Owen Bishop

Electronics

Circuits and Systems

Second edition

Newnes

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Electronics – Circuits and Systems

Preface

This book is written for a wide range of pre-degree courses in electronics. The contents have been carefully matched to current UK syllabuses at Level 3 / A-level, but the topics covered, depth of coverage, and student activities have been designed so that the resulting book will be a student-focused text suitable for the majority of courses at pre-degree level around the world. The only prior knowledge assumed is basic maths and the equivalent of GCSE Double Award Science.

The UK courses covered by this text are:

A-level (AS and A2) specifications from AQA, OCR and WJEC.

AVCE Engineering from Edexel, Unit 14 Electronics (Advanced).

BTEC National Certificate and Diploma courses in Electronic Engineering, Unit 7, Electronics.

The book is essentially practical in its approach, encouraging students to assemble and test real circuits in the laboratory. In response to the requirements of certain syllabuses, the book shows how circuit behaviour may be studied with a computer, using circuit simulator software.

The book is suitable for class use, and also for self-instruction. The main text is backed up by boxed-off discussions and summaries, which the student may read or ignore, as appropriate. There are frequent 'Self Test' questions at the side of the text with answers given in Supplement B. Another feature of the book is the placing of short 'memos' at the side of the text. These are intended to remind the student of facts recently encountered but probably not yet learnt. They also provide definitions of terms, particularly of some of the useful jargon associated with electronics and computing.

Some chapters include Extension Boxes. These usually cover advanced topics, that are not found in all specifications, so they may not be required in the examinations.

Each chapter ends with a batch of examination-type questions, and in most instances with a selection of multiple choice questions. Answers to the multiple choice questions appear in Supplement B.

The text has undergone a major revision to produce this second edition. The formatting has been completely changed to match the style of the author's successful Level 2 text, *Electronics – a First Course*. The more compact layout of the pages has made it possible to include a wealth of new material, as called for by the latest A-level specifications.

Major additions to the content include chapters on microcontrollers, neural networks, power supply circuits, instrumentation systems, and audio systems. The chapters on microelectronics reflect the trends in the new syllabuses by focusing less on computer architecture and much more on microcontroller systems. The programming chapter now includes a wide range of programs set out in the form of flowcharts, with emphasis on applications to control systems. There have been extensive revisions of the chapters on logic circuits, including many new circuits. Other topics that are new or are now dealt with in closer detail include pnp transistors, p-channel MOSFETs, filters, packet switching, mobile telephones and ladder logic.

Owen Bishop

Practical circuits and systems

Circuit ideas

As well as being a textbook, this is a sourcebook of circuit ideas for laboratory work and as the basis of practical electronic projects.

All circuits in this book have been tested on the workbench or on computer, using a circuit simulator. Almost all circuit diagrams are complete with component values, so the student will have no difficulty in building circuits that will work.

Testing circuits

The circuit diagrams in this book provide full information about the types of components used and their values. Try to assemble as many as you can of these circuits and get them working. Check that they behave in the same ways as described in the text. Try altering some of the values slightly, predict what should happen, and then test the circuit to check that it does.

There are two ways of building a test circuit:

- Use a breadboarding system to build the circuit temporarily from individual components or circuit modules.
- Use a computer to run a circuit simulator. 'Build' the circuit on the simulator, save it as a file, and then run tests on it.

The simulator technique is usually quicker and cheaper than breadboarding. It is easier to modify the circuit, and quicker to run the tests and to plot results. There is no danger of accidentally burning out components.

Conventions used in this book

Units are printed in roman type: V, A, s, S, μF.

Values are printed in italic (sloping) type:

Fixed values	V_{CC}, R_1
Varying values	v_{GS}, g_m, i_D
Small *changes* in values	v_{gs}, i_d

Resistors are numbered, R1, R2, and so on. The *resistance* of a resistor R1 is represented by the symbol R_1. The same applies to capacitors (C1, C2) and inductors (L1, L2).

Significant figures

When working the numerical problems in this book, give the answers to three significant figures unless otherwise indicated.

Units in calculations

Usually the units being used in a calculation are obvious but, where they are not so obvious, they are stated in square brackets. Sometimes we show one unit divided by or multiplied by another.

