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Martin Hartley Jones
Excerpt
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Amplification and the transistor

1.1 Amplification

The single most important function in electronics can be expressed in one word: *amplification*. This is the process whereby the power of a signal is increased in magnitude. A simple mechanical example of amplification is provided by the power steering system on cars and commercial vehicles, where a small force applied to the steering wheel by the driver is amplified hydraulically to produce the force required to move the front wheels of the vehicle. Here is the basic feature of an amplifier: a small input signal is used to control a more powerful output signal. The extra power is drawn from some external energy source, the latter being the vehicle engine in this instance.

The earliest example of electrical amplification is the electromagnetic relay, invented by Joseph Henry in 1835, and used by Samuel Morse to increase the power of weak telegraph signals. It was the relay which made possible the first long-distance telegraph line, from Baltimore to Washington, which was opened in 1844. As can be seen in fig. 1.1, the weak incoming signal is used to operate an electromagnet which attracts an armature and closes electrical contacts; these contacts then switch a powerful outgoing signal which is transmitted to the next leg of the line. The dots and dashes of the strong output signal are thus a faithful replica of the weak input. Relays are still used extensively in power switching systems, but are generally being superseded by electronic methods.

Electronic amplifying devices are known generally as *active* components to distinguish them from non-amplifying circuit elements such as resistors, capacitors and inductors, which are grouped under the heading of *passive* components.

The most everyday application of electronic amplification is the ordinary radio, which receives a tiny input signal at its antenna (typically less than one

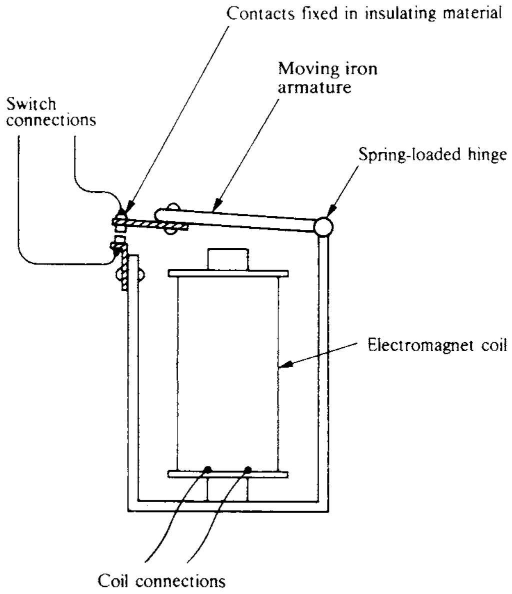

Fig. 1.1. The electromagnetic relay – an example of electrical amplification.

microwatt) and yet can turn out a power of several watts to the loudspeaker. The extra power involved is drawn from a battery or the a.c. mains.

1.2 The transistor as an amplifying device

The *bipolar junction transistor*, better known simply as the transistor, is the most common active device in electronics. Before discussing how a transistor works, it is useful to look at what it can do. For this purpose, we shall regard the transistor as a 'black box' whose circuit symbol is shown in fig. 1.2.

The transistor is a current-controlled amplifying device: if a small current flows between the base and emitter, it gives rise to a much larger current between collector and emitter. The name *transistor* is in fact derived from the two words *transfer-resistor*: a small base current is transferred to the collector circuit in greatly magnified form.

Some simple experiments will demonstrate this high current gain of the transistor. In the simple lamp circuit of fig. 1.3(*a*), it is clear that the bulb should light when the two free wires (numbered 1 and 2) are connected together. It is equally obvious that, if you try to complete the circuit through your body by holding one wire in each hand, insufficient current will flow to

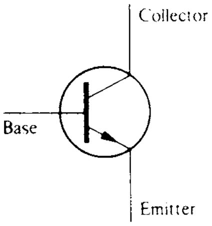

Fig. 1.2. Circuit symbol for the bipolar transistor (npn-type).

