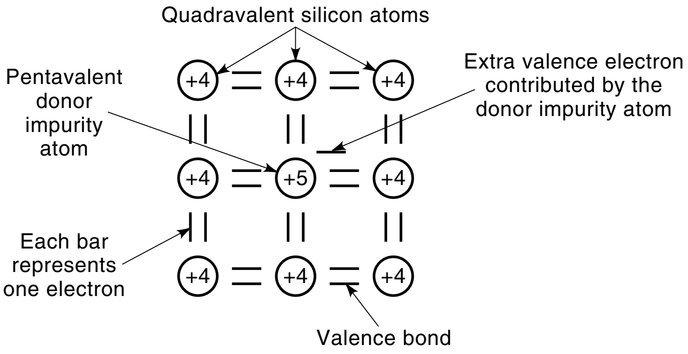
ELECTRIC BREAKDOWN IN SEMICONDUCTORS

Breakdown voltage is defined as the potential difference at which an electrically stressed semiconducting material is transformed from its "insulating" or "semiconducting" state to a "conducting" state. Breakdown voltage depends on a variety of factors, including the material (for example, silicon or germanium), the temperature, the type of voltage applied (for example, direct, low-frequency alternating, high frequency alternating, or impulse), lattice or crystal structure, level of impurities, degree of doping, and degree of preexisting ionization conditions.

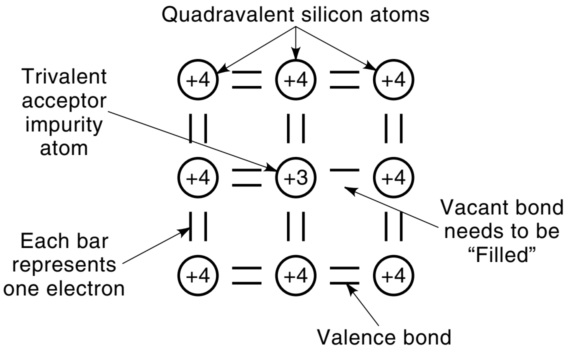
Two types of breakdown phenomena are discussed in this article:

1. Avalanche breakdown
2. Zener breakdown

For example, a silicon or germanium *p*–*n* semiconductor junction wherein the first part of the crystal is grown with a doping of trivalent material (group III elements in the periodic table: boron, aluminum, gallium, indium, and thallium) results in forming a *p*-type material because the added impurity leaves certain of the covalent bonds missing one electron. These trivalent atoms are called acceptor atoms. The second part of the crystal is grown with a doping of pentavalent material (group V elements in the periodic table: phosphorous, arsenic, antimony, and bismuth) results in forming an *n*-type material because the added impurity has an extra electron to contribute to the crystal structure. These pentavalent atoms are called donor atoms. Figure 1 represents the crystal structure. The free electrons near the barrier in the *n*-type material diffuse over the *p*–*n* boundary to the other side, leaving behind positively ionized atoms. This process is known as carrier depletion. In other words, there are no holes or electrons available in this region to carry current. This barrier region is called the depletion region [Fig. 2(a) and 2(b)].



n-type of semiconducting material



p-type of semiconducting material

Figure 1. Crystal structure of silicon with doped impurities.

Let a direct voltage be applied to this semiconductor, where the positive electrode is connected to the side that has the *p*-type material and the negative electrode is connected to the side that has the *n*-type material [Fig. 2(c)]. This is known as forward bias. The depletion region shrinks in width because the "*n*-type" electrons are getting a boost from the voltage source to cross the barrier. However, if the direction of the voltage is reversed, the width of the depletion layer increases because the electrons in the *n*-type material are being "pulled" away from the depletion region by the positive electrode of the supply and the holes are attracted toward the cathode of the source. In this case the *p*–*n* junction is reverse-biased [Fig. 2(d)].

As the voltage applied to the reverse-biased *p*–*n* junction is increased, the electric field in the depletion region increases. Ultimately, the increased field is large enough to break a covalent bond, resulting in the release of electrons that constituted the bond. These electrons are accelerated through the crystal because of the electric force applied on them and in turn collide with other atoms and also break their covalent bonds. The process is called impact ionization. Thus ionization is cumulative and results in an avalanche. The magnitude of the voltage when this avalanche is created and sustained to produce an avalanche current is called the reverse-breakdown voltage of the *p*–*n* junction diode. The resulting current is called avalanche current, and this type of breakdown is called avalanche breakdown. The resulting current may be large enough to destroy the *p*–*n* junction. By using a suitable series resistor, however, it is possible to limit the current and thereby control the power dissipated. The *p*–*n* junction can actually be operated in its breakdown condition continuously.