Example

On p. 59, we state:

$R_1 = 14.3/2.63$ [V/μA] = 5.44 MΩ

A voltage measured in volts is being divided by a current measured in *micro*amperes.

Mathematically, this equation should be written:

$R_1 = 14.3/(2.63 \times 10^{-6}) = 5.44 \times 10^{6}$

Set out in this form, the equation is difficult to understand and to remember. To avoid this problem we quote the *units* instead of powers of 10. When the result is being worked out on a calculator, it is easy to key in the values (14.3, 2.63) and follow each by keypresses for 'EXP -6' or other exponents where required. The result, in Engineering or Scientific format, tells us its units. In this example the display shows 5.437262357^{06}. We round this to 3 significant figures, '5.44', and the '06' index informs us that the result is in megohms.

Contents

Part 3 - Microelectronic systems

Supplements

Part 1 Circuits

1 Transistor switches

Transistors are used in one of two ways:

- as switches
- as amplifiers.

Transistor amplifiers are described later in the book. Transistor switches are described in this chapter, using three different types of transistor.

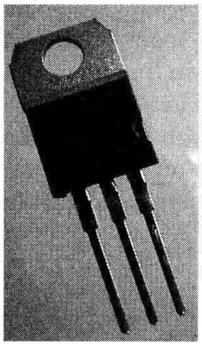
As we shall explain, the purpose of most transistor switches is to control an electrical device such as a lamp, a siren or a motor.

The switched device usually requires a current of several milliamperes, possibly several amperes. The current needed for operating the transistor switch is a lot smaller, often only a few microamperes. This makes it possible to control high-current devices from sensors, logic gates and other circuits with low-current output. The main limitation is that only devices working on direct current can be switched, but not devices powered by alternating current. These points are illustrated by the examples below.

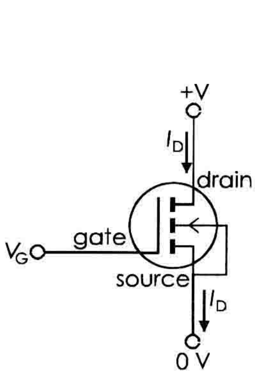
Switching a lamp

The switching component in this circuit is a **metal oxide silicon field effect transistor**. This name is usually shortened to MOSFET. The words 'metal oxide silicon' refer to the fact that the transistor consists of a metal conductor, an insulating layer of oxide (actually silicon oxide), and a semiconducting layer of silicon.

The words 'field effect' refer to the way in which this type of transistor works. It works by placing an electric charge on the 'metal' part of the transistor, known as the **gate**. The charge on the gate results in an electric field, and the effect of this field is to control the amount of current flowing through the semiconductor layer. Current flows from the **drain** terminal to the **source** terminal.



This medium-power MOSFET is rated to switch currents up to 13 A. Note the metal tag for attaching a heat sink.



A MOSFET has three terminals: gate, drain and source

Drain current (I_D) flows from the drain to the source, if:

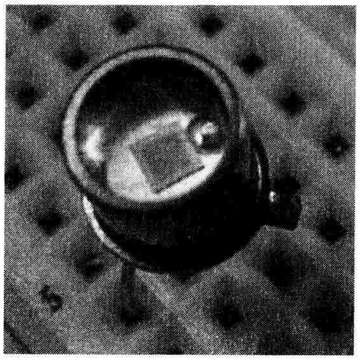
- the drain terminal is positive of the source terminal and,
- the gate is charged to a voltage that is sufficiently positive of the source.

In this way, the MOSFET acts as a **voltage-controlled switch**. The voltage at which the transistor switches on is called the **threshold voltage**.

A MOSFET of the type just described is known as an **n-channel enhancement MOSFET**. There are other types (pp. 8 and 53), but this type is by far the most commonly used.

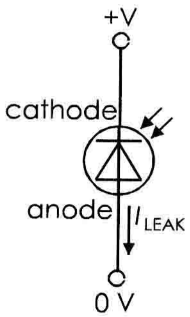
Sensor

The light-sensitive component in this circuit is a **photodiode.** Like any other diode, it conducts in only one direction.



The can of this photodiode has a lens top. The diode is visible through this as a square chip of silicon.

