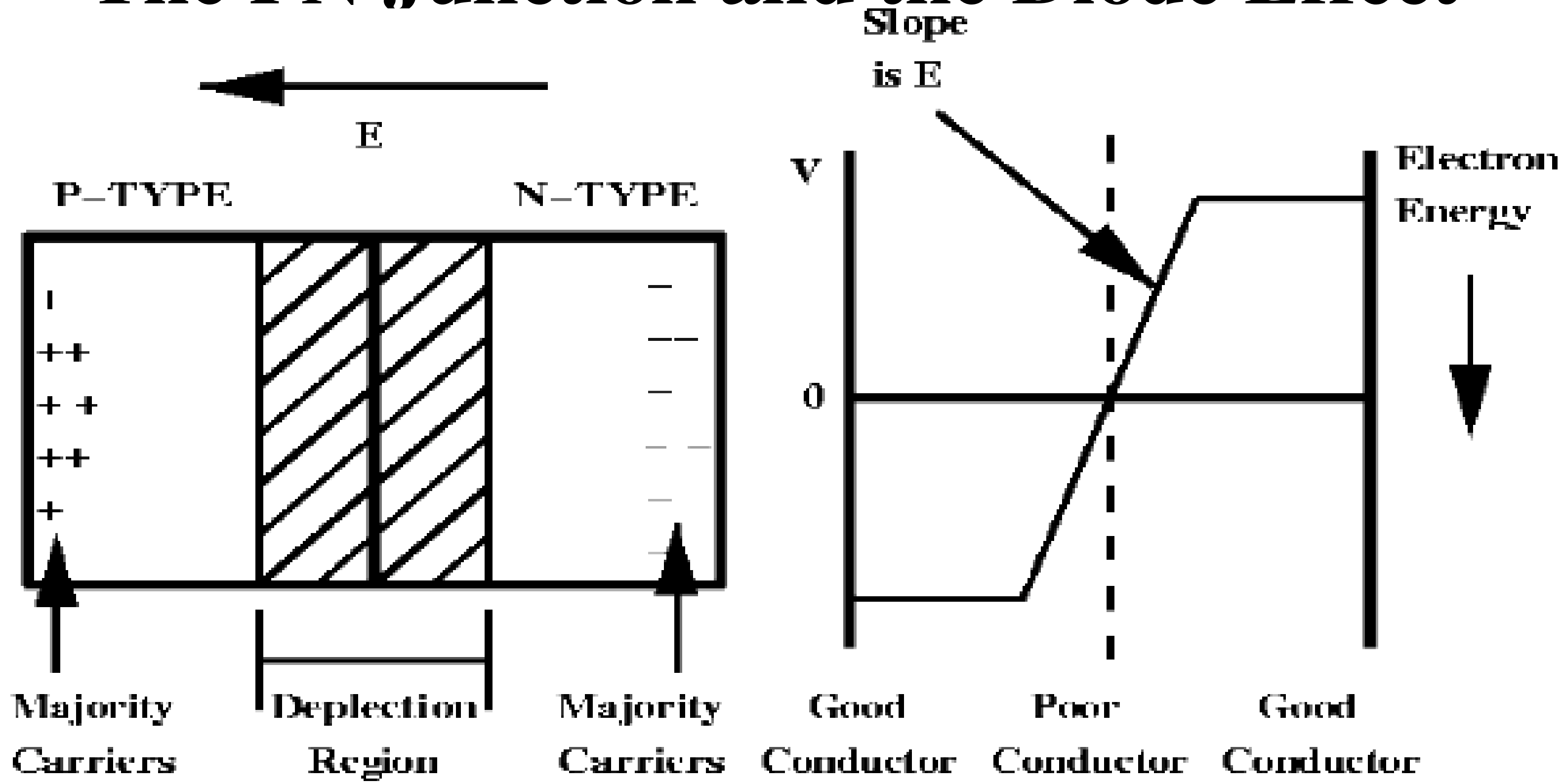
Diode Circuits

The PN Junction and the Diode Effect



Initially both semiconductors are totally neutral. The concentration of positive and negative carriers are quite different on opposite sides of the junction and the thermal energy-powered diffusion of positive carriers into the N-type material and negative carriers into the P-type material occurs. The N-type material acquires an excess of positive charge near the junction and the P-type material acquires an excess of negative charge. Eventually diffuse charges build up and an electric field is created which drives the minority charges and eventually equilibrium is reached. A region develops at the junction called the *depletion region*. This region is essentially un-doped or just intrinsic silicon.

To complete the diode conductor, leads are placed at the ends of the PN junction.

Current in the Diode

The behaviour of a diode depends on its polarity in the circuit (figure 2). If the diode is *reverse biased* (positive potential on N-type material) the depletion region increases. The only charge carriers able to support a net current across the PN junction are the minority carriers and hence the reverse current is very small. A *forward-biased* diode (positive potential on P-type material) has a decreased depletion region; the majority carriers can diffuse across the junction. The voltage may become high enough to eliminate the depletion region entirely.

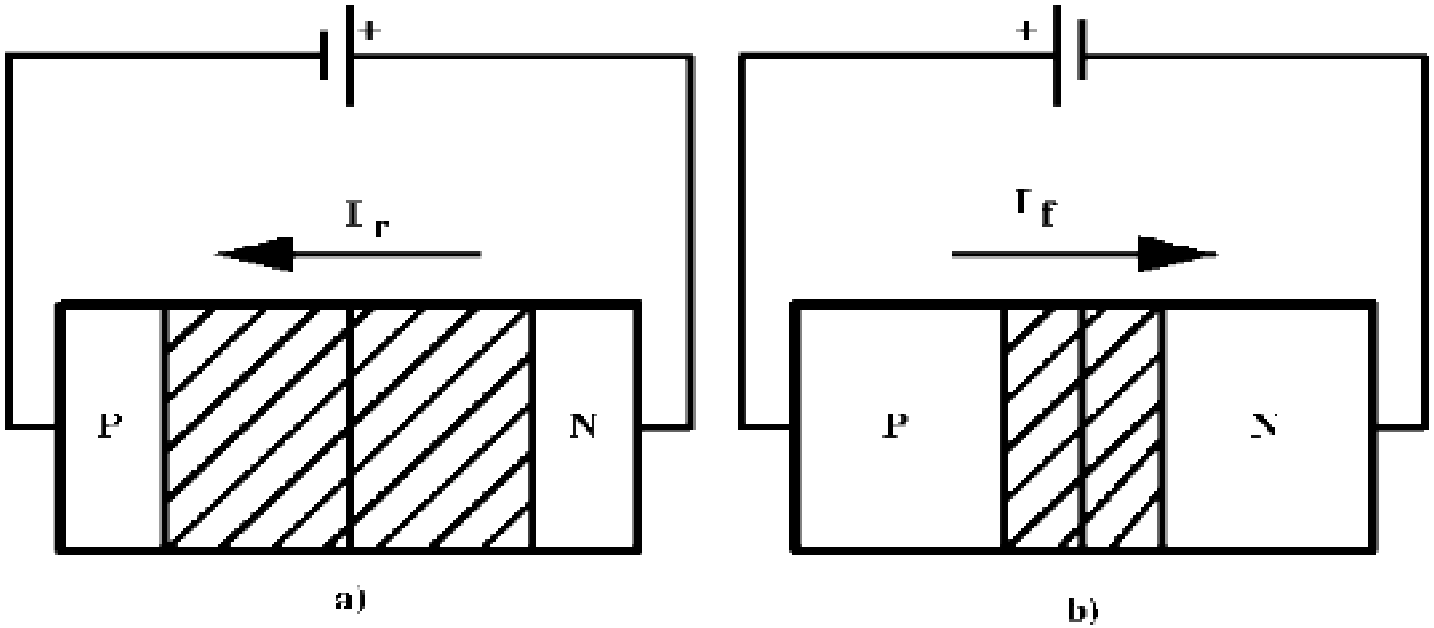


Figure 2: Diode circuit connections: a) reversed biased and b) forward biased.

