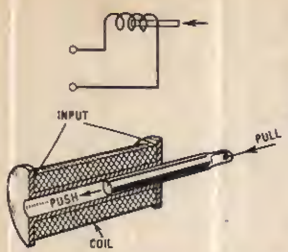

Fig. 7.1a. *Moving core solenoid*

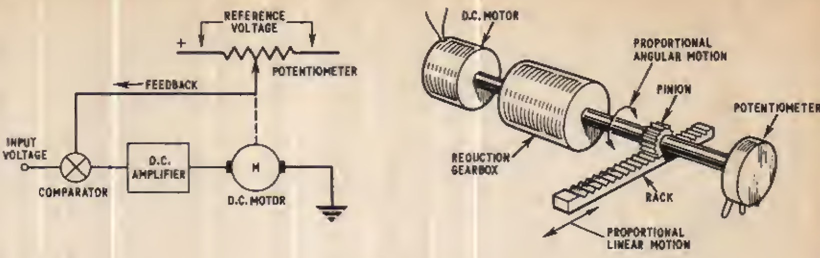

Fig. 7.1c. *Proportional d.c. servo mechanism*

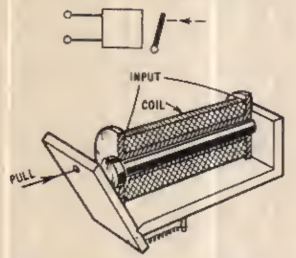

Fig. 7.1b. *Electromagnet relay switch*

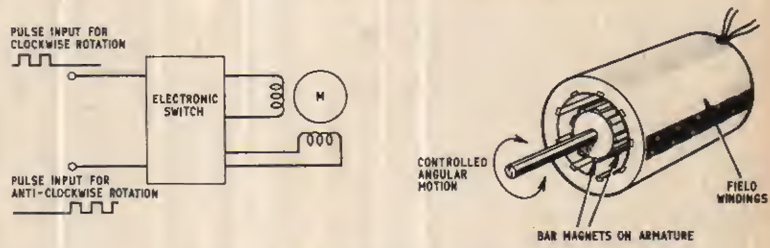

Fig. 7.1d. *Synchronous stepping motor (magslip)*

WAY TO ELECTRONICS 7

RADIATION SENSORS

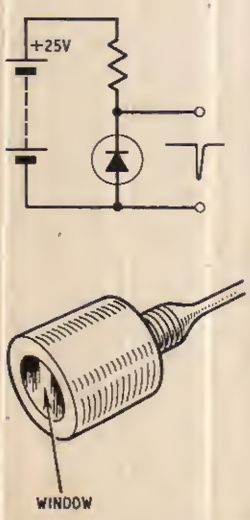

Fig. 7.2a. *Silicon alpha particle detector*

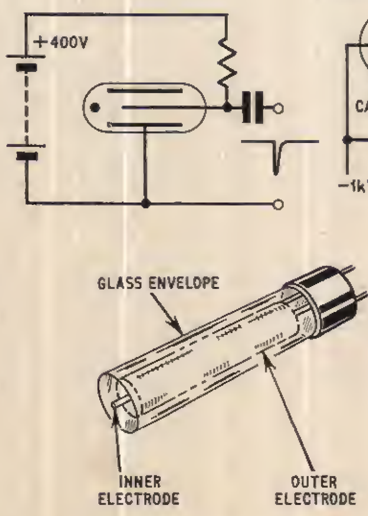

Fig. 7.2b. *Geiger-Müller tube*

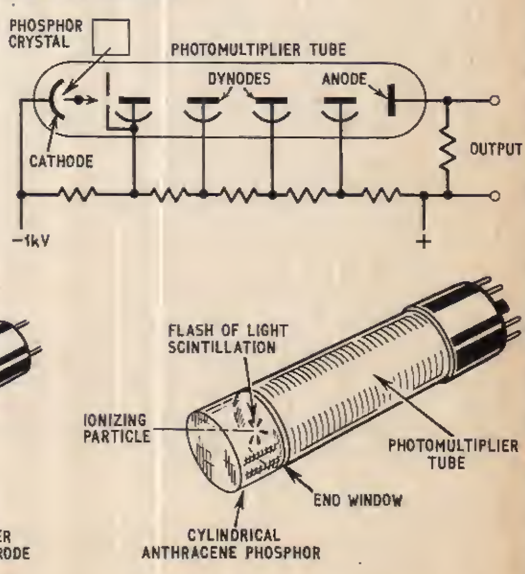

Fig. 7.2c. *Scintillation counter*

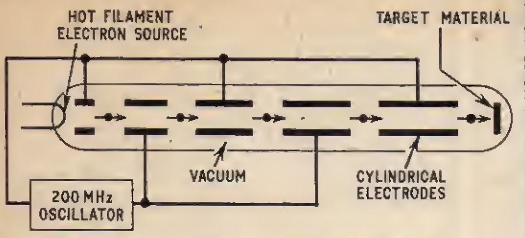

Fig. 7.3a. Linear particle accelerator

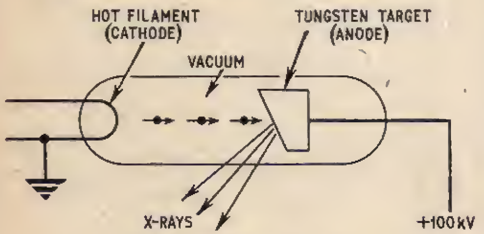

Fig. 7.3b. X-ray tube

On arrival of a particle, a momentary discharge takes place, due to ionisation of gas atoms, thus giving an output pulse. The tube is ready to receive the next particle after a recuperation period of about 200 microseconds.

Scintillation Counter

Certain transparent materials and crystals will emit flashes of light when bombarded by nuclear particles. In the scintillation counter, a photomultiplier tube is employed to detect each flash.

Briefly, the process is as follows, see Fig. 7.2c. A minute flash of light within the transparent block of material is picked up by the photomultiplier cathode, which then ejects a few electrons. The electrons then travel to the first dynode and liberate more electrons. So, at each dynode there is a progressive multiplication of the electron stream, leading to a large electrical output pulse when the electrons finally arrive at the anode.

Particle Accelerator

The linear accelerator in Fig. 7.3a emits a beam of high speed electrons having the same properties as beta particles from a radioactive substance.

Electrons from a hot filament source are accelerated along the tube by an alternating, high frequency field applied to cylindrical electrodes. The electrons are given a "kick" by the high frequency field at each gap between adjacent electrodes, thus gaining velocity and resulting in a high energy beam. This beam can either be used to bombard a target or may be emitted from the tube via a thin window.