Usually a photodiode is connected with **reverse bias.** This would mean that no forward current flows through it. However, a small **leakage current** passes through it. The leakage current is only a few nanoamps in darkness, but rises to several microamps when light falls on the photodiode.

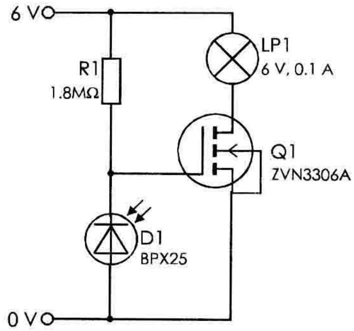


Leakage current passes through the photo-diode only in the light.

Switching circuit

This circuit uses a MOSFET transistor for switching a lamp. We might use this to control a low-voltage porch lamp which is switched on automatically at dusk.

The sensor is a photodiode, which could be either of the visible light type or the type especially sensitive to infra-red radiation. It is connected so that it is reverse-biased. Only leakage current passes through it. The current varies according to the amount of light falling on the diode. In darkness, the current is only about 8 nA but it rises to 3 mA or more in average room lighting.

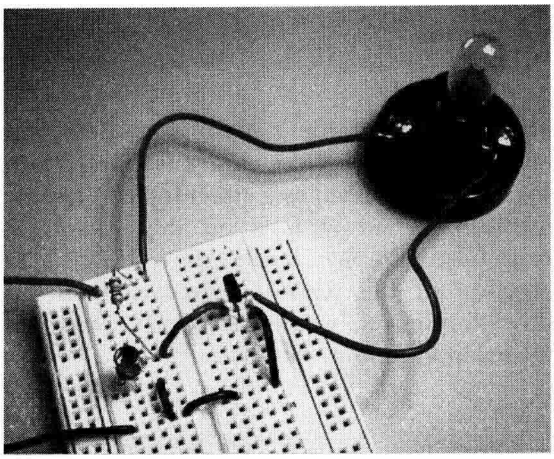


The MOSFET switches on the filament lamp when the light intensity falls below a given level.

The current change is converted into a voltage change by resistor R1. In light conditions, the current is relatively large, so the voltage drop across the resistor is several volts. The voltage at the point between R1 and the diode is low, below the threshold of the transistor. The transistor is off and the lamp is not lit.

At dusk, light level falls, the leakage current falls, and the voltage drop across R1 falls too. This makes the voltage at the gate of the transistor rise well above its threshold, which is in the region of 2.4 V. The transistor turns fully on. We say that it is **saturated**. When the transistor is 'on', its effective resistance is only 5 Ω. Current flows through the lamp and transistor, lighting the lamp.

The current flowing down through the sensor network (R1 and D1) is exceedingly small — no more than a few microamps. Little current is available to charge the gate of Q1. However, a MOSFET has very high input resistance, which means that it requires virtually no current to turn it on. It is the *voltage* at the gate, not the current, that is important.



A breadboarded version of the light-sensitive MOSFET switch. The photodiode and resistor are on the left. The low-power MOSFET is the small black package on the right.

Because the gate requires so little current, a MOSFET is the ideal type of transistor for use in this circuit. If we were to use a BJT (see p. 4), we might find that the sensor network was unable to provide enough current to turn it on.

The lamp specified for this circuit has a current rating of 100 mA. The transistor has a rating of 270 mA, so it is not in danger of burning out. There is no need to use a power MOSFET such as the one shown in the photo on p. 1.

Self test

A BUZ73L MOSFET has an 'on' resistance of 0.4 Ω and is rated at 7 A. If the supply voltage is 9 V, what is the minimum resistance of a device that it can safely switch?

Variations

A useful improvement is to reduce R1 (to 820 kΩ) and wire a variable resistor (about 1 MΩ) in series with it. Connect the gate of Q1 to the wiper of the variable resistor. This allows the switching level of the circuit to be adjusted.

The circuit may be made to operate in the reverse way by exchanging the resistor and photodiode. It may be necessary to alter the value of the resistor.