An approximation to the current in the PN junction region is given by (shown in figure 3a)

$$I = I_o(e^{V/V_T} - 1)$$

where both I_O and V_T are temperature dependent. This equation gives a reasonably accurate prediction of the current-voltage relationship of the PN junction itself - especially the temperature variation - and can be improved somewhat by choosing I_O and V_T empirically to fit a particular diode. However, for a real diode, other factors are also important: in particular, edge effects around the border of the junction cause the actual reverse current to increase slightly with reverse voltage, and the finite conductivity of the doped semi-conductor ultimately restricts the forward current to a linear increase with increasing applied voltage. A better current-voltage curve for the real diode is shown in the figure 3b.

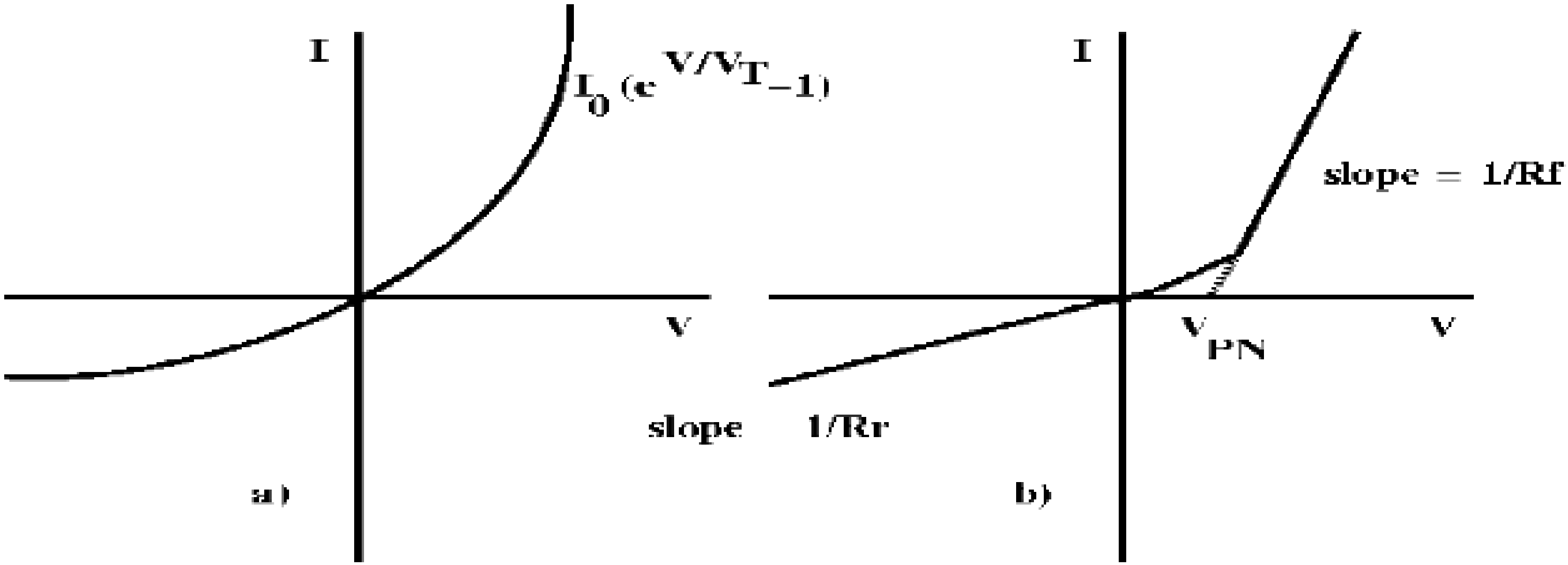


Figure 3: Current versus voltage a) in the PN junction region and b) for an actual PN diode.

Various regions of the curve can be identified: the linear region of forward-biasing, a non-linear transition region, a turn-on voltage (V_{PN}) and a reverse-biased region.

We can assign a dynamic resistance to the diode in each of the linear regions: R_f in the forward-biased region and R_r in the reverse-biased region. These resistances are defined as the inverse slope of the curve: $I / R = \Delta I / \Delta V$

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The voltage V_{PN}, represents the effective voltage drop across a forward-biased PN junction (the turn-on voltage).

For a germanium diode, V_{PN} is approximately 0.3 V, while for a silicon diode it is close to 0.6 V.

The PN Diode as a Circuit Element

Diodes are referred to as non-linear circuit elements because of the above characteristic curve. For most applications the non-linear region can be avoided and the device can be modeled by piece-wise linear circuit elements. Qualitatively we can just think of an ideal diode has having two regions: a conduction region of zero resistance and an infinite resistance non-conduction region. For many circuit applications, this ideal diode model is an adequate representation of an actual diode and simply requires that the circuit analysis be separated into two parts: forward current and reverse current. Figure 4 shows a schematic symbol for a diode and the current-voltage curve for an ideal diode.

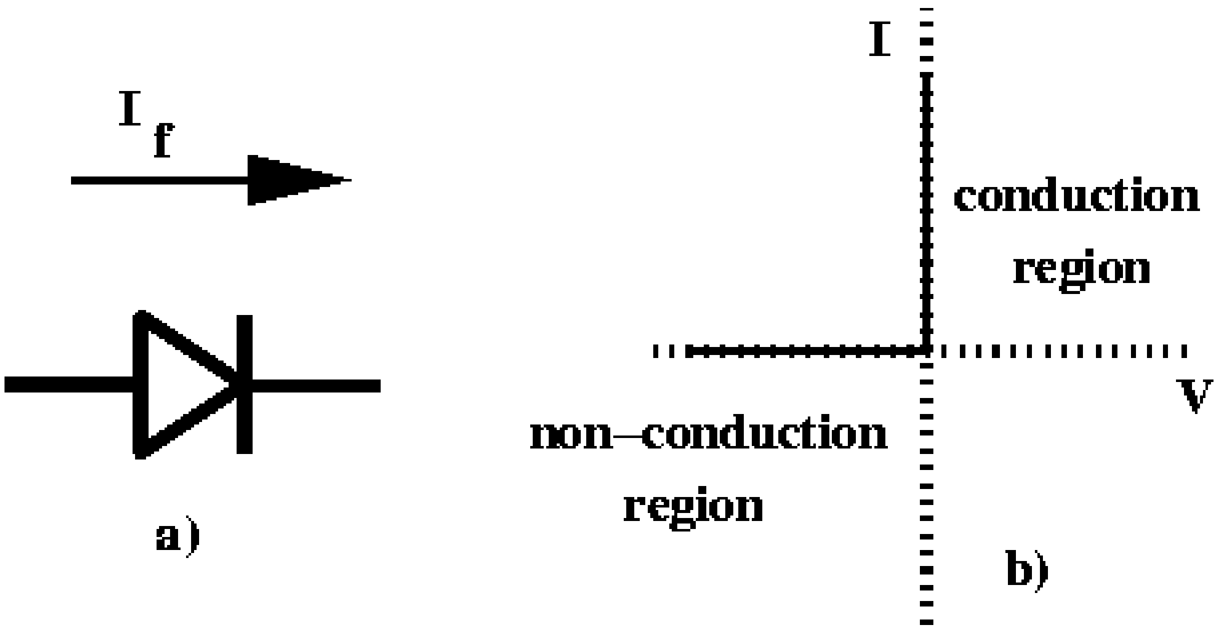


Figure 4: a) Schematic symbol for a diode and b) current versus voltage for an ideal diode.

A diode can more accurately be described using the equivalent circuit model shown in figure 5.
If a diode is forward biased with a high voltage it acts like a resistor (R_f) in series with a voltage source (V_{PN}). For reverse biasing it acts simply as a resistor (R_r). These approximations are referred to as the **linear element model of a diode**.