The *p*-type material and the *n*-type material are each lightly doped in a "general-purpose diode." This type of diode is designed for operation in the forward-biased region and is supposed to carry the rated current continuously, without overheating. When a diode is reverse-biased, a small current is measured in the reverse direction called "reverse saturation current." The breakdown voltage is relatively very high [Fig. 2(e)]. This current, called leakage current, is symbolically represented as I_o.

ZENER BREAKDOWN AND ZENER DIODE

If the *p*-type material and the *n*-type material are each heavily doped, a zener diode is formed. The heavy doping increases the electric field in the depletion region and reduces the reverse-breakdown voltage. In this case, this reverse breakdown is called zener breakdown. In case of the diode *p*–*n* junction,

Average electric field strength in the depletion region
= applied reverse voltage/width of the depletion region

Therefore, it is possible to carefully control the breakdown voltage by adjusting the amount of doping through the width of the depletion region. At some level of the electric field strength, the mechanisms of electric breakdown change from

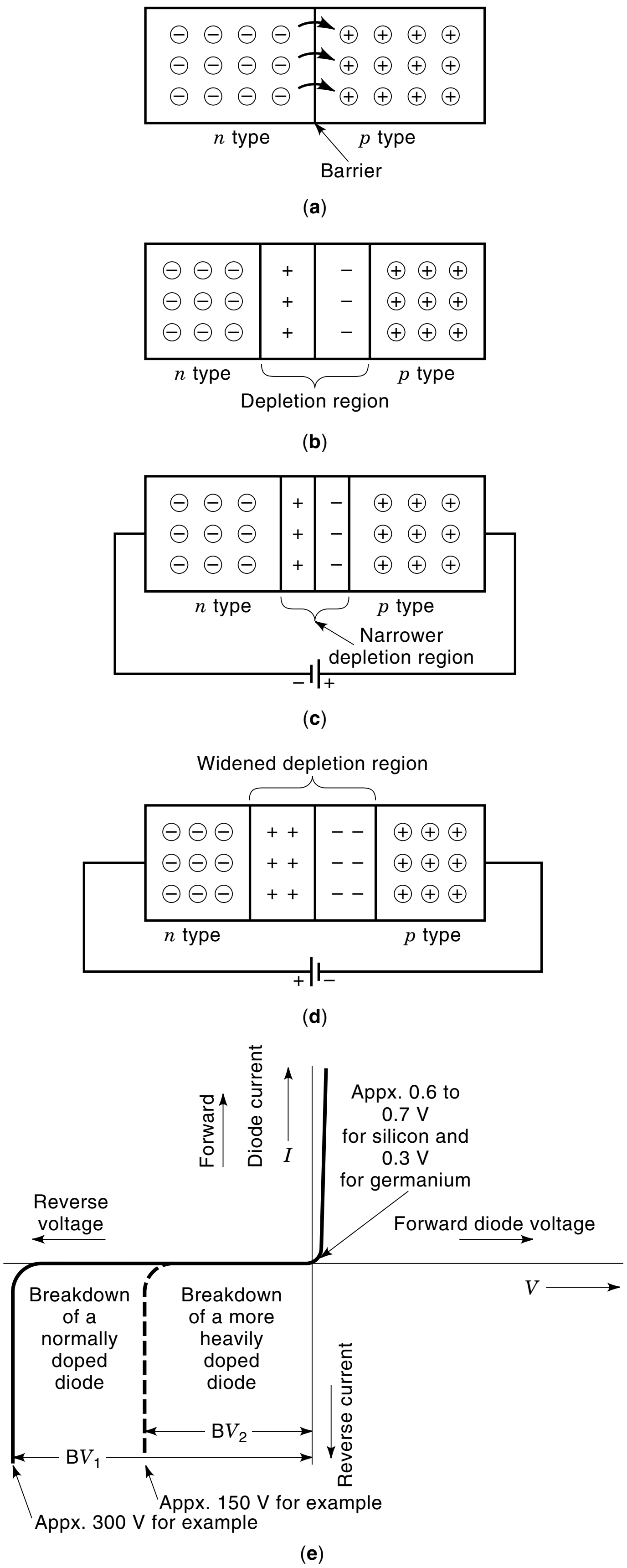


Figure 2. (a)–(d) Depletion region formation in a p–n junction semiconductor; (e) forward characteristics and reverse breakdown characteristics of a p–n junction diode.