A circuit such as this does not normally need a heat sink (p. 113) on the transistor, even if the current being switched is several amps. The circuit is always in either of two states, 'off' or 'on'. When the transistor is off, there is no current and no heating effect. When the transistor is on, it is *fully* on. Its resistance may be only an ohm or two, or even less. Little energy is dissipated within the transistor and it never gets hot.

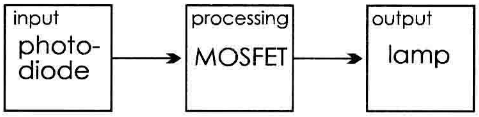
System design

Electronic systems often consist of three stages. The first stage is the **input** stage. This is the stage at which some feature of the outside world (such as a temperature, the light level, or a sound) is detected by the system and converted into some kind of electrical signal.

The last stage is the **output** stage in which an electrical signal controls the action of a device such as a lamp, a motor, or a loudspeaker.

Connecting the input and output stages is the **signal processing** stage. This may comprise several sub-stages for amplifying, level-detecting, data processing, or filtering.

As a system, this circuit is one of the simplest. It has three sections:



The **input** section consists of the photodiode.

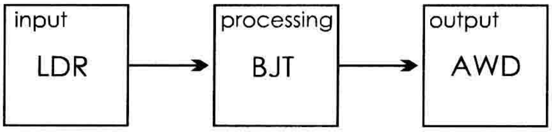
The **processing** section consists of R1 and Q1. R1 generates a voltage, which is fed to the gate of Q1, which is either turned 'off' or 'on'.

The **output** section consists of the lamp, which is switched by Q1.

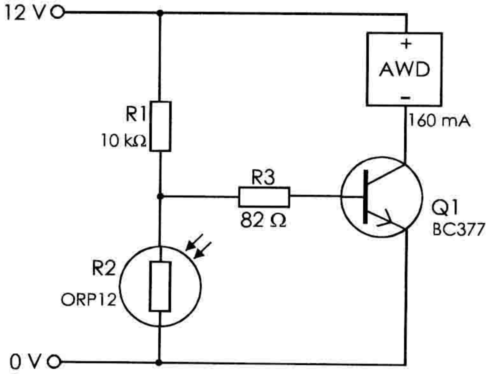
Three-stage systems are very common. There are more examples in this chapter and elsewhere in this book.

Light-sensitive alarm

Compared with the circuit on p. 2, this circuit uses a different type of light sensor, and a different type of transistor. It has a similar three-stage system diagram:

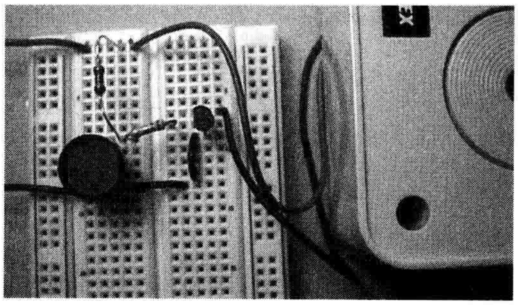


- **Input** is accepted by a **light-dependent resistor** (or LDR). This is made from a semiconductor material such as cadmium sulphide. The resistance of this substance varies according the the amount of light falling on it. The resistance of an LDR ranges between 100 Ω in bright light to about 1 MΩ in darkness.
- **Processing** uses a voltage divider (R1/R2, *see* p. 17) that sends a varying voltage to the **bipolar junction transistor**, Q1. The voltage at the point between the resistors is low (about 10 mV) in very bright light, but rises to about 5 V in darkness. With LDRs other than the ORP12, voltages will be different and it may be necessary to change the value of R1 or replace it with a variable resistor.
- **Output** is the sound from an **audible warning device**, such as a siren.



The audible warning device sounds when the light intensity falls below a given level.

The function of the circuit is to detect an intruder passing between the sensor and a local source of light, such as a street light. When the intruder's shadow falls on the sensor, its resistance increases, raising the voltage at the junction of the resistors. Increased current flows through R3 to the base of Q1. This turns Q1 on and the siren sounds.



The quadruple siren to the right of the breadboard emits an unpleasantly loud scream when the LDR on the left is shaded.

This circuit uses a BJT; almost any npn type will do, provided it is able to carry the current required by the audible warning device, which in this example is a piezo-electric siren. A typical ultra-loud (105 dB) warbling siren suitable for use in a security system takes about 160 mA when run on 12 V. The BC337 transistor is rated at 500 mA.