X-Ray Tube

An x-ray tube is shown in Fig. 7.3b. A hot filament cathode provides a source of electrons, which are accelerated towards the anode by a large positive potential. When the electrons strike the anode target, about one per cent of their energy is converted into x-rays, the remainder is given off as heat. The x-rays emerge from the tube in a conical beam.

THE SEMICONDUCTOR FAMILY

Transistors and semiconductor diodes are important members of a growing family of devices, all depending on the special properties of *pn* junctions. Some of these associated devices will now be examined.

FIELD EFFECT TRANSISTORS

A conventional or bipolar transistor, as explained in Part 3, uses a current on its base terminal to control a flow of current between emitter and collector, and is characterised by an intrinsically low value of input impedance. With the field effect or unipolar transistor (f.e.t.), on the other hand, a voltage on the gate terminal controls a flow of current between source and drain, and input impedance is very high.

The three basic circuit configurations of an f.e.t., common source, common drain, and common gate, behave in much the same way as common emitter, common collector, and common base bipolar circuits respectively. Like a *pnp* bipolar transistor, a *p*-channel f.e.t. has a negative supply voltage on its drain, and the *n*-channel f.e.t. is orientated as an *npn* device. There are two types of f.e.t. construction: junction and insulated gate.

A figure for the d.c. gain of an f.e.t. is obtained from the ratio of a small change of drain current to a small change of gate voltage, called *mutual conductance* or *transconductance* (g_m), and is expressed either as mA/V or μmho, where 1,000 μmho = 1mA/V. A typical g_m for a junction f.e.t. is 4mA/V or 4,000 μmho.

Junction f.e.t.