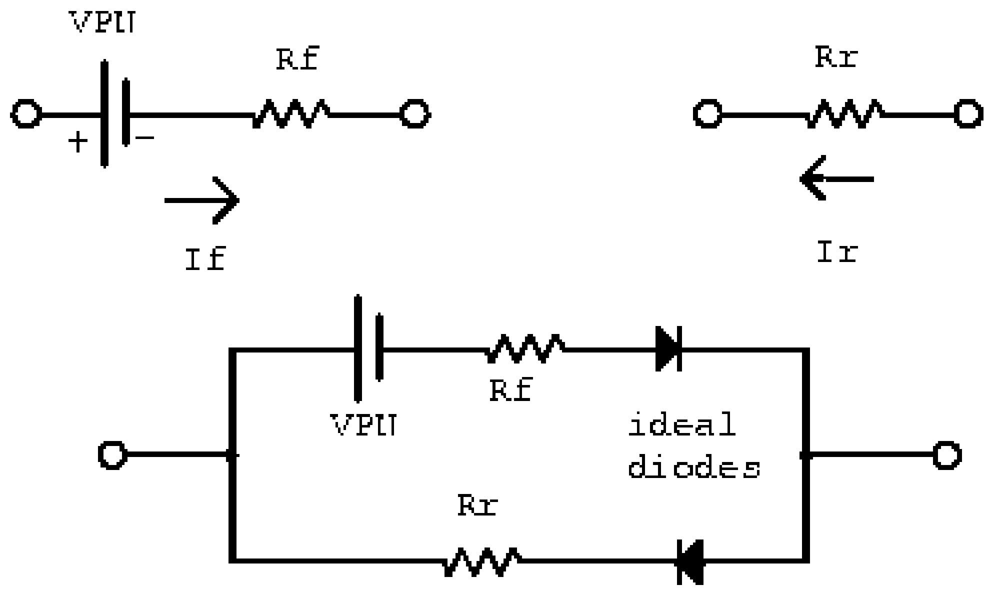


Figure 5: Equivalent circuit model of a junction diode.

The Zener Diode

There are several other types of diodes beside the junction diode. As the reverse voltage increases the diode can avalanche-breakdown (zener breakdown). This causes an increase in current in the reverse direction. *Zener breakdown* occurs when the electric field near the junction becomes large enough to excite valence electrons directly into the conduction band. *Avalanche breakdown* is when the minority carriers are accelerated in the electric field near the junction to sufficient energies that they can excite valence electrons through collisions. Figure 6 shows the current-voltage characteristic of a zener diode, its schematic symbol and equivalent circuit model in the reverse-bias direction. The best zener diodes have a breakdown voltage (V_Z) of 6-7 V.

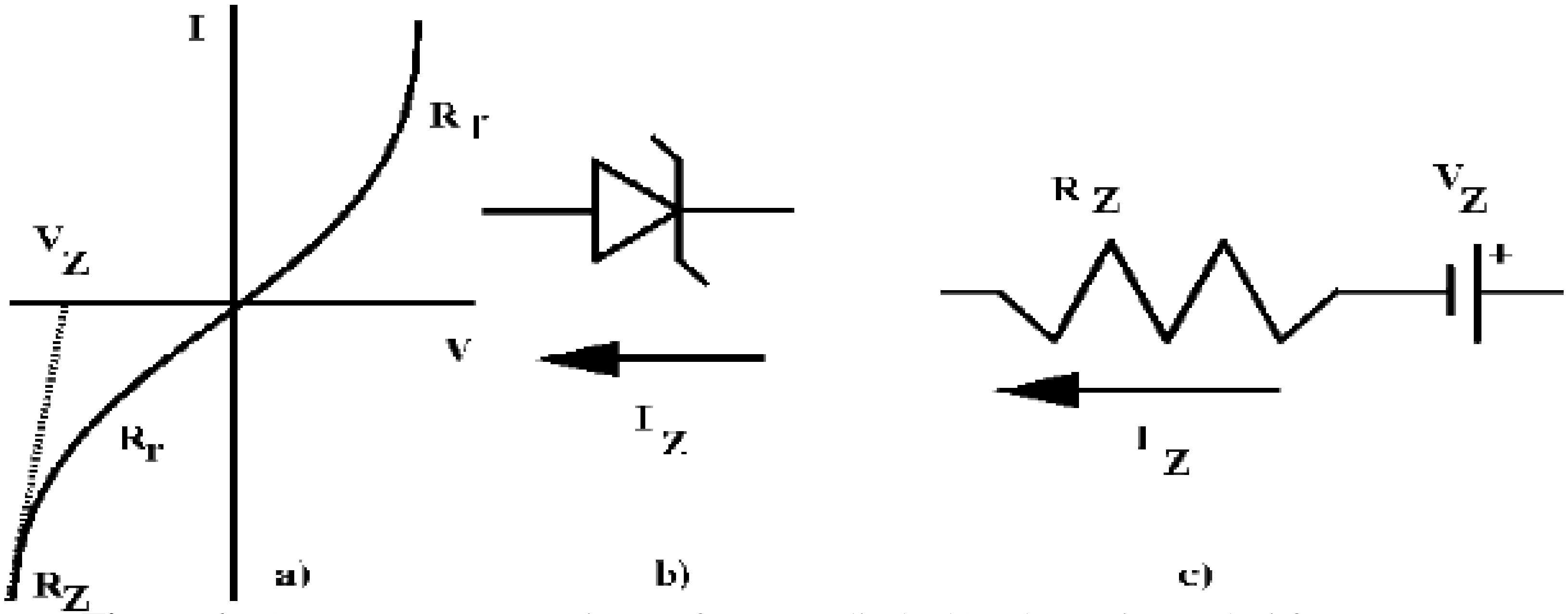


Figure 6: a) Current versus voltage of a zener diode, b) schematic symbol for a zener diode and c) equivalent circuit model of a zener diode in the reverse-bias direction.

Light-Emitting Diodes

Light-emitting diodes (LED) emit light in proportion to the forward current through the diode. LEDs are low voltage devices that have a longer life than incandescent lamps.
They respond quickly to changes in current (10 MHz). LEDs have applications in optical-fiber communication and diode lasers. They produce a narrow spectrum of coherent red or infrared light that can be well collimated.

As an electron in the conduction band recombines with a hole in the valence band, the electron makes a transition to a lower-lying energy state and releases energy in an amount equal to the band-gap energy.
Normally the energy heats the material. In an LED this energy goes into emitted infrared or visible light.

Light-Sensitive Diodes

If light of the proper wavelength is incident on the depletion region of a diode while a reverse voltage is applied, the absorbed photons can produce additional electron-hole pairs.
Photo-diodes or photocells can receive frequency-modulated light signals. LEDs and photodiodes are often used in optica

Circuit Applications of Ordinary Diodes

Lets briefly discuss some applications of ordinary diodes. For many circuits only the basic diode effect is of any significance and these circuits can be analyzed under the assumption that the diode is an ideal device.

Power Supplies

Batteries are often shown on a schematic diagram as the source of DC voltage but usually the actual DC voltage source is a power supply. A more reliable method of obtaining DC power is to transform, rectify, filter and regulate an AC line voltage. Power supplies make use of simple circuits which we will discuss presently.

DC power supplies are often constructed using a common inexpensive three-terminal regulator. These regulators are integrated circuits consisting of several solid state devices and are designed to provide the desirable attributes of temperature stability, output current limiting and thermal overload protection.

In power supply applications it is common to use a transformer to isolate the power supply from the 110 -220 V AC line. A rectifier can be connected to the transformer secondary to generate a DC voltage with little AC ripple. The object of any power supply is to reduce the *ripple* which is the periodic variation in voltage about the steady value.

Rectification

Figure 7 shows a half-wave rectifier circuit. The signal is exactly the top half of the input voltage signal, and for an ideal diode does not depend at all on the size of the load resistor.