BJT switches

Like a MOSFET, a BJT has three terminals. Because the BJT works differently, they have different names: base, collector and emitter.

A BJT is connected so that its collector terminal is several volts positive of the emitter terminal. When current (I_B) flows into the base terminal, a much bigger current (I_C) flows into the collector terminal. The combined currents I_B and I_C flow out of the emitter terminal.

The combined currents make up the emitter current I_E, and:

$$I_E = I_B + I_C$$

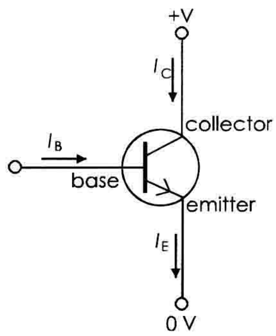
The action of a BJT depends on the fact that I_C is alway very much larger than I_B. For a typical BJT it is about 100 times larger. Thus, small variations in a small current result in large variations in a large current.

When used as a switch, a BJT is a **current-controlled switch**. This contrasts with a MOSFET, which makes a voltage-controlled switch. The amount of current needed to switch on the transistor in this circuit depends on the amount of **collector current** needed to drive the siren. This depends on the **current gain** of the transistor.

The siren used in the demonstration circuit requires 160 mA. The BC377 has a current gain of between 100 and 600. Taking the minimum gain of 100, the base current needs to be:

$$I_B = I_C/\text{gain} = 160/100 = 1.6 \text{ mA}$$

Inside an npn BJT there is a pn junction between the base and emitter terminals. This junction has the properties of a diode. In particular, when it is forward biased, there is a voltage drop of about 0.7 V between the base and emitter terminals. In practice, the voltage drop may be 0.5 V to 0.9 V, depending on the size of I_B. Therefore, when Q1 is in the 'on' state, its base is, on average, 0.7 V positive of its emitter.



In a BJT, a small current controls a much larger current.

Now we can calculate what voltage from the R1/R2 potential divider is needed to switch on Q1 and sound the siren. We need a minimum of 1.6 mA flowing through R3. Given that R3 is 82 Ω, the voltage across R3 must be:

$$\text{current} \times \text{resistance} = 1.6 \times 10^{-3} \times 82 = 1.31 \text{ V}$$

If the voltage at the R1/R2 connection is less than 1.31 V, no current flows through R3 and Q1 is off. I_C is zero and the siren does not sound. If the voltage is greater than 1.31 V, Q1 turns on and becomes **saturated.** I_C rises to 160 mA and the siren sounds. There is a state between Q1 being off and being on and saturated, but we will leave discussion of this until later.

This circuit is able to use a BJT because the sensor network is able to deliver a current of the size required to turn on Q1. It is also possible to use a MOSFET. In this case, R3 is not required as almost no current flows to the gate of a MOSFET.

Heater switch

The heater switch is a circuit for maintaining a steady temperature in a room, a greenhouse, or an incubator. The sensor is a **thermistor**, a semiconductor device. Its resistance decreases with increasing temperature, which is why it is described as a **negative temperature coefficient** (ntc) device. Thermistors are not ideal for temperature *measuring* circuits, because the relationship between temperature and resistance is far from linear. This is no disadvantage if only one temperature is to be set, as in this example.

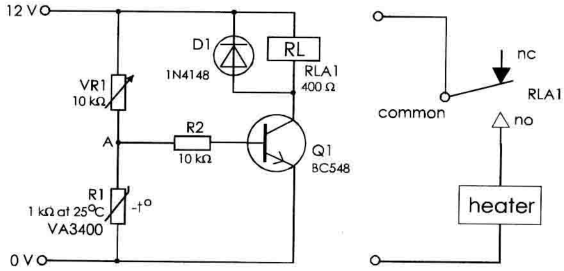
Thermistors have the advantage that they can be made very small, so they can be used to measure temperatures in small, inaccessible places. They also quickly come to the same temperature as their surroundings or to that of an object with which they are in contact. This makes them good for circuits in which rapid reading of temperature is important.

In many applications, these advantages offset the disadvantage of non-linearity.

