Fundamentals of Microelectronics

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Chapter 3 Diode Circuits

- 3.1 Ideal Diode
- 3.2 PN Junction as a Diode
- 3.3 Applications of Diodes

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Diode Circuits

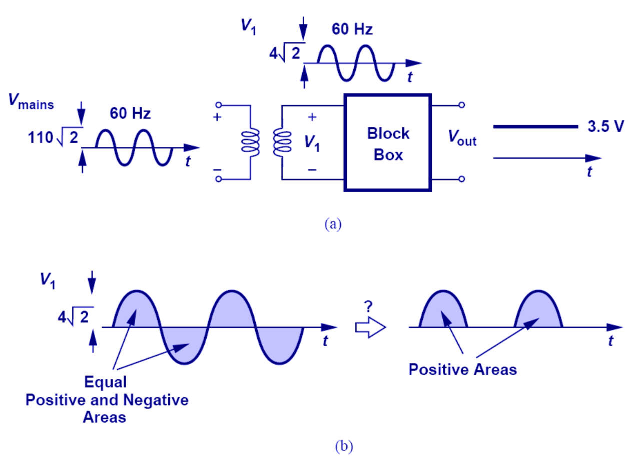
Diodes as Circuit Elements
- Ideal Diode
- Circuit Characteristics
- Actual Diode

⇨

Applications
- Regulators
- Rectifiers
- Limiting and Clamping Circuits

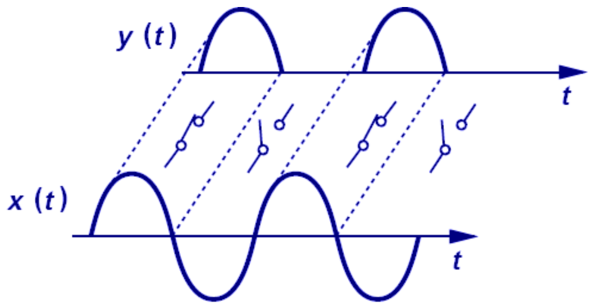
- After we have studied in detail the physics of a diode, it is time to study its behavior as a circuit element and its many applications.

Diode's Application: Cell Phone Charger



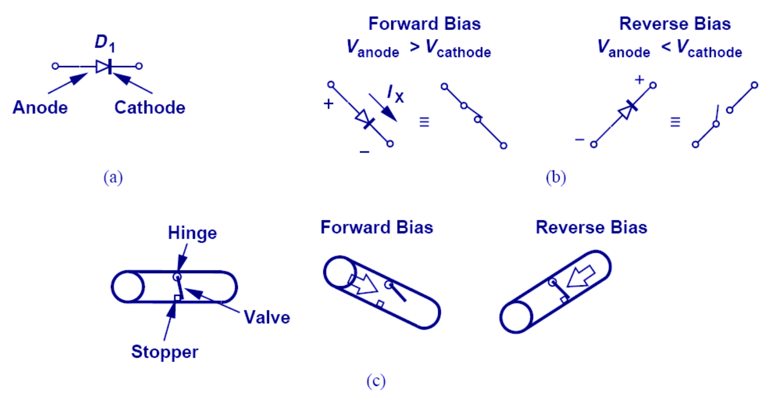
- An important application of diode is chargers.
- Diode acts as the black box (after transformer) that passes only the positive half of the stepped-down sinusoid.

Diode's Action in The Black Box (Ideal Diode)



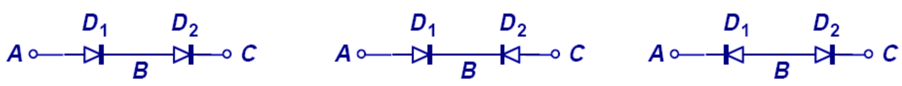
- The diode behaves as a short circuit during the positive half cycle (voltage across it tends to exceed zero), and an open circuit during the negative half cycle (voltage across it is less than zero).

Ideal Diode



- In an ideal diode, if the voltage across it tends to exceed zero, current flows.
- It is analogous to a water pipe that allows water to flow in only one direction.

Diodes in Series

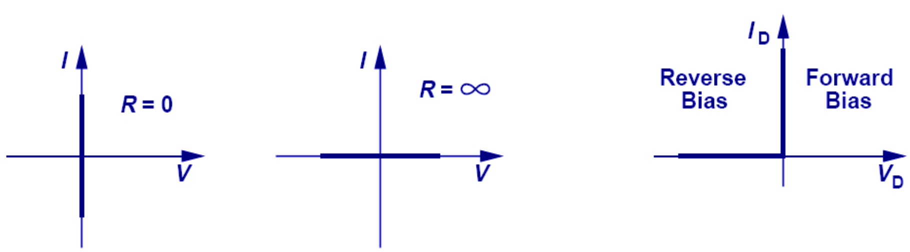


(a) (b) (c)

- Diodes cannot be connected in series randomly. For the circuits above, only a) can conduct current from A to C.