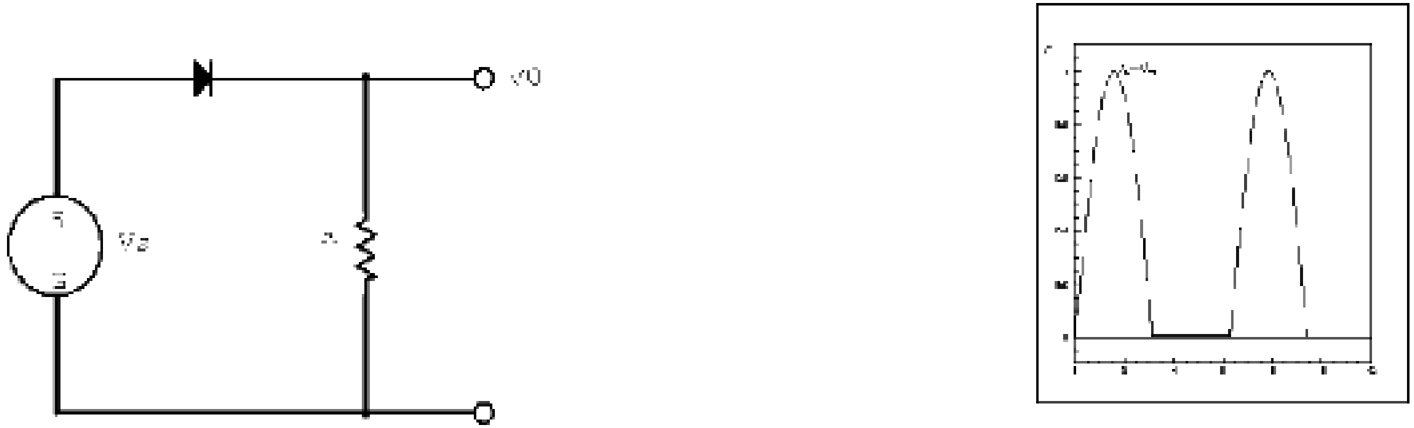


Figure 7: Half-wave rectifier and its output waveform.

The rectified signal is now a combination of an AC signal and a DC component. Generally, it is the DC part of a rectified signal that is of interest, and the un-welcomed AC component is described as ripple. It is desirable to move the ripple to high frequencies where it is easier to remove by a low-pass filter.

When diodes are used in small-signal applications - a few volts - their behaviour is not closely approximated by the ideal model because of the PN turn-on voltage. The equivalent circuit model can be used to evaluate the detailed action of the rectifier under these conditions.

During the part of the wave when the input is positive but less than the PN turn-on voltage, the model predicts no loop current and the output signal voltage is therefore zero. When the input exceeds this voltage, the output signal becomes proportional to v_S-V_{PN} , or about 0.6 V lower than the source voltage.

The diode bridge circuit shown in figure 8 is a full-wave rectifier. The diodes act to route the current from both halves of the AC wave through the load resistor in the same direction, and the voltage developed across the load resistor becomes the rectified output signal. The diode bridge is a commonly used circuit and is available as a four-terminal component in a number of different power and voltage ratings.

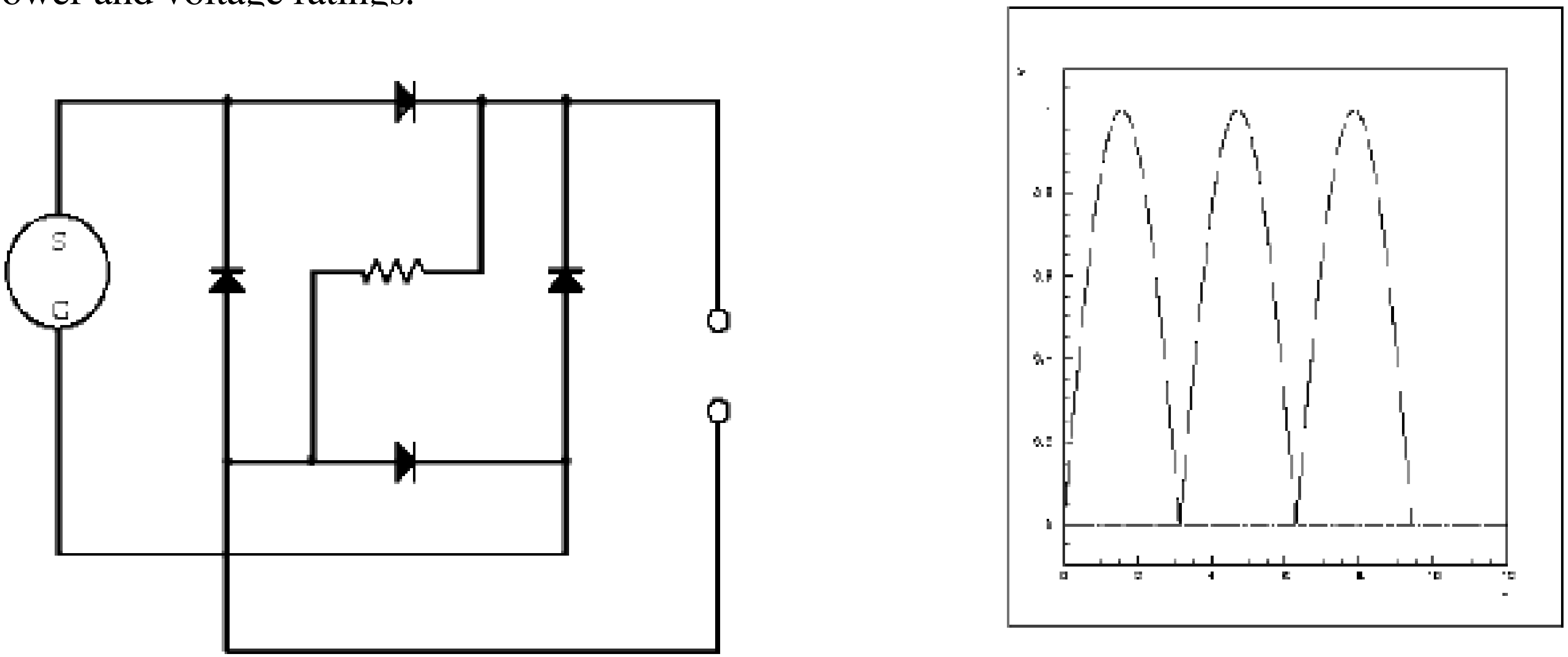


Figure 8: Full-wave rectifier and its output waveform.

Power Supply Filtering

The rectified waveforms still have a lot of ripple that has to be smoothed out in order to generate a genuine DC voltage. This we do by tacking on a low-pass filter. The capacitor value is chosen in order to ensure small ripple, by making the time constant for discharging much longer than the time between re-charging.

Split Power Supply

Often a circuit requires a power supply that provides negative voltage as well as positive voltage. By reversing the direction of the diode and the capacitor (if it is polarized), the half-wave rectification circuit with low-pass filter provides a negative voltage. Similarly, reversing the direction of the diodes and capacitor in the full-wave rectified supply produces a negative voltage supply. A split power supply is shown in figure 9.

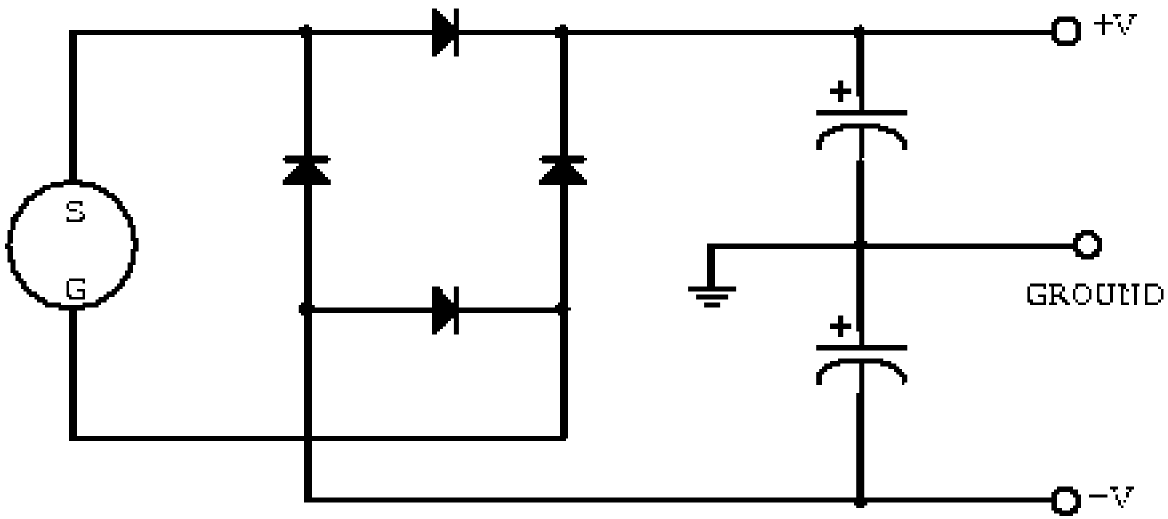


Figure 9: Split power supplies.