The switched device in this example is a **relay**. This consists of a coil wound on an iron core. When current passes through the coil the core becomes magnetised and attracts a pivoted armature. The armature is pulled into contact with the end of the core and, in doing so, presses two spring contacts together. Closing the contacts completes a second circuit which switches on the heater. When the current through the coil is switched off, the core is no longer magnetised, the armature springs back to its original position, and the contacts separate, turning off the heater.

WARNING

The circuit on this page illustrates the switching of a device powered from the mains. **This circuit should not be built or tested except by persons who have previous experience of building and handling mains-powered circuits.**



A relay is necessary to switch a heater which runs from the 230 V AC mains.

Most relays have contacts capable of switching high voltages and currents, so they may be used for switching mains-powered devices running on alternating current. Current ratings of various types of relay range from 1 A up to 40 A. Various arrangements of switch contacts are available, including simple **change-over contacts** (see drawing above) and relays with three or more independent sets of contacts. Changeover contacts are normally-open (no) or normally closed (nc). They can be wired so that a device can be turned off at the same time that another is turned on. Relays are made in an assortment of sizes, including some only a little larger than a transistor, suitable for mounting on printed circuit boards.

Self test

What is the minimum contact rating for a relay required to switch a 1000 W, 230 V floodlamp?

Thermistor

Thermistors are available in several resistance ratings, the one chosen for this circuit having a resistance of 1 kΩ at 25°C. VR1 is adjusted so that the voltage at point A is close to 0.6 V when the temperature is close to that at which the heater is to be turned on. The transistor is just on the point of switching on. As temperature falls further, the resistance of the thermistor R1 increases, raising the voltage at A, and increasing i_B, the base current. This switches on the transistor and collector current passes through the relay coil. The relay contacts close, switching on the heater.

Note that the heater circuit is electrically *separate* from the control circuit. This is why a relay is often used for switching mains-voltage alternating current.

After a while, as the heater warms the thermistor, R1 decreases, the voltage at point A falls and the transistor is turned off. The relay coil is de-energised and the heater is turned off.

This kind of action is called **negative feedback.** It keeps the temperature of the room more or less constant. The action of the circuit, including the extent to which the temperature rises and falls, depends on the relative positions of the heater and thermistor and the distance between them.

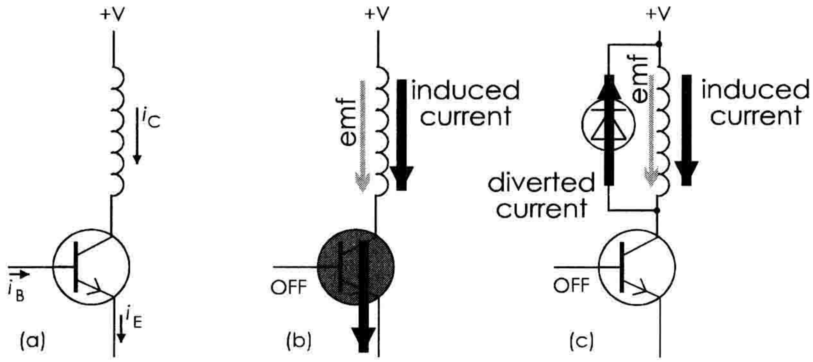
Protective diode

The diode D1 is an important component in this circuit.

At (a) below a transistor is controlling the current through an inductor. When the transistor switches off (b), current ceases to flow through the coil and the magnetic field in the coil collapses. This causes an **emf** to be induced in the coil, acting to *oppose* the collapse of the field. The size of the emf depends on how rapidly the field collapses. A rapid switch-off, as at (b), collapses the field instantly, resulting in many hundreds of volts being developed across the transistor. This emf produces a large current, which may permanently damage or destroy the transistor.

Emf

This stands for electromotive force. Emf is a potential difference produced by conversion of another form of energy into electrical energy. Ways of producing emf include chemical (dry cell), mechanical (dynamo, rubbing a plastic rod with a woollen cloth), and magnetic (collapsing field, car ignition system).