IV Characteristics of an Ideal Diode

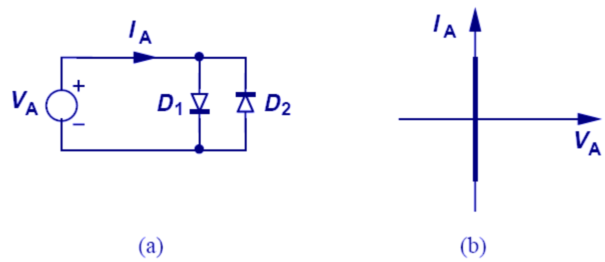
$$R = 0 \Rightarrow I = \frac{V}{R} = \infty \qquad R = \infty \Rightarrow I = \frac{V}{R} = 0$$



(a) (b)

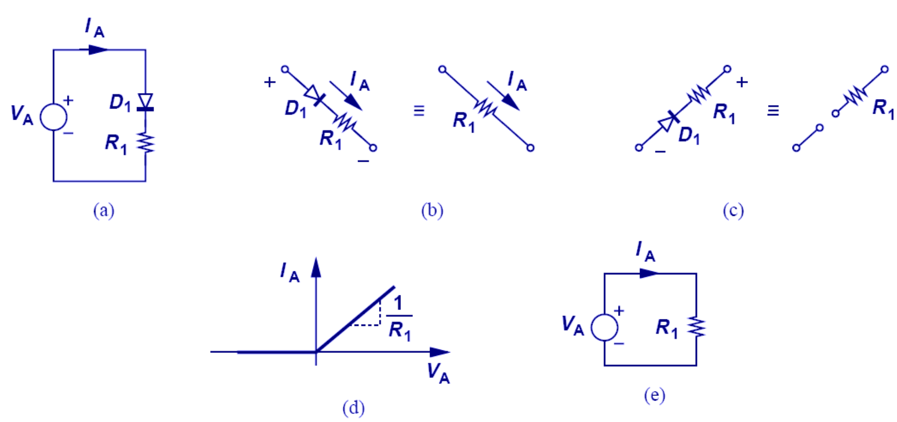
- If the voltage across anode and cathode is greater than zero, the resistance of an ideal diode is zero and current becomes infinite. However, if the voltage is less than zero, the resistance becomes infinite and current is zero.

Anti-Parallel Ideal Diodes



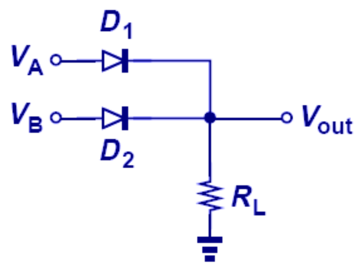
- **If two diodes are connected in anti-parallel, it acts as a short for all voltages.**

Diode-Resistor Combination



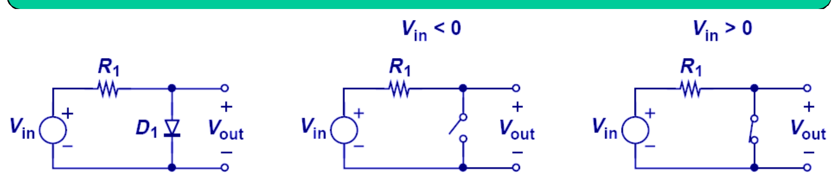
- **The IV characteristic of this diode-resistor combination is zero for negative voltages and Ohm's law for positive voltages.**

Diode Implementation of OR Gate

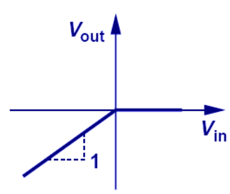


- The circuit above shows an example of diode-implemented OR gate.
- V_{out} can only be either V_A or V_B, not both.

Input/Output Characteristics



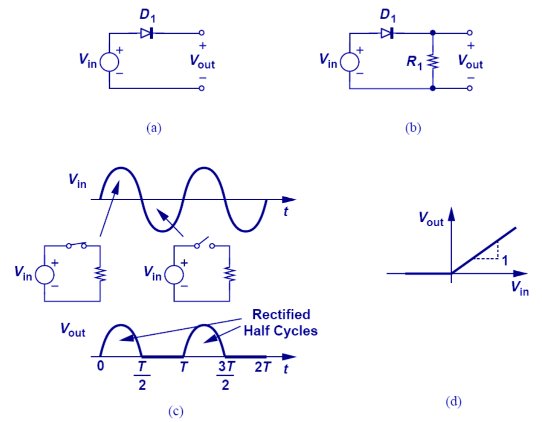
(a) (b) (c)



(d)

- When V_{in} is less than zero, the diode opens, so $V_{out} = V_{in}$.
- When V_{in} is greater than zero, the diode shorts, so $V_{out} = 0$.

Diode's Application: Rectifier



- A rectifier is a device that passes positive-half cycle of a sinusoid and blocks the negative half-cycle or vice versa.
- When Vin is greater than 0, diode shorts, so Vout = Vin; however, when Vin is less than 0, diode opens, no current flows thru R1, Vout = I×R1 = 0.

