Chapter-7: Analog and Digital Interface

1. Sensor:

A **sensor** is a device that produces an output signal for the purpose of sensing a physical phenomenon.

In the broadest definition, a sensor is a device, module, machine, or subsystem that detects events or changes in its environment and sends the information to other electronics, frequently a computer processor. Sensors are always used with other electronics.

Sensors are used in everyday objects such as touch-sensitive elevator buttons (tactile sensor) and lamps which dim or brighten by touching the base, and in innumerable applications of which most people are never aware. With advances in micromachinery and easy-to-use microcontroller platforms, the uses of sensors have expanded beyond the traditional fields of temperature, pressure and flow measurement, for example into MARG sensors.

Analog sensors such as potentiometers and force-sensing resistors are still widely used. Their applications include manufacturing and machinery, airplanes and aerospace, cars, medicine, robotics and many other aspects of our day-to-day life. There is a wide range of other sensors that measure chemical and physical properties of materials, including optical sensors for refractive index measurement, vibrational sensors for fluid viscosity measurement, and electro-chemical sensors for monitoring pH of fluids.

A sensor's sensitivity indicates how much its output changes when the input quantity it measures changes. For instance, if the mercury in a thermometer moves 1 cm when the temperature changes by 1 °C, its sensitivity is 1 cm/°C (it is basically the slope dy/dx assuming a linear characteristic). Some sensors can also affect what they measure; for instance, a room temperature thermometer inserted into a hot cup of liquid cools the liquid while the liquid heats the thermometer. Sensors are usually designed to have a small effect on what is measured; making the sensor smaller often improves this and may introduce other advantages.

Technological progress allows more and more sensors to be manufactured on a microscopic scale as microsensors using MEMS technology. In most cases, a microsensor reaches a significantly faster measurement time and higher sensitivity compared with macroscopic approaches. Due to the increasing demand for rapid, affordable and reliable information in today's world, disposable sensors—low-cost and easy-to-use devices for short-term monitoring or single-shot measurements—have recently gained growing importance. Using this class of sensors, critical analytical information can be obtained by anyone, anywhere and at any time, without the need for recalibration and worrying about contamination.

2. Sensor Rules:

A good sensor obeys the following rules:[4]

- it is sensitive to the measured property
- it is insensitive to any other property likely to be encountered in its application, and
- it does not influence the measured property.

Most sensors have a linear transfer function. The sensitivity is then defined as the ratio between the output signal and measured property. For example, if a sensor measures temperature and has a voltage output, the sensitivity is a constant with the units [V/K]. The sensitivity is the slope of the transfer function. Converting the sensor's electrical output (for example V) to the measured units (for example K) requires dividing the electrical output by the slope (or multiplying by its reciprocal). In addition, an offset is frequently added or subtracted. For example, −40 must be added to the output if 0 V output corresponds to −40 C input.

For an analog sensor signal to be processed, or used in digital equipment, it needs to be converted to a digital signal, using an analog-to-digital converter.

3. Different Types of Sensor:

Chemical sensor

A chemical sensor is a self-contained analytical device that can provide information about the chemical composition of its environment, that is, a liquid or a gas phase. The information is provided in the form of a measurable physical signal that is correlated with the concentration of a certain chemical species (termed as analyte). Two main steps are involved in the functioning of a chemical sensor, namely, recognition and transduction. In the recognition step, analyte molecules interact selectively with receptor molecules or sites included in the structure of the recognition element of the sensor. Consequently, a characteristic physical parameter varies and this variation is reported by means of an integrated transducer that generates the output signal. A chemical sensor based on recognition material of biological nature is a biosensor. However, as synthetic biomimetic materials are going to substitute to some extent recognition biomaterials, a sharp distinction between a biosensor and a standard chemical sensor is superfluous. Typical biomimetic materials used in sensor development are molecularly imprinted polymers and aptamers.

Biosensor

In biomedicine and biotechnology, sensors which detect analytes thanks to a biological component, such as cells, protein, nucleic acid or biomimetic polymers, are called biosensors. Whereas a non-biological sensor, even organic (carbon chemistry), for biological analytes is referred to as sensor or nanosensor. This terminology applies for both in-vitro and in vivo applications. The encapsulation of the biological component in biosensors, presents a slightly different problem that ordinary sensors; this can either be done by means of a semipermeable barrier, such as a dialysis membrane or a hydrogel, or a 3D polymer matrix, which either physically constrains the sensing macromolecule or chemically constrains the macromolecule by bounding it to the scaffold.