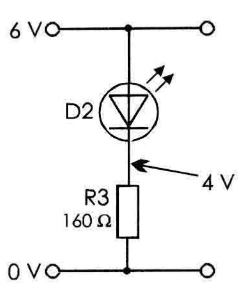


If a diode is wired in parallel with the inductor, as at (c), it protects the transistor by conducting the induced current away to the power line. It is a **protective diode**.

Indicator lamp

An indicator lamp is an optional but useful addition to this heater circuit. It could also be added to the other switching circuits we have studied. The idea is to have a lamp that comes on when the circuit is switched on. We could use a filament lamp (such as a 6 V torch bulb) but a light-emitting diode is generally preferred. This is because, for a given brightness, LEDs do not take as much current as filament lamps. Also, filament lamps

An LED needs a current of a few tens of milliamps. Often 20 mA or 25 mA makes the LED shine brightly. Like any other diode, an LED has a forward voltage drop across it when it is conducting. For most LEDs the drop is about 2 V.



An LED normally has a resistor in series with it.

The LED will burn out if the voltage across it is much more than 2 V. If the LED is being powered by a supply greater than 2 V, we need a resistor (R3) in series with it. This drops the excess voltage.

In the diagram above, the supply is 6 V, so the excess voltage is 4 V. If we decide to have a current of 25 mA through the LED, the same current passing through R3 must produce a drop of 4 V across it. So its resistance must be:

$$R_3 = 4/0.025 = 160\ \Omega$$

Select the nearest standard value. In this case, a 160 Ω resistor can be used, though a 150 Ω resistor would be close enough.

In general, if the supply voltage is V_S and the current is to be i_{LED}, the series resistor R_S is:

$$R_S = (V_S - 2)/i_{LED}$$

Self test

1 Calculate the value of the series resistor when:

a the supply voltage is 9 V and the current required is 20 mA.

b the supply voltage is 24 V and the current required is 15 mA.

2 If the supply is 12 V and the series resistor is 1.5 kΩ, what current flows through the LED?

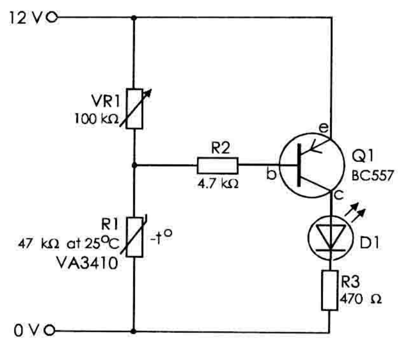
Certain types of LED, such as flashing LEDs, have built-in resistance and do not need a series resistor.

Overheating alert

Previous circuits in this topic have used BJTs of the type known as **npn** transistors. Here we use the other type of BJT, a **pnp transistor**. The action of a pnp transistor is similar to that of an npn transistor. In particular, a small base current controls a much larger collector current. However the polarities are reversed:

- The transistor is connected with its emitter *positive* of its collector.
- Base current flows *out of* the base terminal instead of flowing into it.
- When the transistor is 'on', the base terminal is 0.7 V *negative* of the emitter.

Here is a switching circuit using a pnp BJT:



Compare this circuit with the circuit on p. 6. Note the symbol for a pnp transistor.

The circuit is set by adjusting VR1 until the LED is just extinguished. The base (b) potential is then a little above 11.3 V (that is, the base-emitter voltage drop is a little less than 0.7 V). If the thermistor (R2) is warmed, its resistance decreases. This reduces the voltage at the point between R1 and R2. Current flows out of the base, turning the transistor on. When the transistor is on, the collector current flows in through the emitter (e), out of the collector (c) and on through the LED and series resistor R3. Thus, the LED comes on whenever the temperature of R1 rises. By adjusting VR1, the circuit can be set to switch on the LED at any required temperature in the region of 25°C.

Inverse action

The switching action is the opposite to that of the npn transistor circuit on p. 6. On p. 6, the relay comes on when temperature of the thermistor falls. In this circuit the LED comes on as temperature rises.

We could have achieved the equivalent action with an npn transistor in the relay circuit by exchanging VR1 and the thermistor. The values of the resistors would have needed altering but the action would be to turn on the relay with *falling* temperature.

Pnp or npn?