Signal Strength Indicator

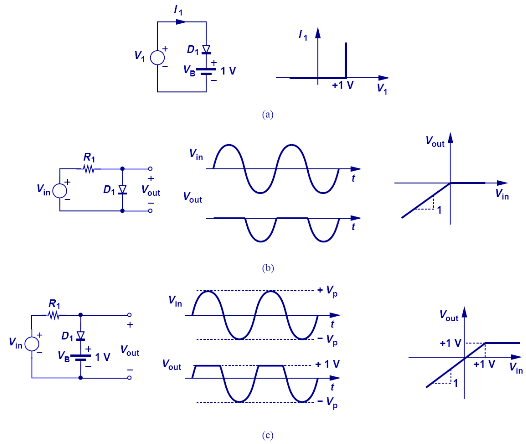
$$V_{out} = V_p \sin \omega t = 0 \qquad for \quad 0 \le t \le \frac{T}{2}$$

$$V_{out,avg} = \frac{1}{T}\int_0^T V_{out}(t)dt = \frac{1}{T}\int_0^{T/2} V_p \sin \omega t dt$$

$$= \frac{1}{T}\frac{V_p}{\omega}\left[-\cos \omega t\right]_0^{T/2} = \frac{V_p}{\pi} \qquad for \quad \frac{T}{2} \le t \le T$$

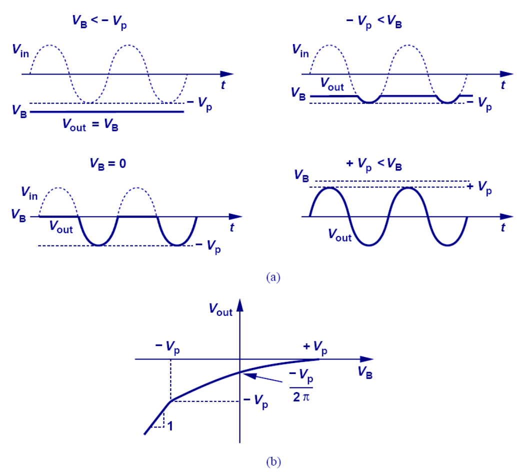
- The averaged value of a rectifier output can be used as a signal strength indicator for the input, since $V_{out,avg}$ is proportional to V_p, the input signal's amplitude.

Diode's application: Limiter



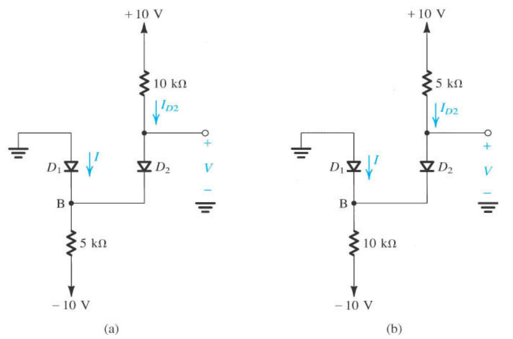
- The purpose of a limiter is to force the output to remain below certain value.
- In a), the addition of a 1 V battery forces the diode to turn on after V1 has become greater than 1 V.

Limiter: When Battery Varies



- An interesting case occurs when VB (battery) varies.
- Rectification fails if VB is greater than the input amplitude.

Diode Example



- Assuming the diodes ideal, find the values of I and V in the circuits above
- In these circuits, it may not be obvious at first sight whether none, one, or both diodes are conducting
- Make a plausible assumption → Proceed with the analysis → Check whether the solution is consistent

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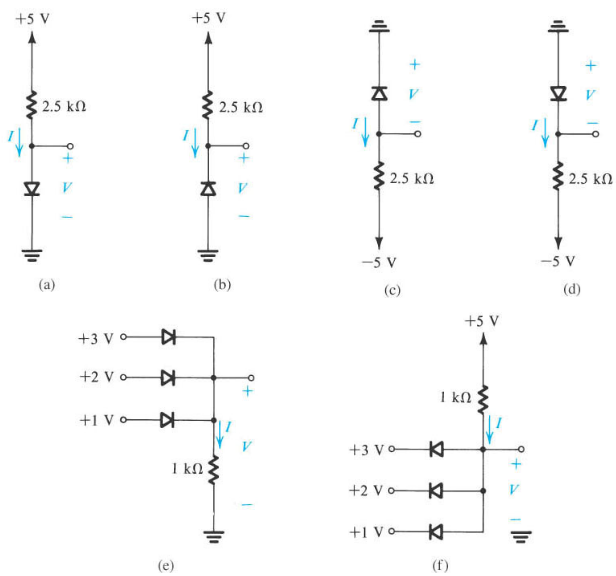
Diode Examples