Voltage Multiplier

A voltage multiplier circuit is shown in figure 10. We can think of it as two half-wave rectifier circuits in series. During the positive half-cycle one of the diodes conducts and charges a capacitor. During the negative half-cycle the other diode conducts negatively to charge the other capacitor. The voltage across the combination is therefore equal to twice the peak voltage. In this type of circuit we have to assume that the load does not draw a significant charge from the capacitors.

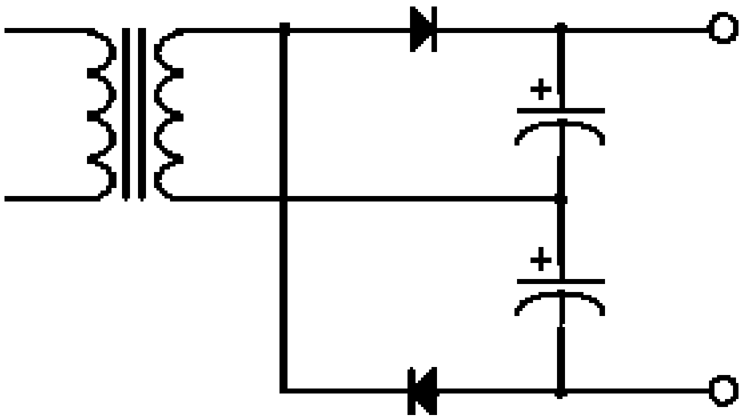
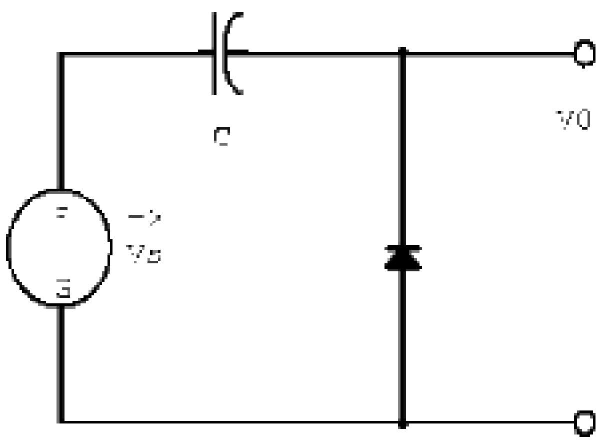


Figure 10: Voltage doubler circuit.

Clamping

When a signal drives an open-ended capacitor the average voltage level on the output terminal of the capacitor is determined by the initial charge on that terminal and may therefore be quite unpredictable. Thus it is necessary to connect the output to ground or some other reference voltage via a large resistor. This action drains any excess charge and results in an average or DC output voltage of zero.

A simple alternative method of establishing a DC reference for the output voltage is by using a diode clamp as shown in figure 11. By conducting whenever the voltage at the output terminal of the capacitor goes negative, this circuit builds up an average charge on the terminal that is sufficient to prevent the output from ever going negative. Positive charge on this terminal is effectively trapped.



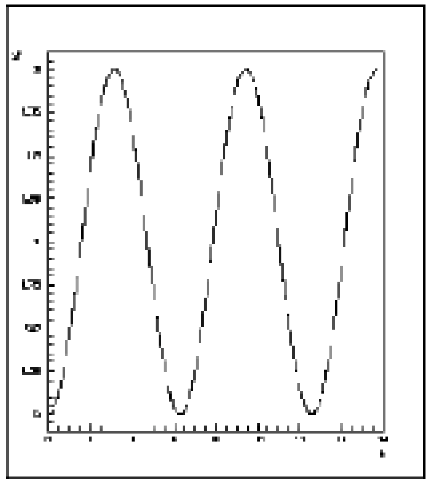
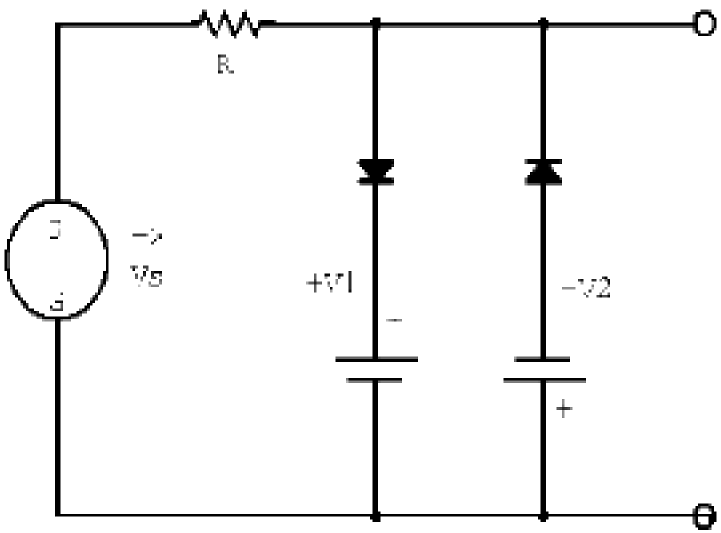


Figure 4.11: Diode clamp circuit and its output waveform.

Clipping

A diode clipping circuit can be used to limit the voltage swing of a signal. Figure 12 shows a diode circuit that clips both the positive and negative voltage swings to references voltages.



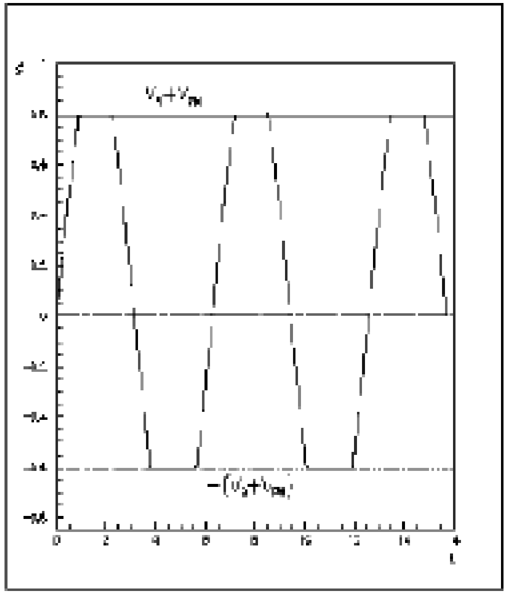


Figure 12: Diode clipping circuit and its output waveform.

Diode Gate

Diodes can also be used to pass the higher of two voltages without affecting the lower. A nifty example is shown in figure 13 The 12 V battery does nothing until the power fails; then it takes over without interruption.