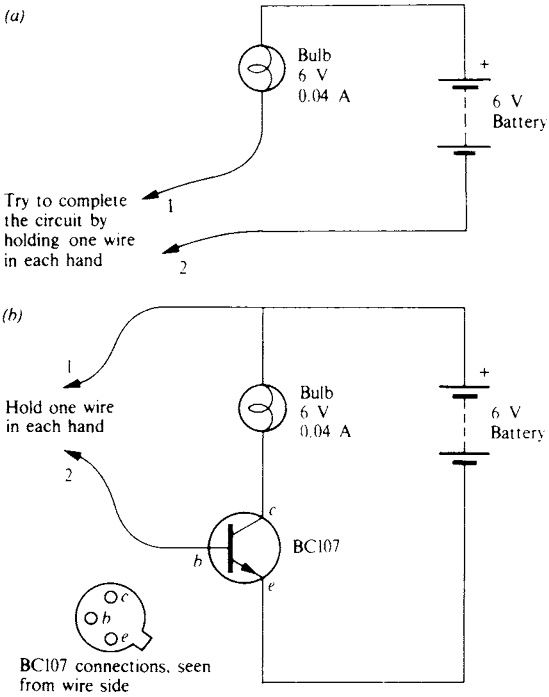

Fig. 1.3. Experimental bulb circuit to illustrate current amplification by transistor. (*a*) Tiny current in body will not light bulb. (*b*) Transistor amplifies body current to light bulb.

light the bulb. In fact the current is limited to less than 1 mA by body resistance, whilst the bulb specified needs 40 mA to light fully.

Now look at the circuit of fig. 1.3(*b*), where the bulb is in the collector–emitter circuit of a transistor. Hold the free wires once again; this time, the small current flows via your body resistance, from the battery into the

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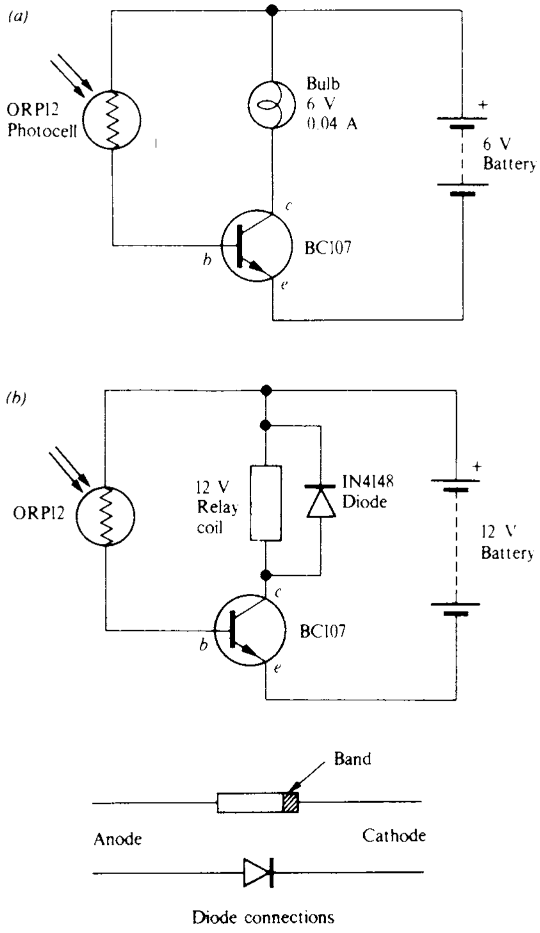

Choice of transistor is rarely critical. In these and other circuits, the 2N2222 can be directly substituted for the BC107.

Fig. 1.4. (*a*) Light-operated light bulb. (*b*) Light-operated relay.

base–emitter circuit of the transistor. The transistor acts as a current amplifier and will light the bulb, albeit dimly. Moistening the hands helps to reduce skin resistance and gives a better result. The tiny current in your body is controlling a current some hundred times larger in the bulb.

The circuit of fig. 1.4(*a*) takes the experiment a stage further by using the transistor to make a simple light-operated switch. The transistor base circuit is completed here by the ORP12 cadmium-sulphide photocell which behaves as a light-dependent resistor. When the cell is in the dark, its resistance is several megohms and negligible base current flows in the transistor. In reasonably bright light, the cell resistance falls to a few kilohms and the base current