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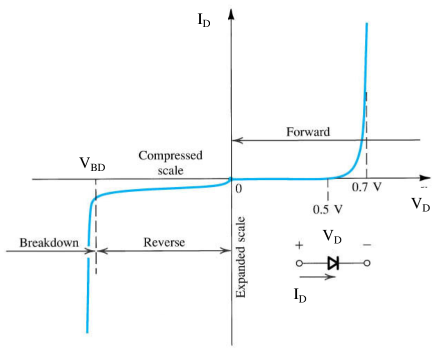
Terminal Characteristics of Junction Diodes



Forward Bias

$I_D = I_S (\exp(V_D/V_T)-1) \approx I_S \exp(V_D/V_T)$

I_S → Saturation current (proportional to surface area of pn junction)

$V_T = kT/q$ → Thermal voltage

k → Boltzmann's constant=1.38 × 10^{-23} joules/Kelvin

T → The absolute temperature in kelvins =273+°C

q → the magnitude of electronic charge = 1.60 × 10^{-19} coulomb

$$V_D = V_T \ln \frac{I_D}{I_S}$$

Three distinct regions

1. $V_D > 0$
2. $V_D < 0$
3. $V_D < V_{BD}$

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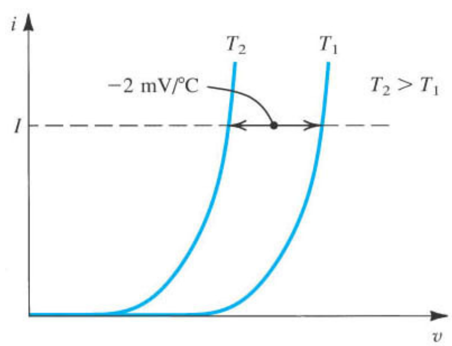
Temperature Dependence of the Diode Forward Characteristics



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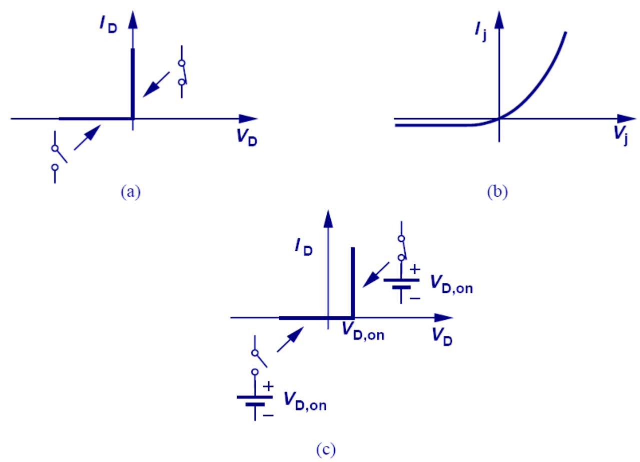
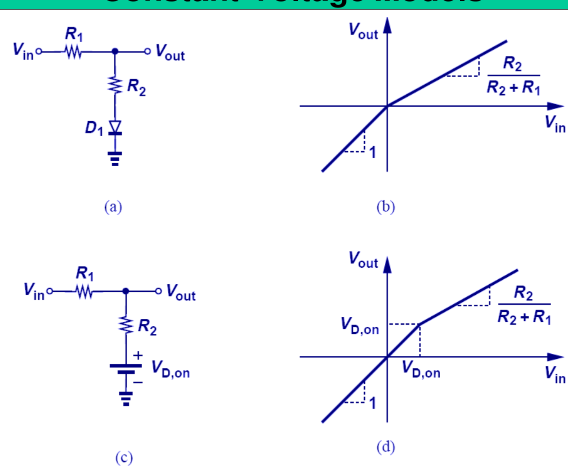
Different Models for Diode



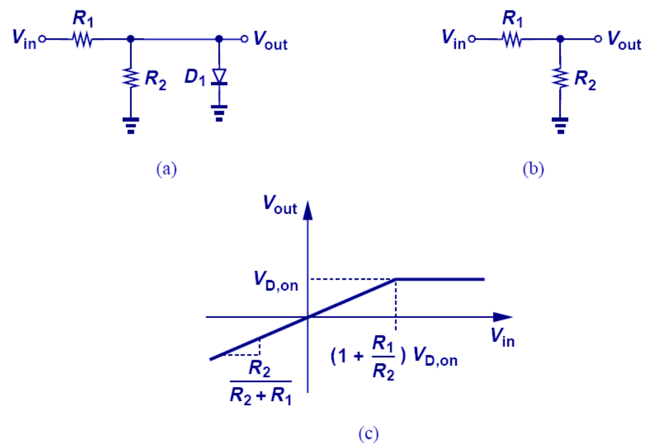
- Thus far, Diode models include the ideal model of diode, the exponential, and constant voltage models.