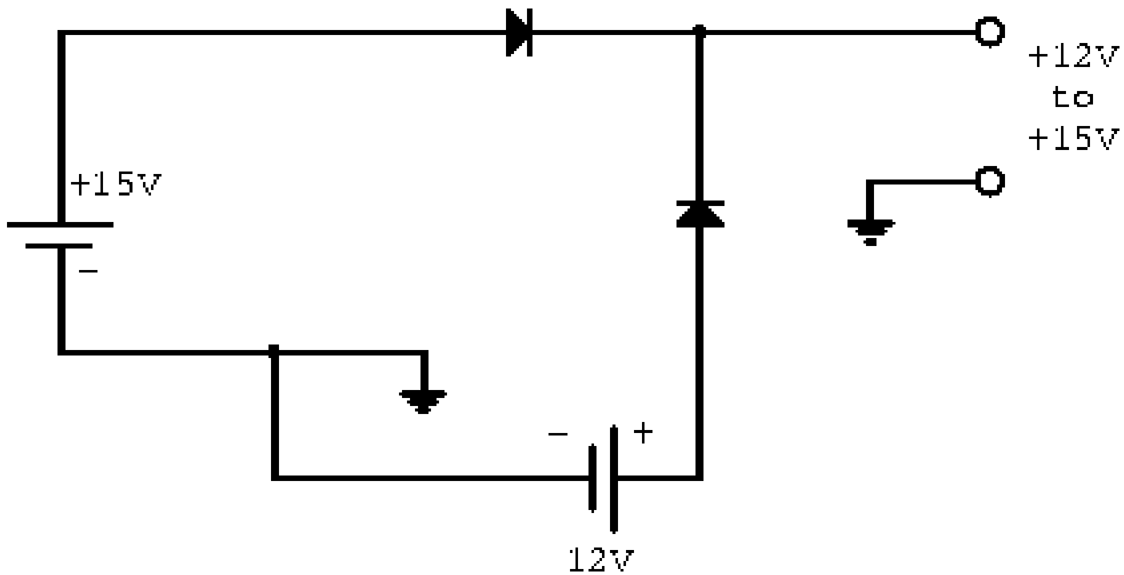


Figure 13: Diode OR gate.

Diode Protection

An important use of diodes is to suppress the voltage surge present when an inductive load is switched out of a circuit - inductive surge suppression. With inductors it is not possible to turn off the current suddenly since the inductor will try to keep the current flowing when the switch is opened.

A diode in a DC circuit or back-to-back zener diodes in an AC circuit can be used to shunt the inductor and prevent it from conducting.

Example: *For each circuit in figure [14](#) sketch the output voltage as a function of time if   V. Assume that the circuit elements are ideal.*

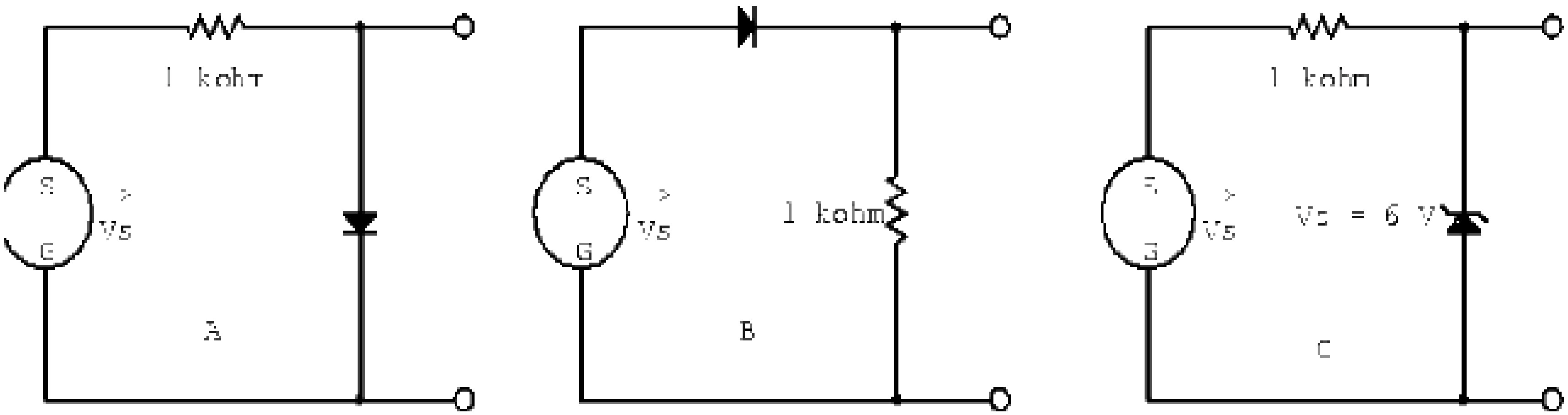
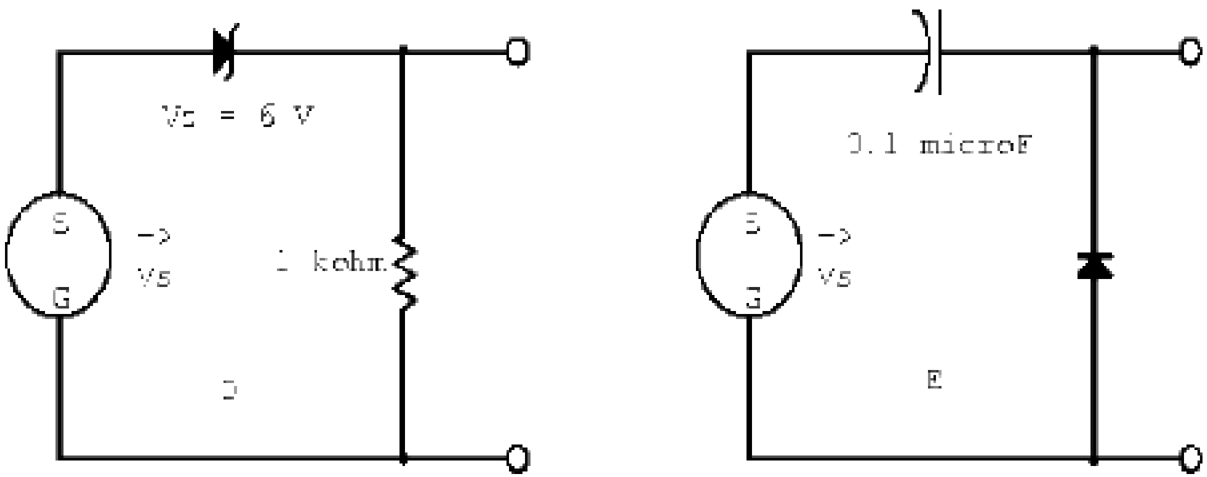


Figure 14: *Circuits with a single ideal diode.*



The forward and reverse biased approximations for the circuit in figure 14a are shown in figure 15 and the output voltage is sketched in figure 20a.

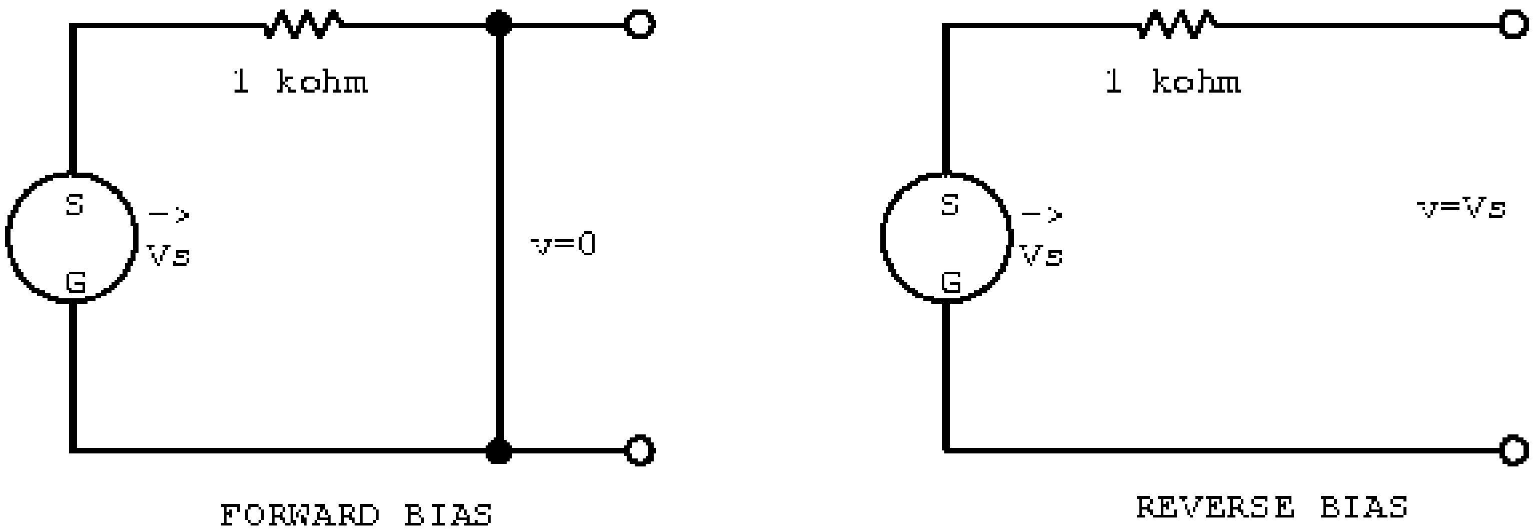


Figure 15: *Single diode circuit a).*

The forward and reverse biased approximations for the circuit in figure 4.14b are shown in figure 4.16 and the output voltage is sketched in figure 4.20b.