Looking at the diagram of an *n*-channel junction f.e.t. in Fig. 7.4, a bar of *n*-type silicon is provided with source and drain connections at each end, termed "ohmic" because the connections do not involve *pn* junctions and the bar behaves as a plain resistance. Two *p*-type silicon gate regions are formed on opposite sides of the bar to create a channel through which electrons moving from source to drain must pass. The gates make two *pn* junctions with the bar, having associated depletion regions as explained in Part 2.

If a voltage is applied between gates and source, to reverse bias the *pn* gate junctions, the depletion regions —shown dotted in Fig 7.4—will extend towards each other, making the channel narrower, and tending to "pinch off" a flow of electrons from source to drain. Gate input impedance is high because only a minute leakage current can pass through the depletion regions as long as the gate junctions remain in the reverse biased condition. It follows that external input biasing of a junction f.e.t. should be such that the gate is always maintained at a lower potential than the source, to preserve the depletion regions.

The two separate gate regions of the junction device are usually joined together internally, but some f.e.t.s have independent gate connections to allow two input signals to be mixed together to yield a combined output; see dual gate f.e.t. circuit symbol, Fig. 7.4.

Insulated gate f.e.t.

The insulated gate field effect transistor or i.g.f.e.t. (also called metal oxide silicon or m.o.s.f.e.t.) has a gate electrode which is completely insulated from source and drain by a layer of metal oxide, irrespective of input voltage polarity. There is also an extra terminal labelled "substrate" which can either be joined externally to the source, or may be used as an independent bias or input terminal. The gain of an

F.E.T. AND U.J.T.

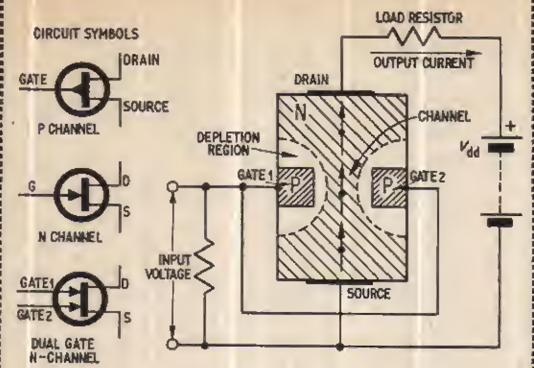

Fig. 7.4. N-channel junction field effect transistor and circuit symbols

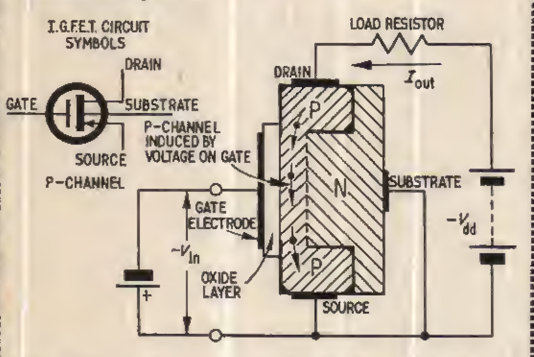

Fig. 7.5a. Enhancement mode P-channel i.g.f.e.t.

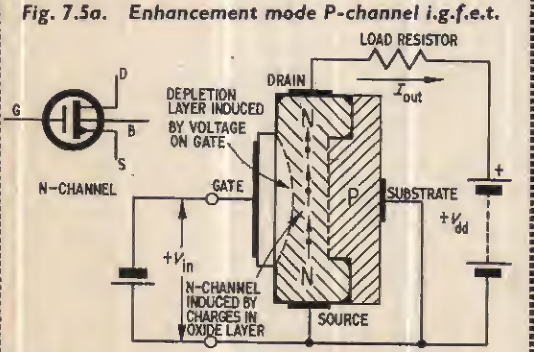

Fig. 7.5b. Depletion mode P-channel i.g.f.e.t.

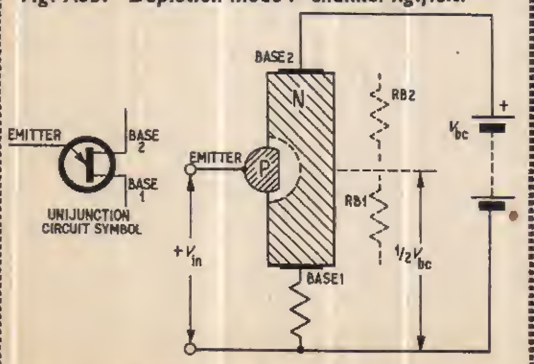

Fig. 7.6. Unijunction transistor

i.g.f.e.t. usually lies somewhere between 0·5–2mA/V, slightly lower than for a junction f.e.t.