Input/Output Characteristics with Ideal and Constant-Voltage Models



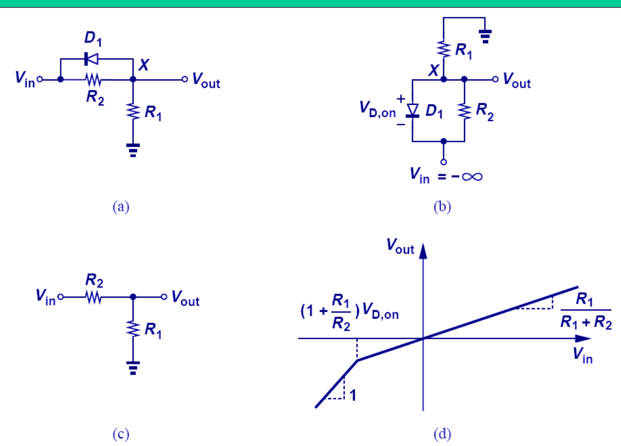
- The circuit above shows the difference between the ideal and constant-voltage model; the two models yield two different break points of slope.

Input/Output Characteristics with a Constant-Voltage Model



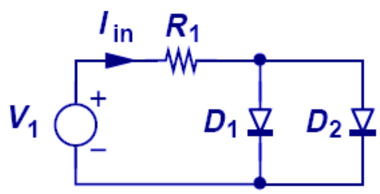
- When using a constant-voltage model, the voltage drop across the diode is no longer zero but $V_{d,on}$ when it conducts.

Another Constant-Voltage Model Example



- In this example, since Vin is connected to the cathode, the diode conducts when Vin is very negative.
- The break point where the slope changes is when the current across R1 is equal to the current across R2.

Exponential Model

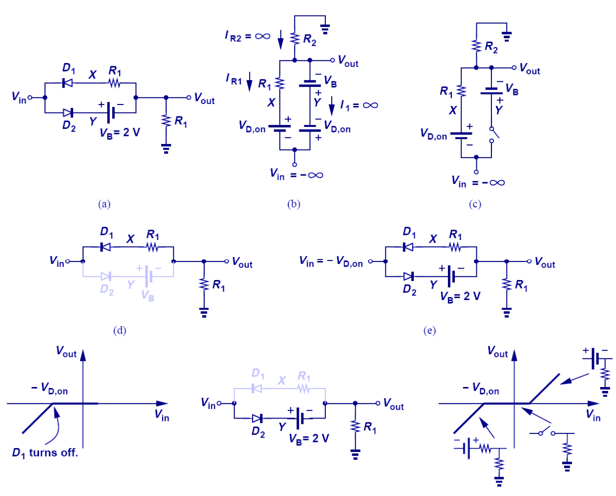


$$I_{D1} = \frac{I_{in}}{1 + \frac{I_{s2}}{I_{s1}}}$$

$$I_{D2} = \frac{I_{in}}{1 + \frac{I_{s1}}{I_{s2}}}$$

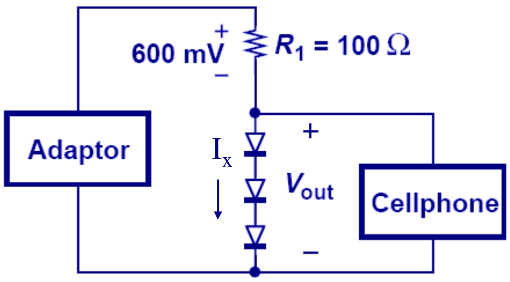
- In this example, since the two diodes have different cross-section areas, only exponential model can be used.
- The two currents are solved by summing them with Iin, and equating their voltages.

Another Constant-Voltage Model Example



- This example shows the importance of good initial guess and careful confirmation.

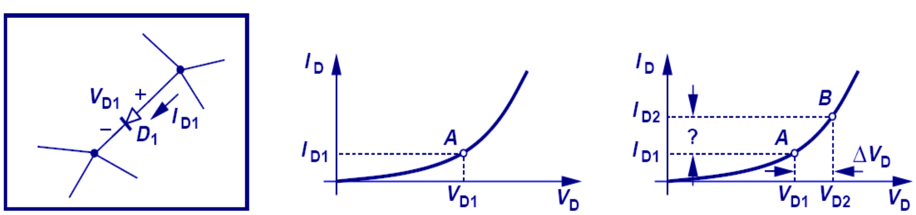
Cell Phone Adapter



$$V_{out} = 3V_D$$
$$= 3V_T \ln \frac{I_X}{I_s}$$

- Vout = 3 VD,on is used to charge cell phones.
- However, if Ix changes, iterative method is often needed to obtain a solution, thus motivating a simpler technique.

Small-Signal Analysis

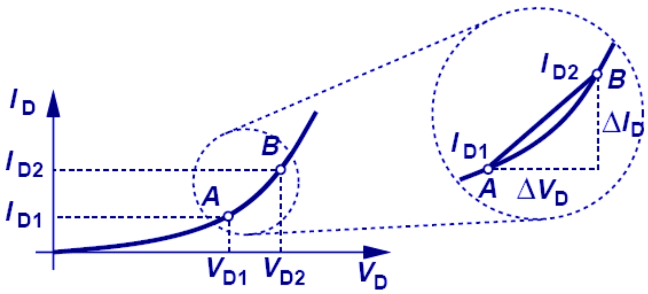


(a) (b) (c)

$$\Delta I_D = \frac{\Delta V}{V_T} I_{D1}$$

- Small-signal analysis is performed around a bias point by perturbing the voltage by a small amount and observing the resulting linear current perturbation.