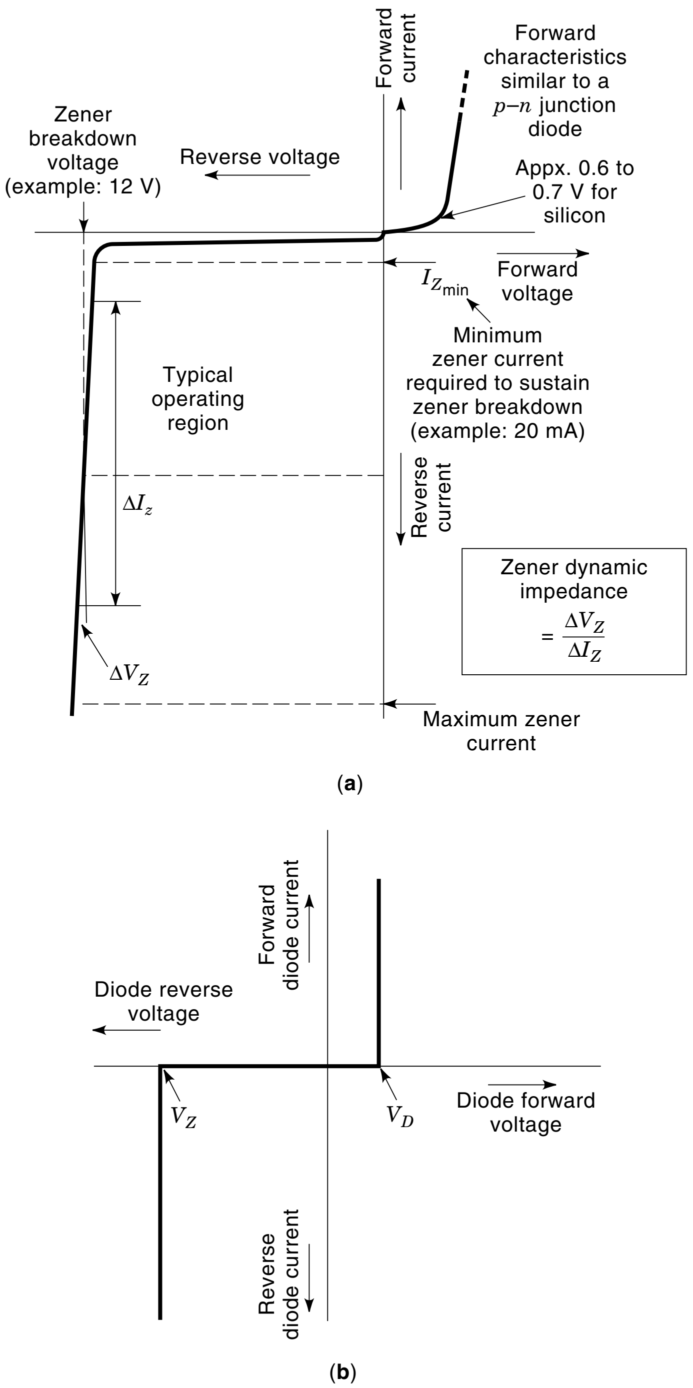


Figure 3. (a) An example of zener breakdown characteristics; (b) ideal characteristics of a zener diode.

avalanche multiplication to tunnel or zener breakdown. Zener breakdown is estimated to take place at approximately 300,000 V/cm. (As a comparison, the breakdown strength of air is 33,000 V/cm.)

Zener breakdown and avalanche breakdown may occur independently or simultaneously. Zener breakdown takes place typically at low values of reverse-bias voltages.

A typical zener diode (abbreviated zener) characteristic is shown in Figs. 3(a) and 3(b). The forward-bias characteristic of the diode is not of particular interest in the case of zener. In the reverse, the zener maintains a voltage of V_Z regardless of the magnitude of the current in the reverse direction. Therefore, the principal application of the zener is for voltage regulation. With zeners, it is possible to maintain the output voltage (of a power supply, for example) constant, regardless of the changes in the load current. An example is shown in Fig. 4(a). This is a simplified version of a power supply regulator circuit. The input from a rectifier circuit has a dc voltage of 11 V but has a 1 V peak-to-peak ac component superimposed on it. A 10 V zener along with a current limiting protective resistor, connected as shown, eliminates the ac component and yields a pure dc voltage of 10 V [Figs. 4(b) and 4(c)]. A zener diode may require a minimum threshold current of 20 mA (for example) for it to operate satisfactorily, sustaining a zener breakdown. It may be capable of carrying a maximum current of I_{ZM}. The maximum current is obviously limited by the maximum power dissipation permitted by the zener. Zener diodes are sometimes called breakdown diodes or reference diodes.