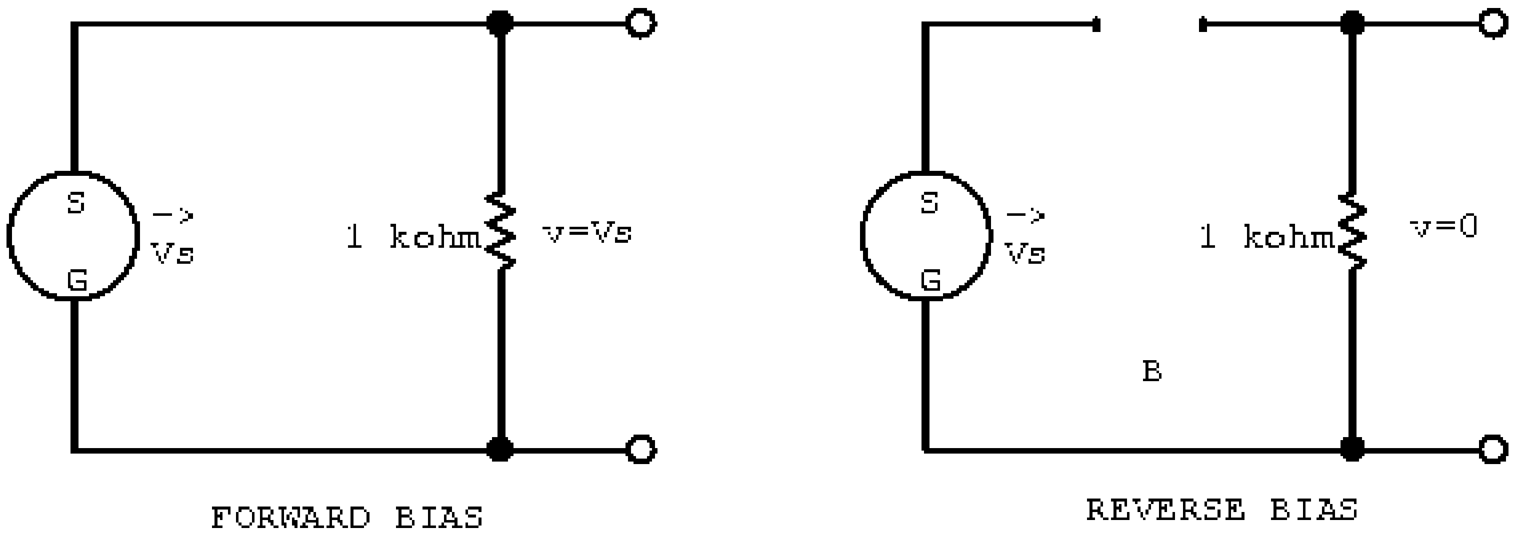


Figure 4.16: *Single diode circuit b).*

The forward and reverse biased approximations for the circuit in figure 14c are shown in figure 17 and the output voltage is sketched in figure 20c.

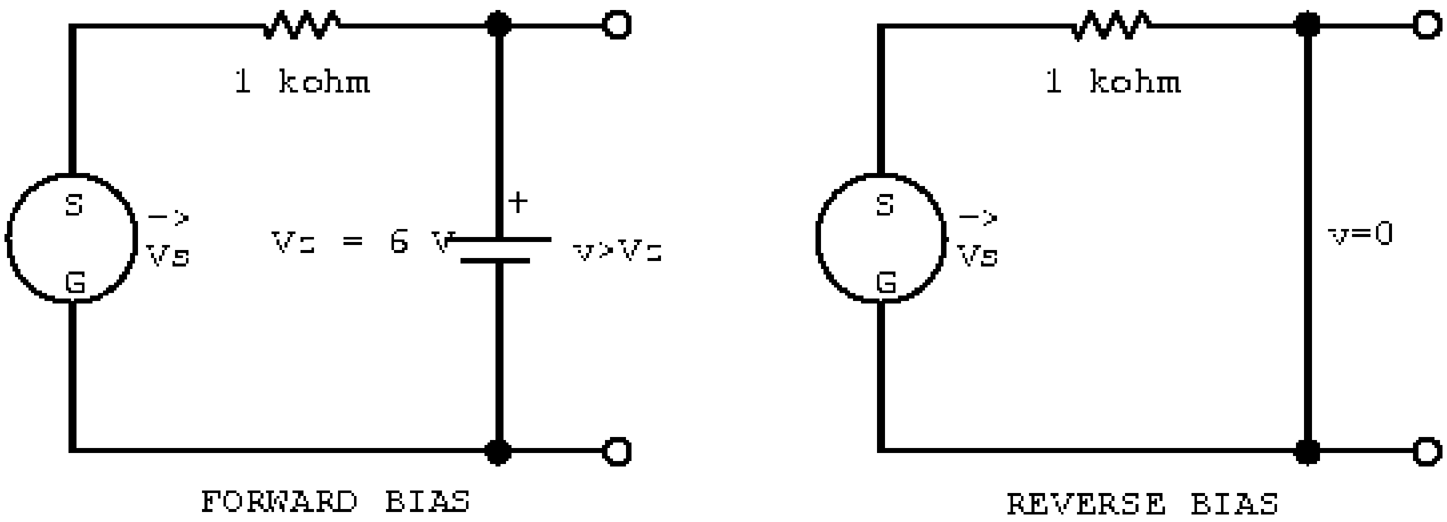


Figure 17: *Single diode circuit c).*

The forward and reverse biased approximations for the circuit in figure 14d are shown in figure 18 and the output voltage is sketched in figure 20d.