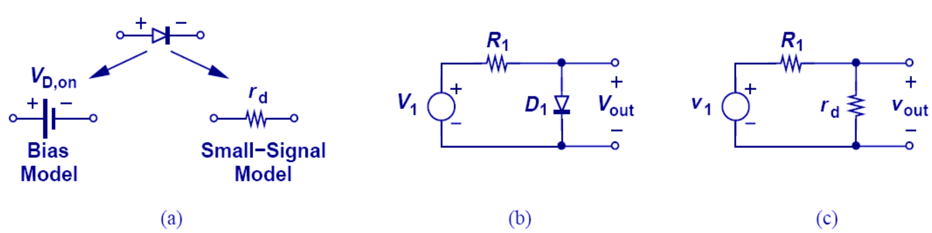
Small-Signal Analysis in Detail



$$\frac{\Delta I_D}{\Delta V_D} = \frac{dI_D}{dV_D}\Big|_{VD=VD1}$$
$$= \frac{I_s}{V_T}\exp\frac{I_{D1}}{V_T}$$
$$= \frac{I_{D1}}{V_T}$$

- If two points on the IV curve of a diode are close enough, the trajectory connecting the first to the second point is like a line, with the slope being the proportionality factor between change in voltage and change in current.

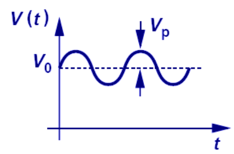
Small-Signal Incremental Resistance



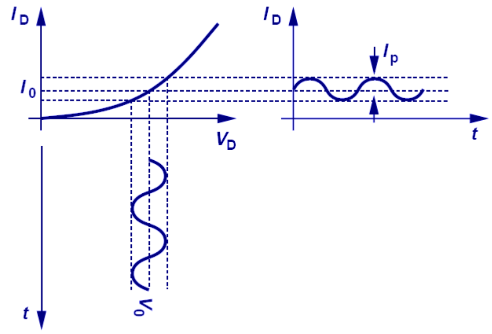
$$r_d = \frac{V_T}{I_D}$$

- Since there's a linear relationship between the small signal current and voltage of a diode, the diode can be viewed as a linear resistor when only small changes are of interest.

Small Sinusoidal Analysis



(a)



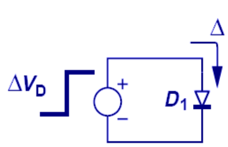
(b)

$$V(t) = V_0 + V_p \cos \omega t$$

$$I_D(t) = I_0 + I_p \cos \omega t = I_s \exp \frac{V_0}{V_T} + \frac{V_T}{I_0} V_p \cos \omega t$$

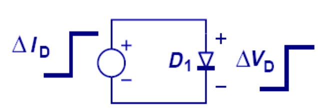
- **If a sinusoidal voltage with small amplitude is applied, the resulting current is also a small sinusoid around a DC value.**

Cause and Effect



(a)

$$\Delta I_D = \frac{\Delta V_D}{r_d} = \Delta V_D \frac{I_{D1}}{V_T}$$

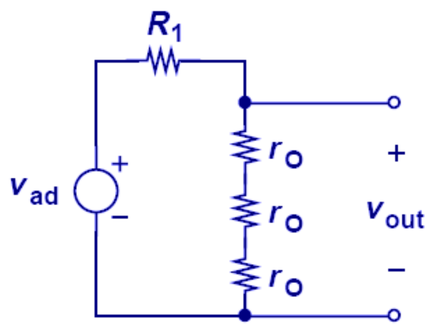


(b)

$$\Delta V_D = \Delta I_D\, r_d = \Delta I_D \frac{V_T}{I_{D1}}$$

- **In (a), voltage is the cause and current is the effect. In (b), the other way around.**

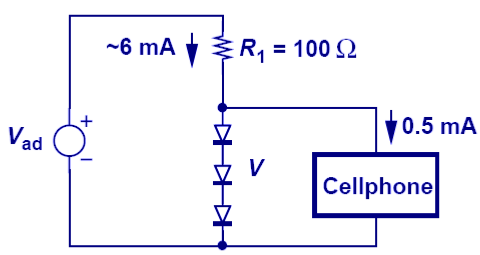
Adapter Example Revisited



$$v_{out} = \frac{3r_d}{R_1 + 3r_d} v_{ad}$$
$$= 11.5mV$$

- With our understanding of small-signal analysis, we can revisit our cell phone charger example and easily solve it with just algebra instead of iterations.