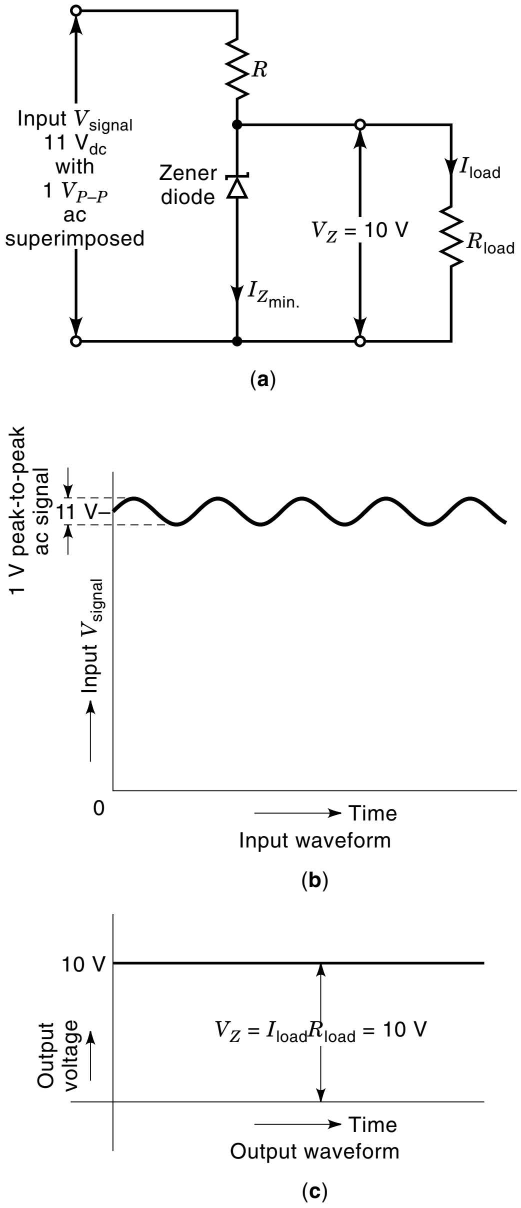


Figure 4. (a) Power supply regulator circuit uses zener breakdown to provide constant voltage to the load resistance; (b) voltage waveform of input signal; (c) voltage waveform of output signal.

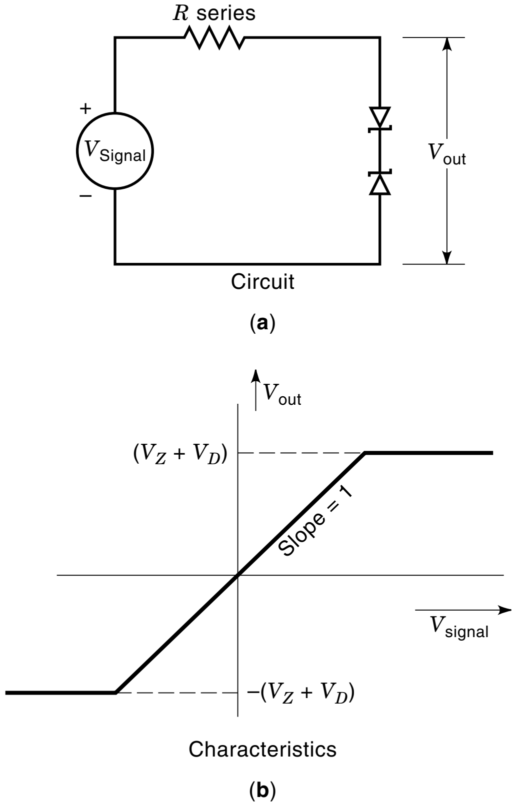


Figure 5. (a) and (b), Symmetrical zener limiter circuit and characteristics.

When two zener diodes are connected in a back-to-back configuration, it is called a double-breakdown diode or a varistor diode. The symbolic representation and the characteristic curve are shown in Figs. 5(a) and 5(b).