Neuromorphic sensors

Neuromorphic sensors are sensors that physically mimic structures and functions of biological neural entities. One example of this is the event camera.

MOS sensors

Metal-oxide-semiconductor (MOS) technology originates from the MOSFET (MOS field-effect transistor, or MOS transistor) invented by Mohamed M. Atalla and Dawon Kahng in 1959, and demonstrated in 1960. MOSFET sensors (MOS sensors) were later developed, and they have since been widely used to measure physical, chemical, biological and environmental parameters.

4. Transducer

The physical variable is normally a nonelectrical quantity. A transducer is a device that converts the physical variable to an electrical variable. Some common transducers include thermistors, photocells, photodiodes, flow meters, pressure transducers, and tachometers. The electrical output of the transducer is an analog current or voltage that is proportional to the physical variable it is monitoring. For example, the physical variable could be the temperature of water. Let's say that the water temperature varies from 800 to 1500 F and that a thermistor and its associated circuitry convert this water temperature to a voltage ranging from 800 to 1500mV. Note that the transducer's output is directly proportional to temperature; such that each 10 F produces a 10mV output. Analog-to-digital converter (ADC) and digital-to-converter (DAC) are used to interface a computer to the analog world so that the computer can monitor and control a physical variable Fig. 1.

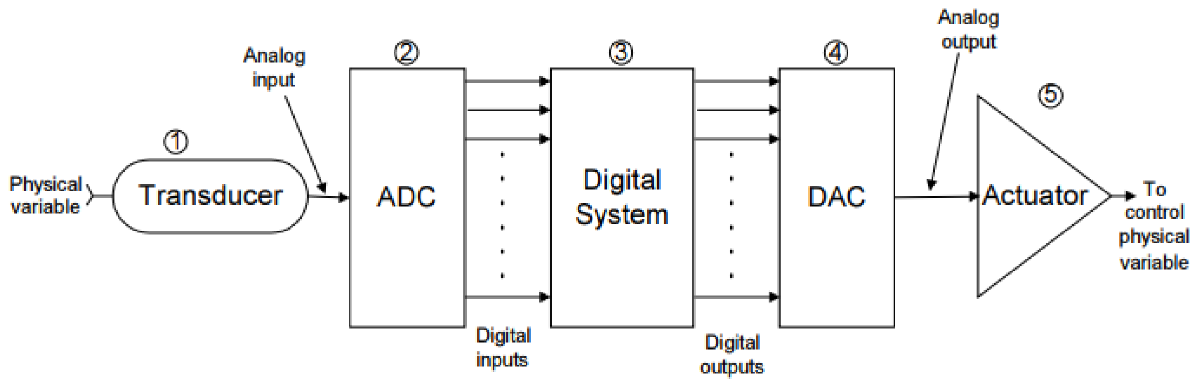
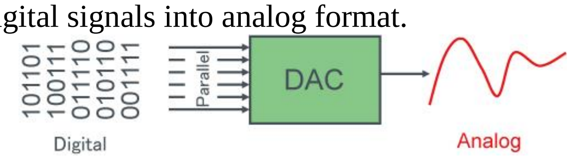


Fig.1 : Interfacing with the analog world using Analog-to-Digital Converter (ADC) and Digital-to-Analog Converter (DAC).

5. D/A Converters

D/A converters convert digital signals into analog format.



Digital Data:

Evenly spaced discontinuous values

Temporally discrete, quantitatively discrete

Analog Data (Natural Phenomena):

Continuous range of values

Temporally continuous, quantitatively continuous

D/A Converter Applications

Digital Audio :

CD, MD, 1-bit Audio

Digital Video :

DVD, Digital Still Camera

Communication Equipment：

Smartphones, FAX, ADSl equipment

PCs：

Audio, video cards

Measurement instruments：

Programmable power supplies, etc.

Basic Operation of a D/A Converter

A D/A converter takes a precise number (most commonly a fixed-point binary number) and converts it into a physical quantity (example: voltage or pressure). D/A converters are often used to convert finite-precision time series data to a continually varying physical signal.