Simple is Beautiful



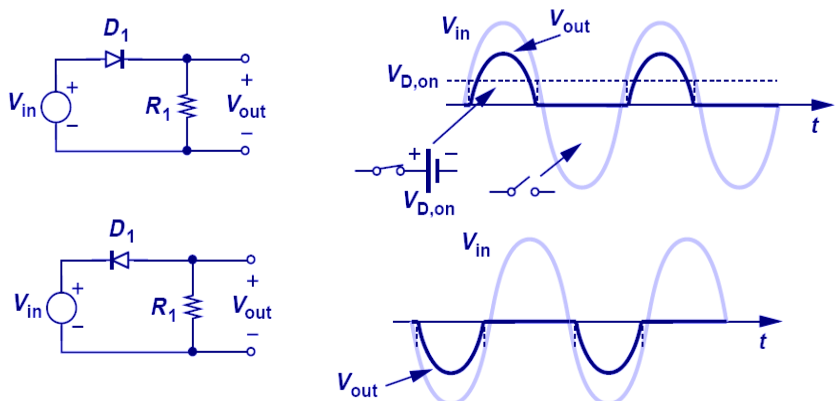
$$\Delta V_{out} = \Delta I_D \cdot (3r_d)$$
$$= 0.5mA(3 \times 4.33\Omega)$$
$$= 6.5mV$$

- In this example we study the effect of cell phone pulling some current from the diodes. Using small signal analysis, this is easily done. However, imagine the nightmare, if we were to solve it using non-linear equations.

Applications of Diode

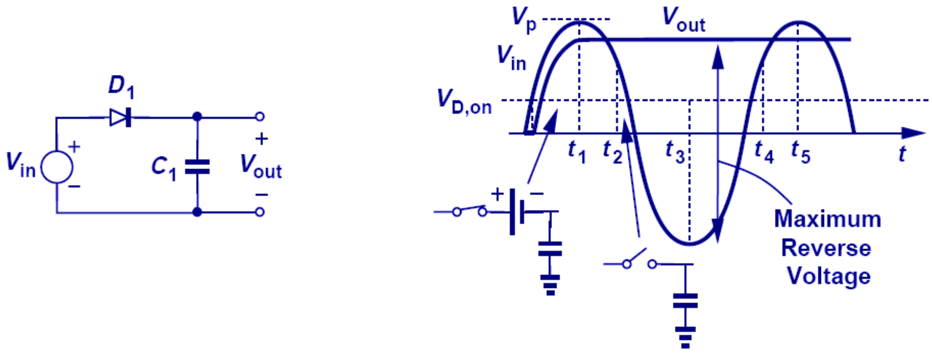
Half−Wave and Full−Wave rectifiers ⇨ Limiting Circuits ⇨ Clamping Circuits ⇨ Regulators ⇨ Voltage Doublers

Half-Wave Rectifier



- A very common application of diodes is half-wave rectification, where either the positive or negative half of the input is blocked.
- But, how do we generate a constant output?

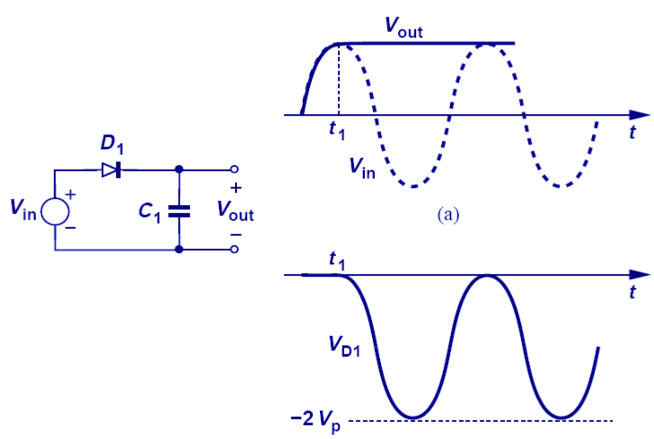
Diode-Capacitor Circuit: Constant Voltage Model



(a) (b)

- If the resistor in half-wave rectifier is replaced by a capacitor, a fixed voltage output is obtained since the capacitor (assumed ideal) has no path to discharge.

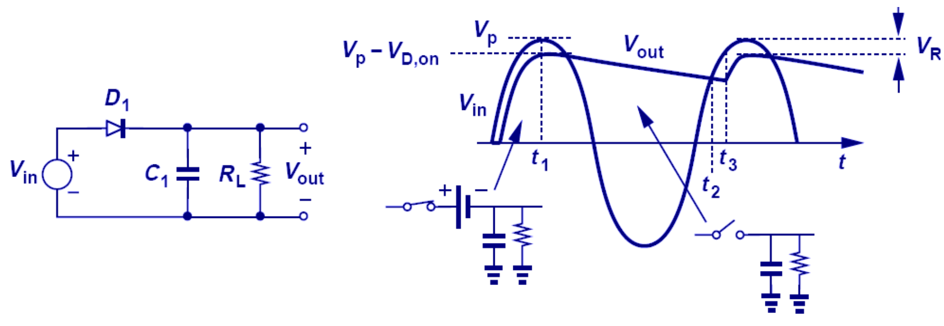
Diode-Capacitor Circuit: Ideal Model



(b)

- Note that (b) is just like Vin, only shifted down.