BREAKDOWN IN JUNCTION TRANSISTORS

A bipolar junction transistor can be a *p–n–p* junction or an *n–p–n* junction device. A transistor connected as a common-emitter amplifier configuration is shown in Fig. 6(a). In this case, the base-emitter junction is forward-biased and the base-collector junction is reverse-biased. The forward-biased junction drops by approximately 0.6 V to 0.7 V for silicon and 0.3 V for germanium. However, there is a possibility of voltage breakdown at the base–collector junction because it is reverse-biased and there is a maximum permissible voltage that the junction can safely carry. Two types of breakdown are possible:

1. Avalanche breakdown
2. Punch-through

An example of collector current versus collector voltage characteristics for a transistor is shown in Fig. 6(b). For the specified base currents, the collector current increases slightly as the collector-emitter voltage increases. When the voltage is high enough (approximately 50 V on the graph), however, an avalanche sets in, and the transistor breaks down. As seen in

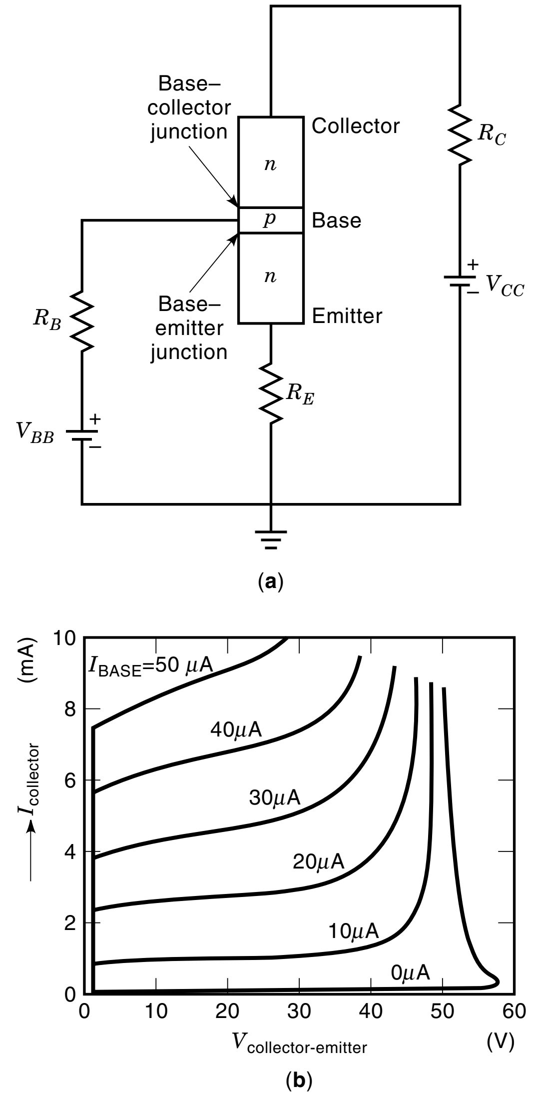


Figure 6. (a) Common-emitter amplifier circuit shows that the base-emitter junction is forward-biased, whereas the base-collector junction is reverse-biased and avalanche may set in; (b) collector characteristics for a common-emitter amplifier's characteristics show that an avalanche sets in at approximately 50 V resulting in huge currents.

Fig. 6(b), avalanche breakdown voltages vary depending on the base current for a given transistor, in the common-emitter configuration.

Punch-through takes place because of changes in the width of the depletion region, known as the *early effect.* Again the area of interest is the base-collector junction because of its reverse-bias voltage. The width of this reverse-biased, junction-depletion region increases as the magnitude of the voltage applied across the collector and emitter increases. As a result, the "effective base width" decreases. This reduction in base width, called early effect, can result in:

1. Decreased chances for the recombination of electrons and holes because the effective base width is narrower
2. An increase in the concentration gradient of the minority carriers in the neutral base region
3. The width of the neutral base between the emitter–base and collector–base junctions approaching zero or becoming almost equal to zero.

Combination of all three results in a base that is extremely thin compared with the emitter and the collector. This results in the passage of current from the emitter to the collector without any resistance in the base and is called punch-through.