An ideal D/A converter takes abstract numbers from a sequence of impulses that are then processed by using a form of interpolation to fill in data between impulses. A conventional D/A converter puts the numbers into a piecewise constant function made up of a sequence of rectangular functions that is modeled with the zero-order hold.

A D/A converter reconstructs original signals so that its bandwidth meets certain requirements. With digital sampling comes quantization errors that create low-level noise which gets added to the reconstructed signal. The minimum analog signal amplitude that can bring about a change in the digital signal is called the Least Significant Bit (LSB), while the (rounding) error that occurs between the analog and digital signals is referred to as quantization error.

6. A/D Converters

An A/D converter is a device that converts analog signals (usually voltage) obtained from environmental (physical) phenomena into digital format

Conversion involves a series of steps, including sampling, quantization, and coding.

A/D Converter Applications

Digital Audio:

Digital audio workstations, sound recording, pulse-code modulation

Digital signal processing:

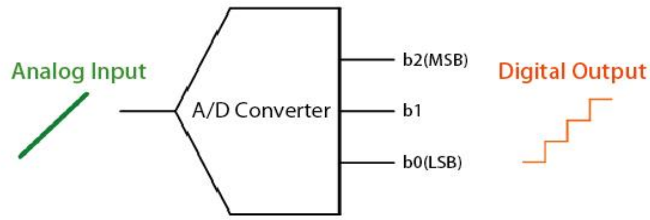
TV tuner cards, microcontrollers, digital storage oscilloscopes

Scientific instruments:

Digital imaging systems, radar systems, temperature sensors

Basic Operation of an A/D Converter

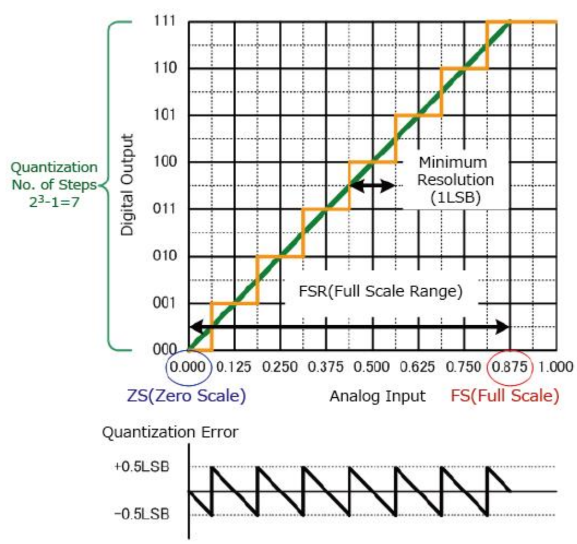
Now, let's take a look at the basic operation of an A/D converter.



The A/D converter breaks up (samples) the amplitude of the analog signal at discrete intervals, which are then converted into digital values. The resolution of an analog to digital converter (indicating the number of discrete values it can produce over a range of analog values) is typically expressed by the number of bits. In the above case of a 3bit A/D converter, the upper value (b2) is referred to as the Most Significant Bit (MSB) and the lowest value (b0) the Least Significant Bit (LSB).

The graph below shows the relationship between the analog input and digital output.

In addition, the first digital change point (000→001) below 0.5LSB is the zero scale, while the last digital change point (110→111) is termed full scale and the interval from zero to full scale referred to as the full scale range.



7. Analog Signal to Digital Signal Conversion Methods

Sampling:

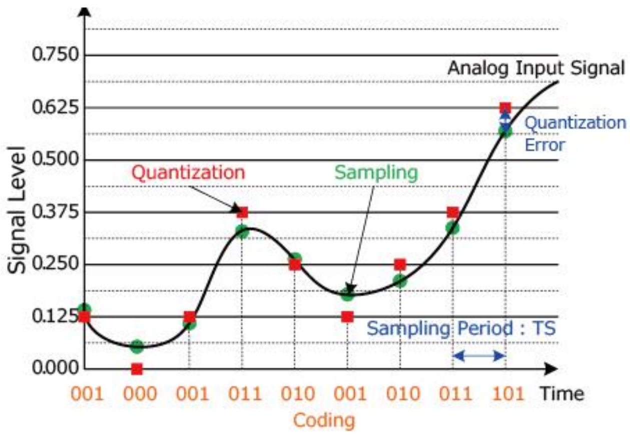
Sampling is the process of taking amplitude values of the continuous analog signal at discrete time intervals (sampling period Ts).
[Sampling Period Ts = 1/Fs (Sampling Frequency)]
Sampling is performed using a Sample and Hold (S&H) circuit.