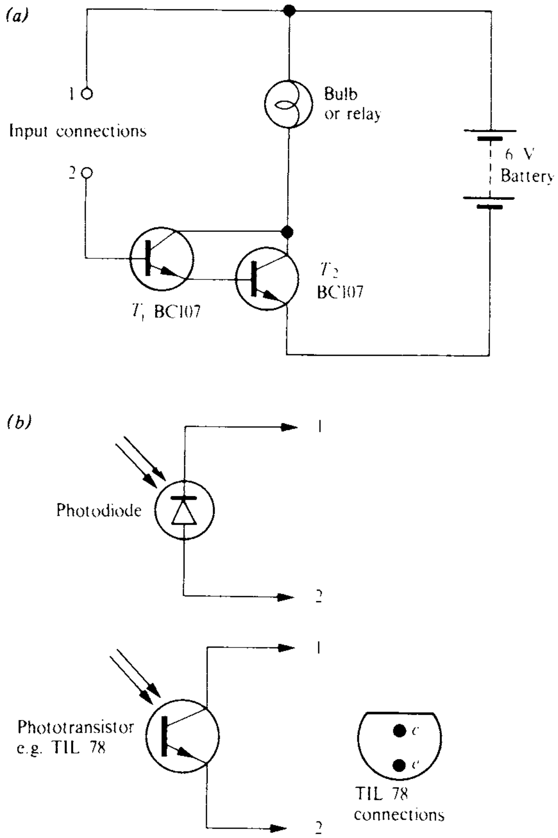

Fig. 1.5. (*a*) Darlington pair increases current gain. (*b*) Connection of photodiode and phototransistor to Darlington pair.

of about a milliamp lights the lamp, thanks to the amplification of the transistor.

Turning the cell to face the bulb makes an ‘electronic candle’: in the dark, the bulb is out, but if light momentarily falls on the cell, the bulb lights and remains lit, the photocell current being sustained by its light. To extinguish the ‘candle’, it is only necessary to interrupt the light path between bulb and photocell.

In fig. 1.4(*b*), the collector current is used to operate the coil of a relay; the relay contacts can then be used to switch on or off any required device, such as a motor to open a garage door when the car headlamps illuminate the ORP12 cell. The IN4148 diode connected across the relay coil serves to clip off the voltage surge which occurs in the coil inductance when the current is switched off. A diode should always be connected across a solenoid which is transistor-controlled; the voltage surge can otherwise cause breakdown in the transistor.

Fig. 1.5 shows a way of further increasing the current gain of a circuit. Known as a *Darlington pair*, the two transistors give a current gain equal to the products of their individual current gains. This is because the base–emitter current of T_2 is equal to the collector–emitter current of T_1. If the connections 1 and 2 are held, one in each hand, the bulb will light brightly: the circuit is much more sensitive than fig. 1.4(*a*). The extra current gain means that a photodiode or phototransistor can be used as a light sensor if connected as shown in fig. 1.5(*b*).

The current gain of a transistor is normally given the symbol h_{FE}, and its value may be anything from 10 to 1000 depending on the type of transistor. The current gain of the BC107 transistor usually lies in the range 100 to 400; current gain is not a closely controlled parameter.

In the Darlington pair,

$$h_{FE\text{total}} = h_{FE1} \times h_{FE2}.$$

1.3 Introduction to solid-state devices

1.3.1 General

The transistor is made up of two different types of semiconductor material. In order to understand how a transistor works it is necessary to look at some of the properties of that unusual class of materials called semiconductors.

1.3.2 Semiconductors

Solid materials may be divided into three classes as far as electrical properties are concerned: conductors, insulators and semiconductors. The class into which a material falls depends on the behaviour of the electrons in the outermost orbit of the atoms. In the case of an insulator, such as polythene, these *valence* electrons are tightly bound to the nucleus; very few are able to break free from their atoms to conduct an electric current. A conductor, however, such as copper, has a great cloud of free electrons present at all temperatures above absolute zero; the valence electrons are very weakly bonded indeed to their parent atoms so that they drift freely.

Semiconductors are exceptional materials. The one most commonly used in transistors is silicon; germanium is also in use. Both these elements are tetravalent, i.e. there are four electrons in the outer orbit of the atoms. Silicon and germanium crystals have a very neat system by which the atoms are held together in stable form: this is known as covalent bonding. It is a fact that when an atom has eight valence electrons it turns out to be in a very stable state (the inert gases are in such a state). Atoms in a silicon or germanium crystal have a mutual sharing arrangement whereby each nucleus has a 'half share' in eight valence electrons instead of the exclusive possession of four valence electrons that an isolated atom would have. Such an arrangement of silicon atoms is shown diagrammatically in fig. 1.6(*a*); each bond drawn between the atoms represents a shared valence electron. It is interesting to note at this stage that the extreme hardness of diamond is due to the tetravalent carbon atoms adopting this type of ordered covalent crystal structure. Diamond is actually classed as a semiconductor, though the tight bonding which gives rise to its physical hardness renders it a very poor electrical conductor indeed. It is fortunate that we have much better and cheaper alternative materials available for transistors!