Punch-through takes place at a fixed voltage given by

$$V_{\text{JUNCTION}} = [q(N_{\text{D}})W^2]/[2\epsilon_0\epsilon_{\text{r}}]$$

where

q = the charge on an electron = 1.602×10^{-19} Coulombs
N_{D} = the concentration of donor ions in the semiconductor
W = the width of the base
ϵ_0 = the dielectric constant of free space = 8.852×10^{-12} F/m
ϵ_{r} = the relative permittivity of the semiconductor material

Breakdown in junction field-effect transistors (JFETs) is again due to the creation of an *avalanche.* An example of an *n*-channel JFET biasing and its characteristics is shown in Fig. 7. The JFET must be operated in the saturation region and below the breakdown voltage specified by the manufacturer. Sometimes this may be as high as 120 V.

BREAKDOWN DEVICES

The phenomenon of breakdown has been utilized to develop several semiconductor devices, such as the unijunction transistor (UJT), the Schottky diode (the four-layer diode), the silicon-controlled rectifier (SCR), the directional diode thyrister (diac), and the bidirectional triode thyrister (triac).

Unijunction Transistor

The unijunction transistor is also called a *double-based diode.* It has two doped regions, as shown in Fig. 8(a). The symbolic representation is shown in Fig. 8(b). It can be viewed as two transistors connected as shown in Fig. 8(c) along with two resistors R_1 and R_2. It has three leads, identified as emitter, Base 1, and Base 2 (instead of emitter, base and collector).

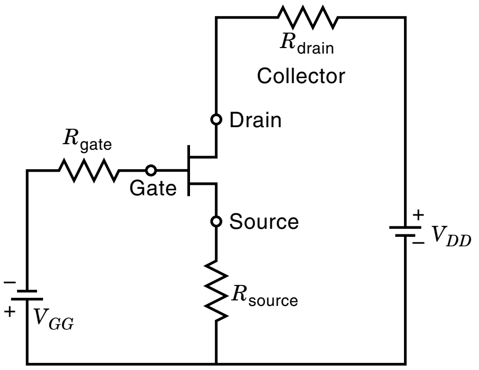


Figure 7. *n*-Channel JFET biasing: common-source configuration.

The ratio $(R_1)/(R_1 + R_2)$ is called the intrinsic standoff ratio and is denoted by the Greek letter η. Its value is approximately in the range between 0.5 and 0.8. The transistor is off as long as the emitter voltage is less than the standoff voltage. Once the emitter voltage exceeds the standoff voltage, the unijunction transistor fires, the transistor is turned on, and remains on as long as the emitter current is greater than the holding current. This holding current is also called the valley current. A typical characteristic of a unijunction transistor is shown in Fig. 8(d). One of the most common uses of this type of breakdown device is in the "relaxation oscillator" circuit. Figure 8(e) shows a simple circuit that uses a resistance and a capacitance connected to the UJT to perform as a relaxation oscillator. A sawtooth waveform can be generated using this circuit. Base 1 is grounded, and Base 2 receives a voltage V_{B2}. This voltage charges the capacitor via the resis-