The inverse action can be achieved either by exchanging components or by using a pnp transistor. This illustrates a point about electronic circuits, that there are often two or more ways of doing the same thing. Sometimes both ways are equally effective and convenient. In other instances we may have reason to prefer one way to the other.

In practice, npn transistors are used far more often than pnp transistors. Although sometimes a resistor or logic gate may be saved in a circuit by using pnp, it is usually just as convenient to swap components to invert the action.

The main reason for using pnp is when we want a given signal to produce an action and its inverse *at the same time*. Then we use a pair of transistors, npn and pnp, with equal but opposite characteristics. Examples are seen in the power amplifiers described on pp. 111-2.

MOSFET types

MOSFETs too are made that work with polarities opposite to those of the n-channel MOSFETs described in this chapter. These are known as **p-channel MOSFETs** (p. 53).

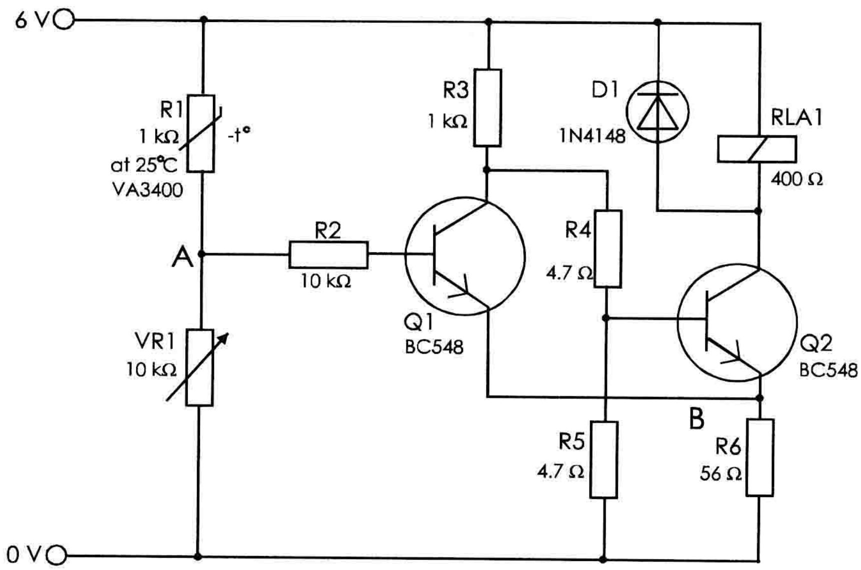
Schmitt trigger

In the two previous circuits, the resistance of the thermistor changes relatively slowly, so that the circuit spends several minutes in a state intermediate between 'off' and 'fully on'. The transistor is partly, not fully, switched on. In the heater switch circuit, the coil of the relay is not fully energised and the armature tends to vibrate rapidly, switching the heater on and off several times per second. This leads to sparking at the contacts, which may become fused together so that the relay is permanently 'on'. In an LED switching circuit, the LED gradually increases in brightness as temperature increases. It gives no clear indication of whether or not the temperature is too high. The circuit below avoids these problems, giving a sharp trigger switching action.

This is necessary because we have *two* inverting transistors in this circuit. The resistance of R3 must be greater than that of the relay coil, so that more current flows through R6 when Q2 is on, and less flows when Q1 is on.

Snap action

As temperature falls and Q1 begins to turn off, Q2 begins to turn on. The increasing current through R6 raises the voltage at the Q1 emitter. As the Q1 base voltage continues to fall its emitter voltage starts to rise, rapidly reducing the base current and turning Q1 off very rapidly. If Q1 turns off faster, then Q2 turns on faster. The circuit spends much less time in its intermediate state.



The Schmitt trigger circuit has a 'snap' action, which is suitable for switching heaters, indicator lamps and many other devices.

This **Schmitt trigger** consists of two npn transistors. Q1 is switched by the sensor network. Q2 is switched by Q1 and in turn switches the relay.

The thermistor and variable resistor are arranged so that the voltage at point A *falls* as temperature falls. This is the opposite action to that in the circuit on p. 6.

Hysteresis

In this circuit the temperature at which the relay is turned on or off depends on whether the temperature is rising or falling. The action of the circuit is such that the 'turn-on' temperature is lower than the 'turn-off' temperature. We call this action **hysteresis**.