Quantization:

Quantization involves assigning a numerical value to each sampled amplitude value from a range of possible values covering the entire amplitude range (based on the number of bits).
[Quantization error: Sampled Value - Quantized Value]

Coding:

Once the amplitude values have been quantized they are encoded into binary using an Encoder.



8. A/D Digital Interfaces

As with D/A converters, A/D converters are available as chips (monolithic or hybrids) that can be interface easily to a microcomputer as if they were standard peripheral chips. Most types of D/A converters need to be supplied with a periodic clock signal, a “start conversion” signal and they generate a “conversion complete” status signal when the conversion is done. The software that handles the A/D must give the command to start the conversion (e.g. by setting a control bit), and then wait until the status bit indicates that the conversion is complete before reading the result. Successive-approximation ADCs often provide their outputs in a serial format, one bit at a time, as the conversion takes place.

9. Short notes on some related topics:

Sample and Hold

If the analog signal changes while a conversion is taking place, the ADC could produce an incorrect result. A device called a sample-and-hold can be used before the ADC to hold the signal at the input to the ADC constant. This device samples the analog signal at its input for a short time and then holds that value fixed at its output until the next sample is required. The diagram below shows how the device works. An electronic switch is used to connect the analog input to a capacitor during the sampling time. During the “hold” time the switch is opened. An output amplifier with a very high input impedance is used in order to avoid discharging the capacitor during the hold time.

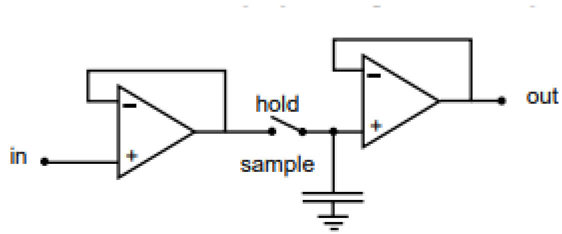


Figure: Sample and hold circuit

Multiplexers

Often several analog signals need to be monitored. If a sufficiently fast A/D converter is available, its input can be switched between the various signals using an electronic single-pole multiple-throw switch. This device is called a multiplexer. Many ADC chips have built-in multiplexers and S/H circuits.

Differential Amplifiers

Often the quantity of interest is the difference between two voltages (e.g. the voltage drop across a resistor) rather than the difference between a signal and ground. The circuit shown below combines an inverting and a non-inverting amplifier into a device called a differential amplifier. This circuit is also useful when an undesired signal (noise) is present on both inputs. Since the differential amplifier only responds to the difference between the two voltages, it will not respond to this common-mode noise.

Low-Pass Filters

Often the signal of interest is changing slowly (e.g. the voltage output of a battery as it discharges) but has an additional higher-frequency component superimposed on it (e.g. voltage fluctuations due to a rapidly changing load). A circuit called a low-pass filter will allow the slowly-changing (low-frequency) signal component to pass through to the output while removing or attenuating the fast-changing (high frequency) component. Filters (low-pass as well as other types) can be built using op-amps, resistors and capacitors.

10. Principle of Solid State Relay

Unlike electro-mechanical relays (EMR) which use coils, magnetic fields, springs and mechanical contacts to operate and switch a supply, the solid state relay, or SSR, has no moving parts but instead uses the electrical and optical properties of solid state semiconductors to perform its input to output isolation and switching functions.

Just like a normal electro-mechanical relay, SSR's provide complete electrical isolation between their input and output contacts with its output acting like a conventional electrical switch in that it has very high, almost infinite resistance when nonconducting (open), and a very low resistance when conducting (closed). Solid state relays can be designed to switch both AC or DC currents by using an SCR, TRIAC, or switching transistor output instead of the usual mechanical normally-open (NO) contacts.

While the solid state relay and electro-mechanical relay are fundamentally similar in that their low voltage input is electrically isolated from the output that switches and controls a load, electro-mechanical relays have a limited contact life cycle, can take up a lot of room and have slower switch speeds, especially large power relays and contactors. Solid state relays have no such limitations.