1.3.3 Electrons and holes

The perfect array of silicon atoms in fig. 1.6(*a*) is only found at temperatures near absolute zero. At room temperature, thermal vibration of the atoms causes a few bonds to fracture; electrons break away from the atoms and are free to wander through the crystal. Where an electron breaks free it leaves behind a *hole* or absence of negative charge, which can also appear to move if it is filled by an electron from an adjacent atom. Fig. 1.6(*b*) represents a section of silicon crystal structure at room temperature with a free electron and the resulting hole.

This availability of free electrons makes the silicon a conductor of electricity, albeit a very poor one. If the silicon is connected into circuit, for instance across a battery, then the applied field draws the free electrons towards the positive terminal, whilst further free electrons are made available at the negative terminal and can travel through the semiconductor by hopping from hole to hole. Thus a current flow is established. As the temperature of the semiconductor is raised, more bonds are broken, more electrons and holes become available and the conductivity increases. It is interesting to note that this temperature effect is directly opposite to the effect observed in conducting metals: in a conductor there is already such a cloud of free electrons available,

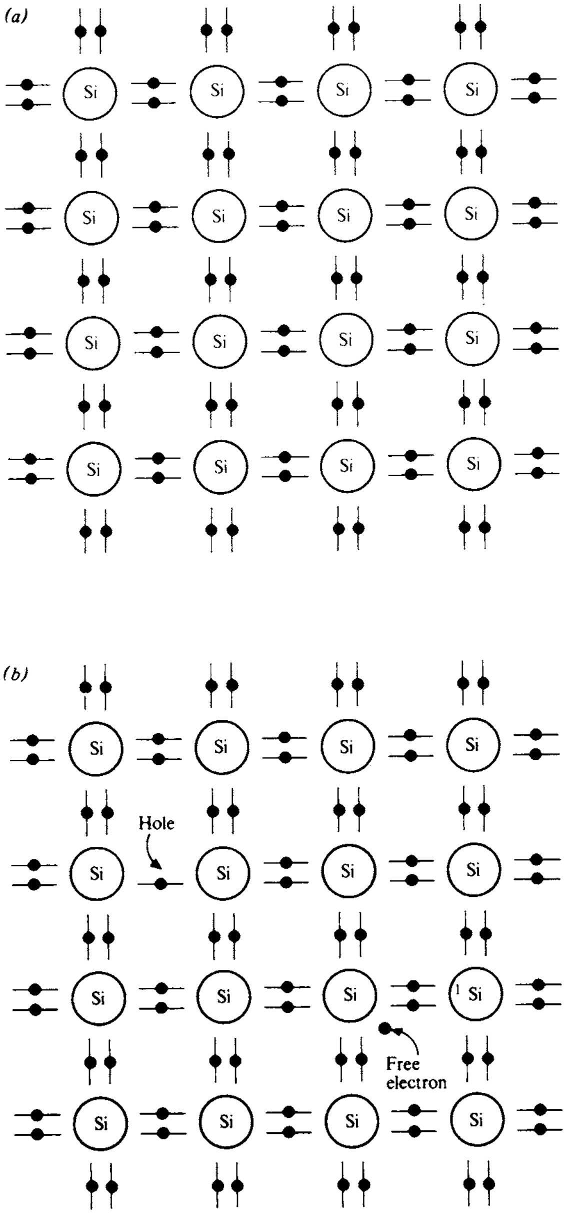

Fig. 1.6. (*a*) Atoms in a silicon crystal showing covalent electron bonds. (*b*) Crystal lattice as (*a*), but with free electron and hole produced by thermal agitation.

even at low temperatures, that the limiting factor as far as conduction is concerned is not the availability of free electrons, but the ability of those electrons to flow past the metal atoms. As the temperature increases in a conductor, the amplitude of vibration of the atoms is increased so that they offer a greater obstruction to the free electrons. Thus, in a conductor, resistance increases with increasing temperature whilst, in a semiconductor, resistance decreases with increasing temperature. The very weak conductivity exhibited by semiconductors in their pure form is known as *intrinsic* conductivity.