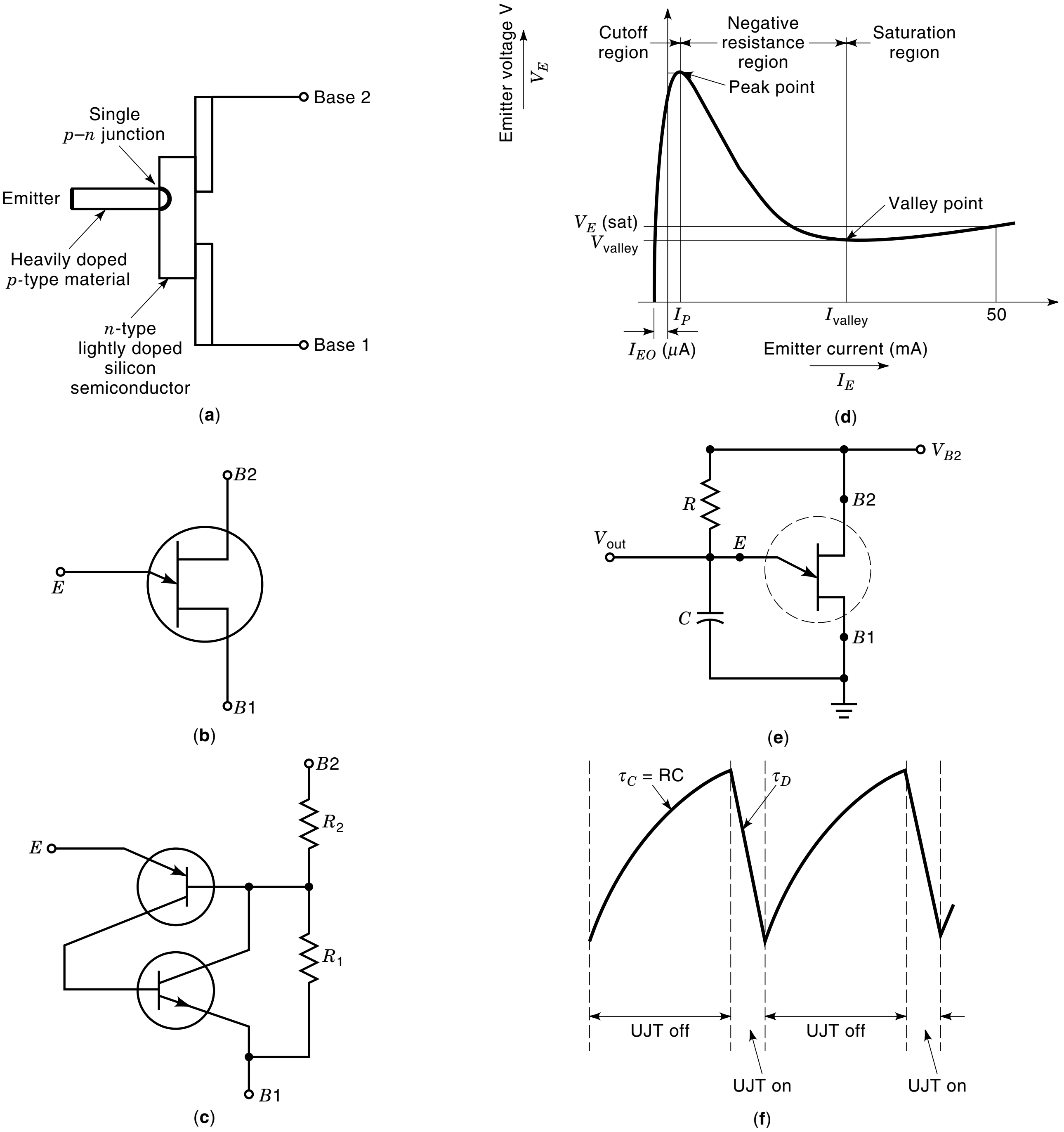


Figure 8. (a) Unijunction transistor constructional features (formerly known as duo-base diode); (b) UJT symbol; (c) UJT can be viewed as two transistors connected as shown above and $\eta = [(R_1)/(R_1 + R_2)]$; (d) unijunction transistor characteristics showing the negative resistance region; (e) UJT relaxation oscillator circuit; (f) sawtooth waveform generation using a UJT relaxation oscillator circuit. Discharge is fast and rapid because of breakdown phenomenon.

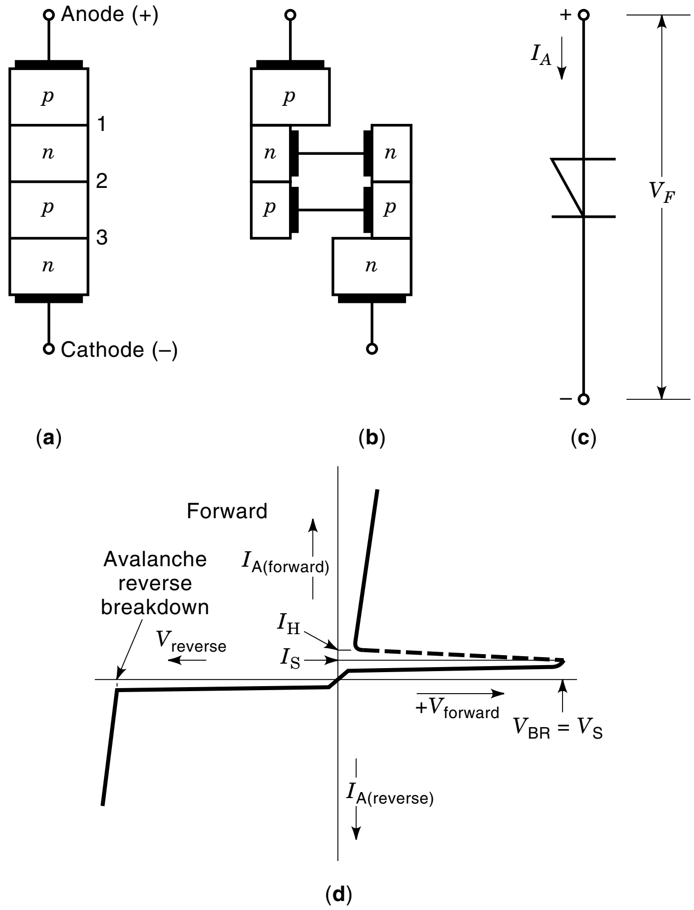


Figure 9. (a) and (b) The Schottky diode is a four-layer *p–n–p–n* diode; (c) Schottky diode symbol; (d) characteristics of the Schottky diode show that an avalanche sets in to break down the reverse-biased *n–p* junction at V_{BR} (called the forward switching voltage, also represented as V_S). I_S is the corresponding switching current and I_H is the corresponding "holding" current.