Thus the main advantages solid state relays have over conventional electro-mechanical relays is that they have no moving parts to wear out, and therefore no contact bounce issues, are able to switch both "ON" and "OFF" much faster than a mechanical relays armature can move, as well as zero voltage turn-on and zero current turn-off eliminating electrical noise and transients.

Solid state relays can be bought in standard off-the-shelf packages ranging from just a few volts or amperes to many hundreds of volts and amperes of output switching capability. However, solid state relays with very high current ratings (150A plus) are still too expensive to buy due to their power semiconductor and heat sinking requirements, and as such, cheaper electro-mechanical contactors are still used.

Similar to an electro-mechanical relay, a small input voltage, typically 3 to 32 volts DC, can be used to control a much large output voltage, or current. For example 240V, 10Amps. This makes them ideal for microcontroller, PIC and Arduino interfacing as a low-current, 5-volt signal from say a micro-controller or logic gate can be used to control a particular circuit load, and this is achieved with the use of opto-isolators.

11. <u>Solid State Relay Input</u>

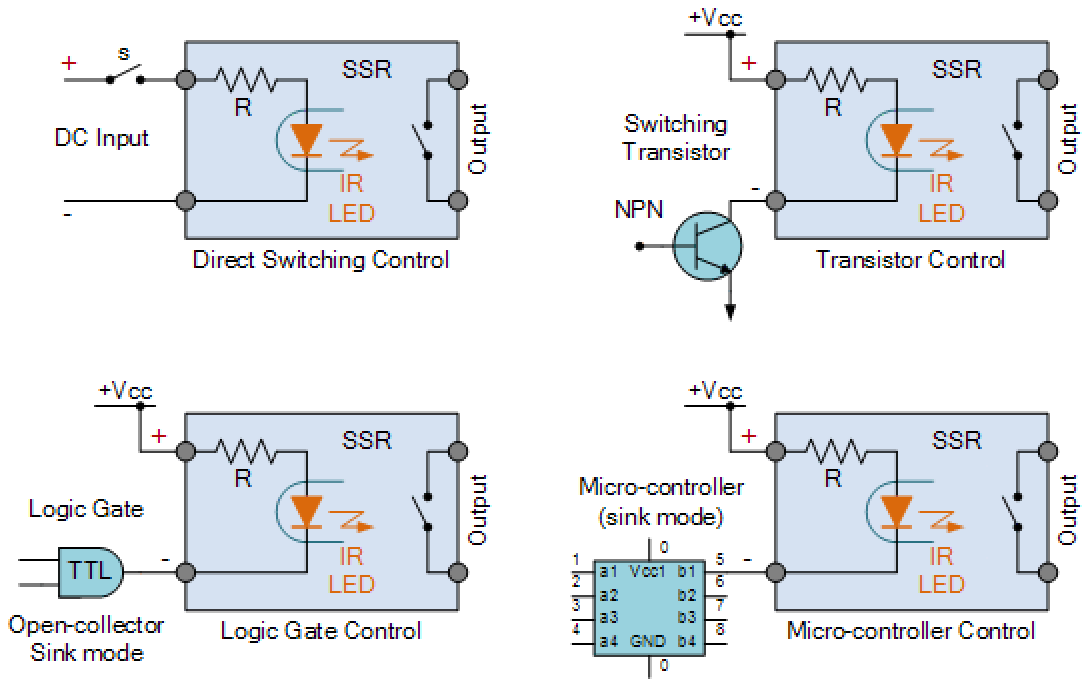
One of the main components of a solid state relay (SSR) is an opto-isolator (also called an optocoupler) which contains one (or more) infra-red light-emitting diode, or LED light source, and a photo sensitive device within a single case. The opto-isolator isolates the input from the output.

The LED light source is connected to the SSR's input drive section and provides optical coupling through a gap to an adjacent photo sensitive transistor, darlington pair or triac. When a current passes through the LED, it illuminates and its light is focused across the gap to a photo-transistor/photo-triac.

Thus the output of an opto-coupled SSR is turned "ON" by energising this LED, usually with low-voltage signal. As the only connection between the input and output is a beam of light, high voltage isolation (usually several thousand volts) is achieved by means of this internal opto-isolation.