1.3.4 Extrinsic conductivity

The addition of impurities to a semiconductor can produce interesting results. Certain impurity atoms are able to fit into the crystal lattice without introducing undue strain and, if the valency of these atoms is different from that of the semiconductor, then conductivity is greatly increased. Fig. 1.7 shows the effect of introducing pentavalent phosphorus atoms into a silicon crystal. Four of the five valence electrons are involved in bonding with the silicon lattice, but the remaining electron is so weakly bound that it is free to move about the crystal and thus to conduct current. The introduction of impurities to semiconductors is known as *doping* and the resulting conductivity known as

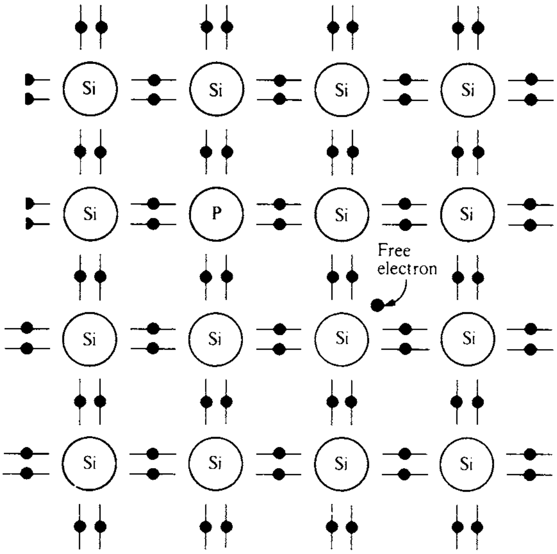

Fig. 1.7. Silicon lattice with phosphorus impurity atom. A free electron is now available for conduction (n-type semiconductor).

extrinsic conductivity. A pentavalent impurity such as phosphorus is known as a *donor* impurity, since it gives free electrons to the lattice. Because the extrinsic conductivity is due to free *negative* charges (electrons), this type of doped semiconductor is known as *n-type*.

Fig. 1.8 shows the effect of introducing tervalent boron atoms into a crystal of silicon. Although it has only three valence electrons, the boron atom accepts an extra electron from one of the adjacent silicon atoms to complete its covalent bonds. This leaves a *hole* or absence of a valence electron in the lattice and this hole is free to move and thus act as a means of conduction. Of course, it is the valence electrons that do the shifting, but the result is that the hole is shuffled from atom to atom. A tervalent impurity such as boron is known as an *acceptor* impurity because of its ability to accept an electron when it enters the lattice. Because conduction is now due to the *positive* holes, the doped semiconductor is known as *p-type*.

It is important to realize that neither p-type nor n-type material possesses an *overall* electric charge. In each case, the total number of electrons is balanced by an identical number of protons in the atomic nuclei. The p and n designations simply refer to the type of charge responsible for conduction within the crystal.

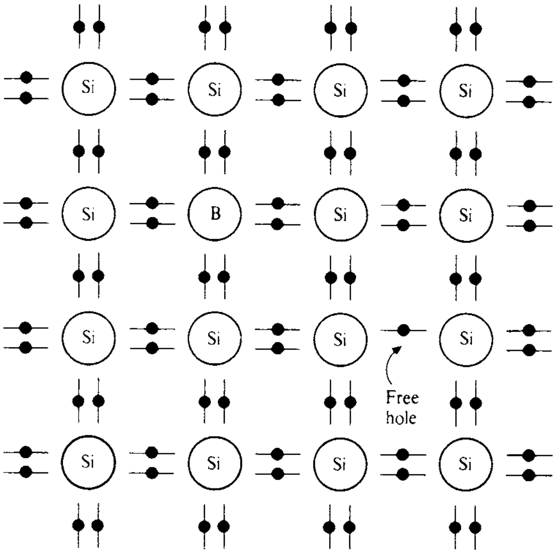

Fig. 1.8. Silicon lattice with boron impurity atom. A free hole is now available for conduction (p-type semiconductor).