There are two distinct kinds of i.g.f.e.t. In the enhancement mode there is no flow of current between source and drain when the gate is at source potential. A depletion mode device, on the other hand, has mean conductivity between source and drain when the gate is at source potential.

Enhancement mode

An enhancement mode *p*-channel i.g.f.e.t. is shown in Fig. 7.5a. Source and drain are formed by two *p*-type regions which are separated physically and electrically by an *n*-type substrate. For a current to flow between source and drain, the intervening substrate must be given *p*-type properties. How then is this achieved?

Consider the gate electrode and substrate as the plates of a capacitor, separated by the oxide insulator. A negative charge on the gate electrode will induce a positive charge in the substrate by normal capacitor action, in effect replacing the *n*-type surplus of electrons with a *p*-type surplus of holes directly under the oxide layer, and this forms a narrow channel linking source and drain.

Because the enhancement mode device can only conduct as a result of a voltage on its gate, it is normally biased so that the gate is at about $0{\cdot}5\,V_{dd}$, or alternatively with the gate directly coupled to the drain of a previous, similar stage.

Depletion mode

The depletion mode *n*-channel i.g.f.e.t. shown in Fig. 7.5b operates in the following manner. With the gate at source potential, electrical charges naturally present in the oxide layer will induce a narrow *n*-type channel in the *p*-type substrate, thus linking *n*-type source and drain regions and permitting a current to flow. If the gate is made negative with respect to source, a depletion region will be induced in the channel and source-drain current will be reduced.

The interesting thing here is that a positive voltage applied to the gate merely increases the width of the existing *n*-channel and promotes a greater flow of current between source and drain, without lowering input impedance, as would be the case with a junction f.e.t. or thermionic triode. So, the depletion mode i.g.f.e.t. can operate satisfactorily with zero external bias on its gate.

UNIJUNCTION TRANSISTOR

A unijunction transistor is a three terminal device with one *pn* junction, which acts as a voltage controlled switch by changing from a high to a low impedance state when an input voltage reaches a set value.

It can be seen from Fig. 7.6 that the structure of a unijunction resembles a junction f.e.t. with a single gate, but the mode of operation is quite different. A bar of *n*-type silicon has ohmic connections at each end—termed base 1 and base 2—with a pellet of *p*-type semiconductor fused into one side of the bar to form an emitter region.

If a voltage V_{bc} is applied to base 1 and base 2, the bar will behave like a plain resistance, with a voltage gradient distributed along its length. Assume that the potential midway along the bar, in the vicinity of the emitter pellet is $0{\cdot}5\,V_{bc}$, and that the bar resistance is represented by two equal resistances R_{B1} and R_{B2}. As long as the emitter potential is less than $0{\cdot}5\,V_{bc}$, the *pn* junction will be reversed biased and non-conducting, with a high internal impedance. However, if the

THYRISTOR

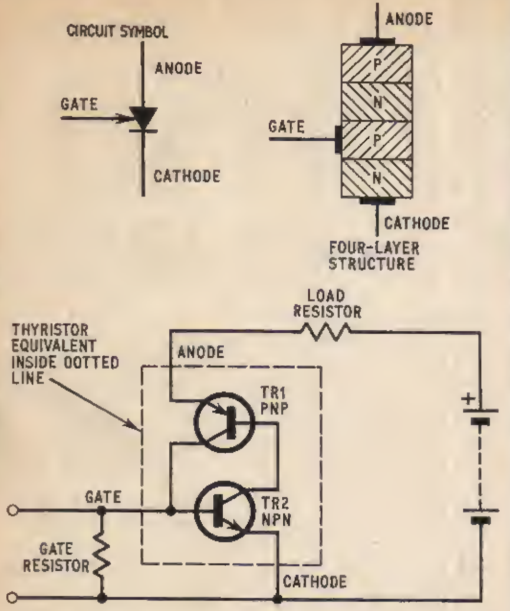

Fig. 7.7. The thyristor and an equivalent circuit showing the principle of operation

potential of the emitter should exceed $0{\cdot}5V_{bc}$, the *pn* junction will start to conduct with forward bias, and in this condition the resistance of R_{B1} is lowered by a mechanism of hole injection from the emitter region. As R_{B1} grows smaller so current flow and hole injection increase, creating an avalanche effect which rapidly lowers emitter impedance. To reset the unijunction to its former high impedance state, the emitter voltage must be brought down almost to the level of base 1 potential.