tance *R*. Once the capacitor voltage reaches the standoff voltage of the UJT, the UJT fires and discharges the capacitor because the resistance between the emitter and the grounded Base 1 is very small. This causes a collapse in the capacitor voltage. Therefore the current ceases to exist, and the UJT is returned to its open state because there is no current to sustain the UJT in the fired state. The cycle repeats, resulting in the sawtooth waveform shown in Fig. 8(f).

Schottky Diode

A four-layer silicon device with a *p–n–p–n* junction is called a Schottky diode. A slight variation of this device is also called the silicon unilateral switch. In this case there are three junctions, identified as 1, 2, and 3 in the diagram shown in Fig. 9(a). Figure 9(b) shows the characteristics of the Schottky diode. When the device is connected as shown in the sketch, junctions 1 and 3 are forward-biased, whereas junction 2 is reverse-biased. When the voltage increases, the forward current increases only very slightly, as shown in Fig. 9(c). At V_{BR} an avalanche breakdown takes place at junction 2, and this permits the current flow to increase, as shown in Fig. 9(d). Only a few volts are dropped across the conducting diode, as shown in the diagram. The minimum current required is called the *holding current* represented by I_H. Schottky diodes switch on within a microsecond and are very useful in triggering various electronic circuits.

BIBLIOGRAPHY

1. C. L. Alley and K. W. Atwood, *Microelectronics,* Englewood Cliffs, NJ: Reston Prentice-Hall, 1986.
2. G. L. Batten, Jr., *Programmable Controllers,* New York: McGraw-Hill, 1994.
3. D. A. Bell, *Electronic Devices and Circuits,* 3rd ed., Englewood Cliffs, NJ: Reston Prentice-Hall, 1980.
4. J. J. Carr, *Elements of Electronic Instrumentation and Measurement,* 3rd ed., Englewood Cliffs, NJ: Prentice-Hall, 1996.
5. J. J. Carr, *Sensors and Circuits,* Englewood Cliffs, NJ: PTR Prentice-Hall, 1993.
6. J. R. Carstens, *Electrical Sensors and Transducers,* Englewood Cliffs, NJ: Regents Prentice-Hall, 1993.
7. G. M. Chute and R. D. Chute, *Electronics in Industry,* 5th ed., New York: McGraw-Hill, 1979.
8. E. O. Doebelin, *Measurement Systems,* 4th ed., New York: McGraw-Hill, 1990.
9. R. C. Dorf and R. H. Bishop, *Modern Control Systems,* 7th ed., Reading, MA: Addison-Wesley, 1995.
10. R. C. Dorf and J. A. Svoboda, *Introduction to Electric Circuits,* 3rd ed., New York: Wiley, 1996.
11. J. R. Eaton and E. Cohen, *Electric Power Transmission Systems,* 2nd ed., Englewood Cliffs, NJ: Prentice-Hall, 1983.
12. A. R. Hambley, *Electronics,* New York: Macmillan, 1994.
13. E. N. Lurch, *Fundamentals of Electronics,* 3rd ed., New York: Wiley, 1981,
14. A. P. Malvino, *Electronic Principles,* 2nd ed., New York: McGraw-Hill, 1979.
15. J. Millman and A. Grabel, *Microelectronics,* 2nd ed., New York: McGraw-Hill, 1987.
16. M. H. Rashid, *Microelectronic Circuits,* Boston: PWS Publishing, 1999.

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ELECTRIC CIRCUITS, INTERVAL ANALYSIS FOR.

See INTERVAL ANALYSIS FOR CIRCUITS.

ELECTRIC CIRCUITS, SENSITIVITY.

See SENSITIVITY ANALYSIS.

ELECTRIC COMPONENTS.

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ELECTRIC CONDUCTORS.

See CONDUCTORS, ELECTRIC.