Not only does the opto-isolator provide a higher degree of input/output isolation, it can also transmit dc and low-frequency signals. Also, the LED and photo-sensitive device could be totally separate from each other and optically coupled by means of an optical fibre.
The input circuitry of an SSR may consist of just a single current limiting resistor in series with the LED of the opto-isolator, or of a more complex circuit with rectification, current regulation, reverse polarity protection, filtering, etc.
To activate or turn "ON" a sold state relay into conduction, a voltage greater than its minimum value (usually 3 volts DC) must be applied to its input terminals (equivalent to the electro-mechanical relay coil). This DC signal may be derived from a mechanical switch, a logic gate or micro-controller, as shown.

Solid State Relay DC Input Circuit



When using mechanical contacts, switches, push-buttons, other relay contacts, etc, as the activating signal, the supply voltage used can be equal to the SSR's minimum input voltage value, whereas when using solid state devices such as transistors, gates and micro-controllers, the minimum supply voltage needs to be one or two volts above the SSR's turn-on voltage to account for the switching devices internal voltage drop.
But as well as using a DC voltage, either sinking or sourcing, to switch the solid state relay into conduction, we can also use a sinusoidal waveform as well by adding a bridge rectifier for full-wave rectification and a filter circuit to the DC input as shown.

12. Solid State Relay Output

The output switching capabilities of a solid state relay can be either AC or DC similar to its input voltage requirements. The output circuit of most standard solid state relays are configured to perform only one type of switching action giving the equivalent of a normally-open, single-pole, single-throw (SPST-NO) operation of an electro-mechanical relay.

For most DC SSR's the solid state switching device commonly used are power transistors, Darlington's and MOSFETs, whereas for an AC SSR, the switching device is either a triac or back-to-back thyristors. Thyristors are preferred due to their high voltage and current capabilities. A single thyristor can also be used within a bridge rectifier circuit as shown.

13. <u>Insulated-Gate Bipolar Transistor (IGBT)</u>

IGBT combines the physics of both BJTs and power MOSFETs to gain the advantages of both worlds. It is controlled by the gate voltage. It has a high input impedance like a power MOSFET and has low on-state power loss as in the case of BJT. There is no even secondary breakdown and not have long switching time as in the case of BJT. It has better conduction characteristics as compared to MOSFET due to its bipolar nature. It has no body diode as in the case of MOSFET but this can be seen as an advantage of using an external fast recovery diode for specific applications. They are replacing the MOSFET for most of the high voltage applications with fewer conduction losses. Its physical cross-sectional structural diagram and equivalent circuit diagram are presented in Figures below. It has three terminals called collector, emitter, and gate.

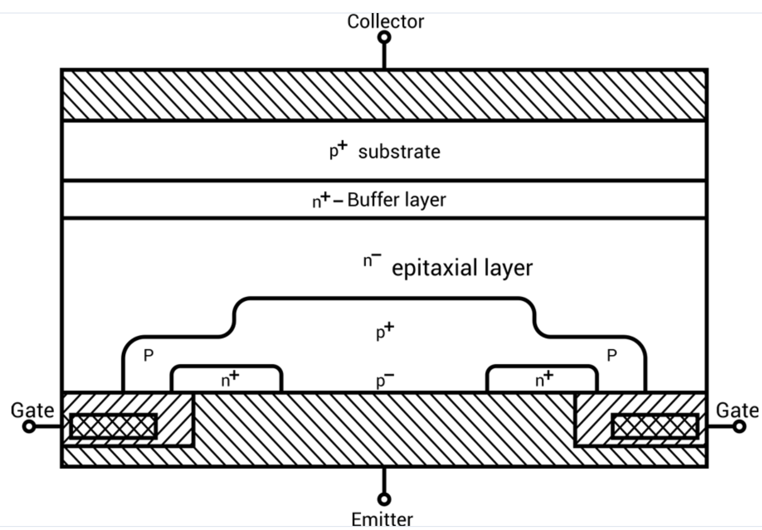


Figure 1. *IGBT structure view*

There is a p+ substrate that is not present in the MOSFET and responsible for the minority carrier injection into the n-region. Gain of NPN terminal is reduced due to wide epitaxial base and n+ buffer layer.