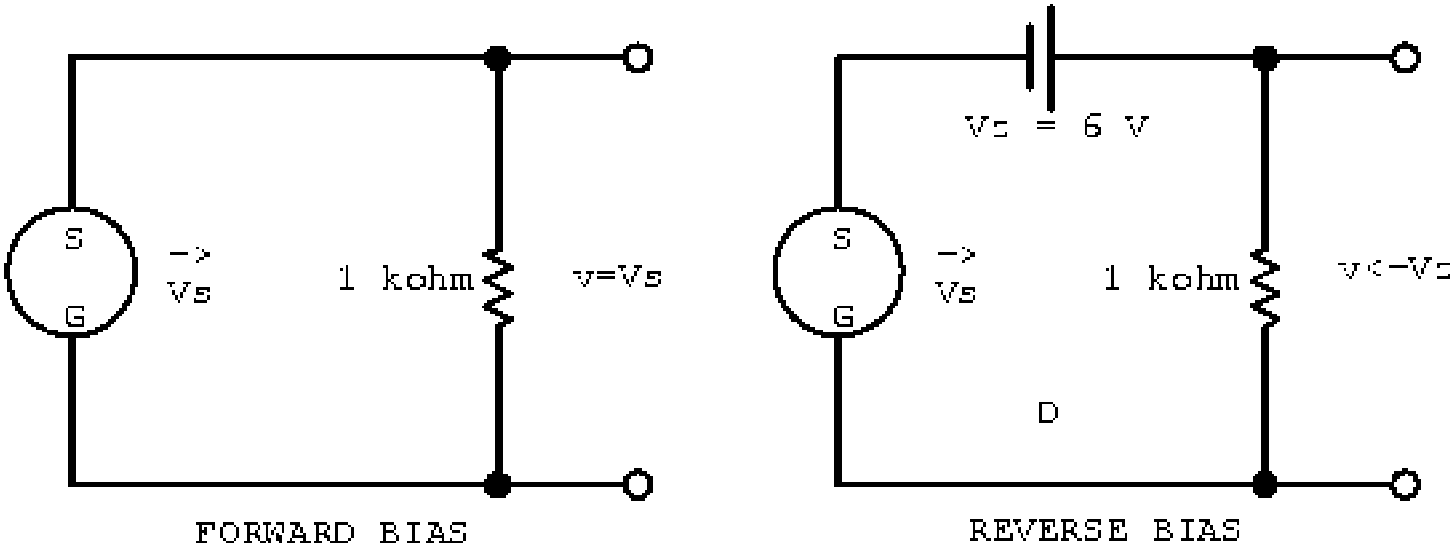


Figure 18: *Single diode circuit d).*

The forward and reverse biased approximations for the circuit in figure 14e are shown in figure 19 and the output voltage is sketched in figure 20e.

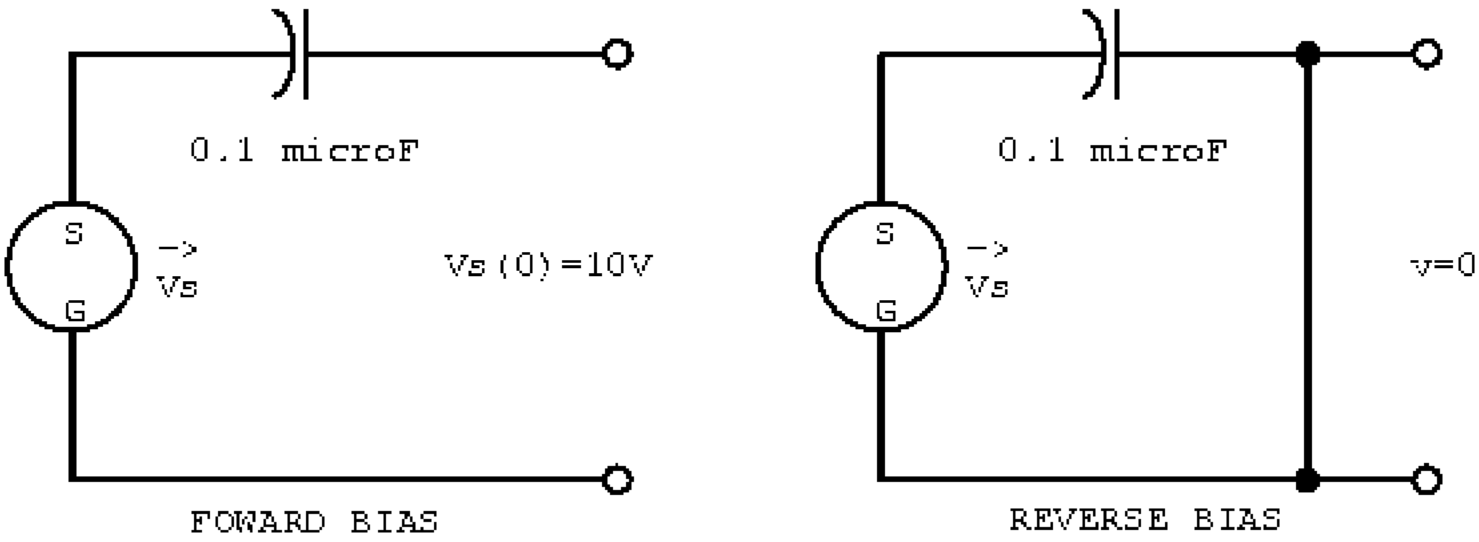


Figure 19: *Single diode circuit e).*

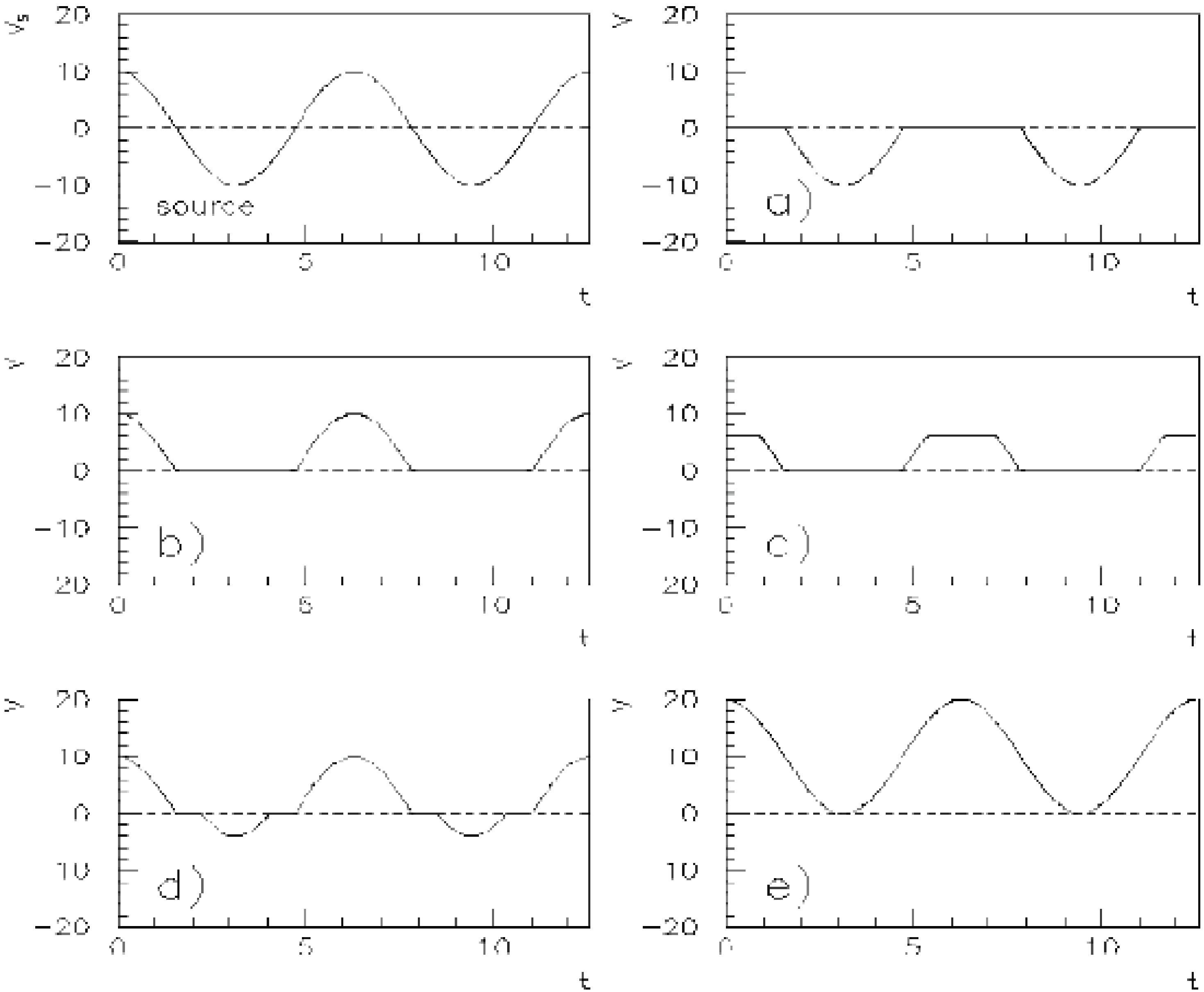


Figure 20: *Sketch of the output voltage as a function of time.*