The unijunction is often employed as a capacitor discharger in timing circuits.

CIRCUIT SYMBOLS

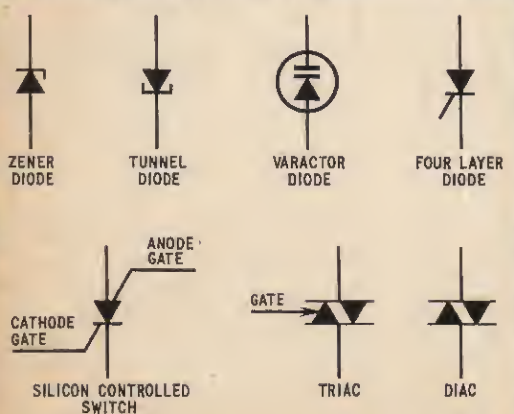

Fig. 7.8. Circuit symbols of various other devices

THYRISTOR

The thyristor, or silicon controlled rectifier (s.c.r.) is a three terminal, four layer *pnpn* device which conducts in one direction only, like a diode, when triggered by an input current. Because the thyristor has four semiconductor layers and three junctions, with built-in transistor action, its operation is best explained by using a simplified model or equivalent circuit where two complementary transistors TR1 and TR2 represent the thyristor, as in Fig. 7.7.

In the absence of an input current on the gate terminal (base of TR2), both transistors are switched off and no current flows between anode and cathode terminals. It can be seen that TR1 and TR2 are connected so that a flow of collector current in one will cause a flow of base current in the other.

If a small positive input current is applied to the gate terminal, it will tend to turn TR2 on, and TR2 collector current turns TR1 on. As TR1 goes on, its collector current reinforces the gate input current (positive feedback), and so the circuit rapidly reaches the condition where TR1 and TR2 are holding each other fully on, and remain so when the gate input current is removed. In other words, the thyristor has a self-latching action, and can only be reset by removal of the anode supply voltage.

If the battery of Fig. 7.7. circuit is replaced by an a.c. supply, the thyristor will behave like a half-wave rectifier when a continuous gate signal is present, conducting during alternate half-cycles via the load resistor. When the gate signal is removed, the device turns off as soon as the a.c. potential reaches zero during a cycle, and then remains off until another gate signal is applied.

So, the mean current flowing via the load resistor can be controlled by timed gate pulses, and this is the principle of one type of electric motor speed controller. The outstanding advantage of thyristors is that they are capable of handling large output currents at high voltages with minimum heat dissipation, and are therefore useful for controlling mains powered equipment.

OTHER SEMICONDUCTOR DEVICES

There are, in addition to those already covered in this series, a few devices which have been designed to exploit some special semiconductor property, or are derived from more common devices, see circuit symbols Fig. 7.8 and following list.

Zener diode. Variant of the silicon diode used for voltage stabilisation or as a voltage reference.

Tunnel diode. Specially doped diode which can be made to function as an amplifier, switch, or oscillator at high frequencies.

Varactor diode. Behaves like a small variable capacitor when biased by a variable reverse voltage.

Four layer diode. A small, two terminal version of the thyristor; switches on when the anode-cathode voltage reaches a set value.

Silicon controlled switch. A four layer device akin to the thyristor which has each semiconductor layer made accessible. Used for switching applications.

Triac. Bidirectional thyristor used for full-wave control of a.c. currents.

Diac. Bidirectional version of a four layer diode. Normally employed with triac in control circuits.

This series of articles has attempted to introduce the beginner to basic principles in electronic components and circuitry. A wealth of more detailed information appears in some of our other published articles and in books usually available in public libraries. ★