There are two structures of IGBTs based on doping of the buffer layer:

a) Punch-through IGBT: Heavily doped n buffer layer ➔ less switching time

b) Non-Punch-through IGBT: Lightly doped n buffer layer ➔ greater carrier lifetime ➔ increased conductivity of drift region ➔ reduced on-state voltage drop

(Note: ➔ means implies)

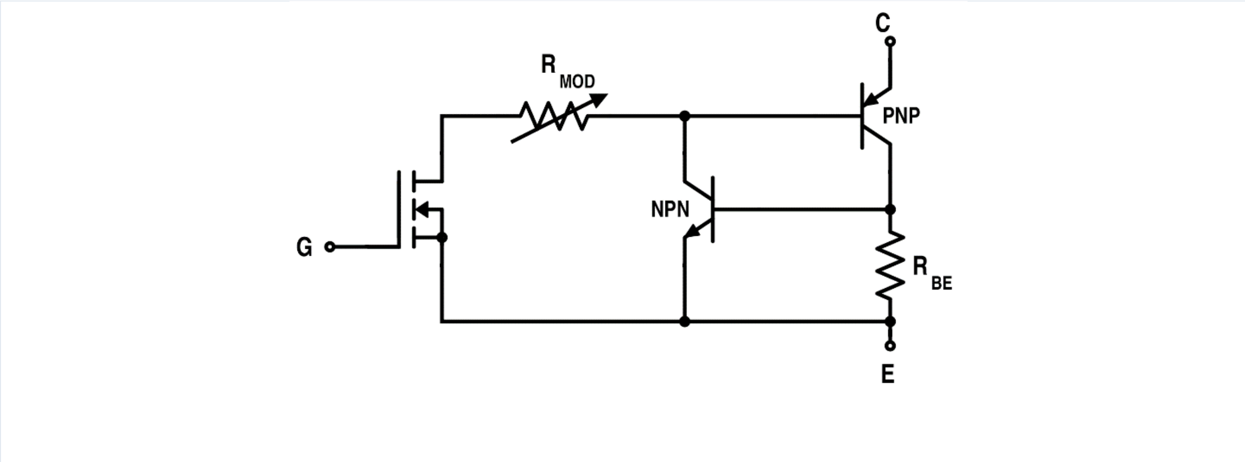


Figure 28. *Equivalent circuit for IGBT*

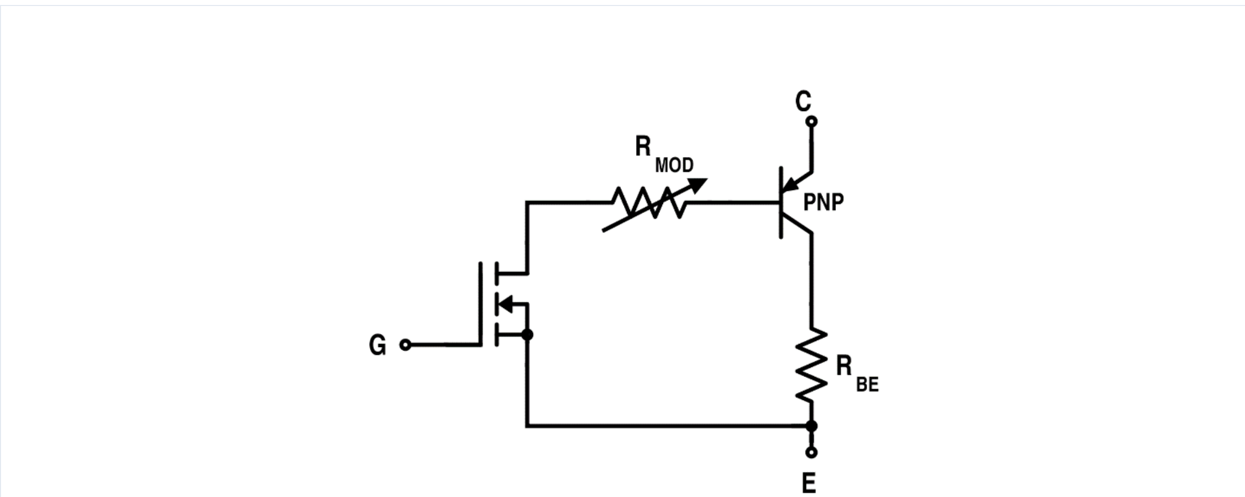


Figure 29. *Simplified equivalent circuit for an IGBT*