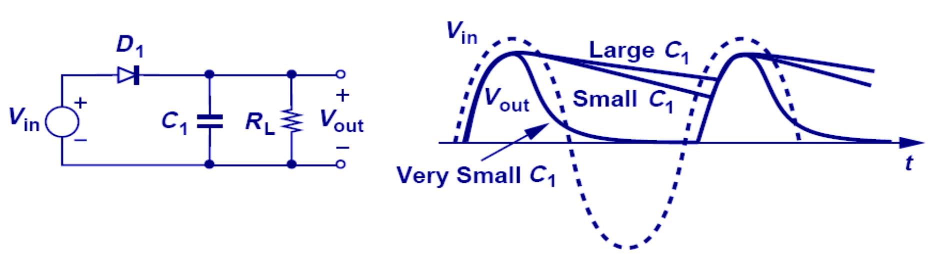
Diode-Capacitor With Load Resistor



(a) (b)

- A path is available for capacitor to discharge. Therefore, Vout will not be constant and a ripple exists.

Behavior for Different Capacitor Values



- For large C1, Vout has small ripple.

Peak to Peak amplitude of Ripple

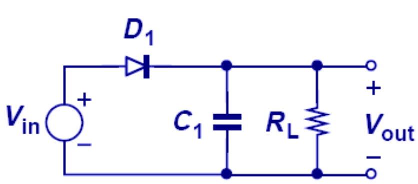
$$V_{out}(t) = (V_p - V_{D,on})\exp\frac{-t}{R_L C_1} \qquad 0 \le t \le T_{in}$$

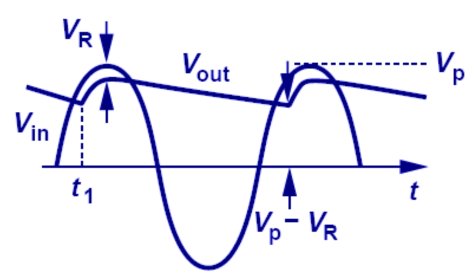
$$V_{out}(t) \approx (V_p - V_{D,on})(1 - \frac{t}{R_L C_1}) \approx (V_p - V_{D,on}) - \frac{V_p - V_{D,on}}{R_L}\frac{t}{C_1}$$

$$V_R \approx \frac{V_p - V_{D,on}}{R_L} \cdot \frac{T_{in}}{C_1} \approx \frac{V_p - V_{D,on}}{R_L C_1 f_{in}}$$

- **The ripple amplitude is the decaying part of the exponential.**
- **Ripple voltage becomes a problem if it goes above 5 to 10% of the output voltage.**

Maximum Diode Current

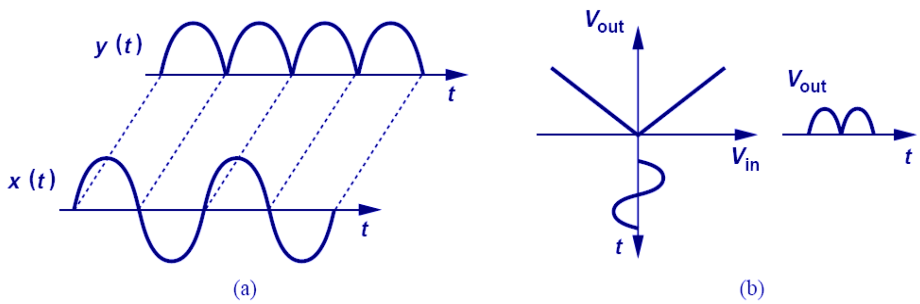




$$I_p \approx C_1 \omega_{in} V_p \sqrt{\frac{2V_R}{V_p}} + \frac{V_p}{R_L} \approx \frac{V_p}{R_L}(R_L C_1 \omega_{in} \sqrt{\frac{2V_R}{V_p}} + 1)$$

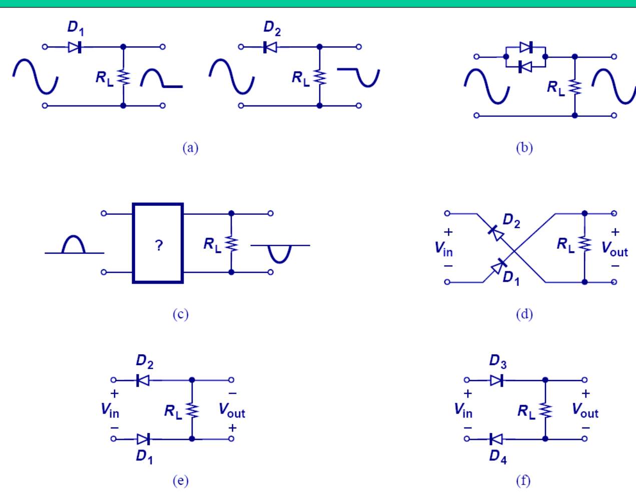
- **The diode has its maximum current at t1, since that's when the slope of Vout is the greatest.**
- **This current has to be carefully controlled so it does not damage the device.**

Full-Wave Rectifier



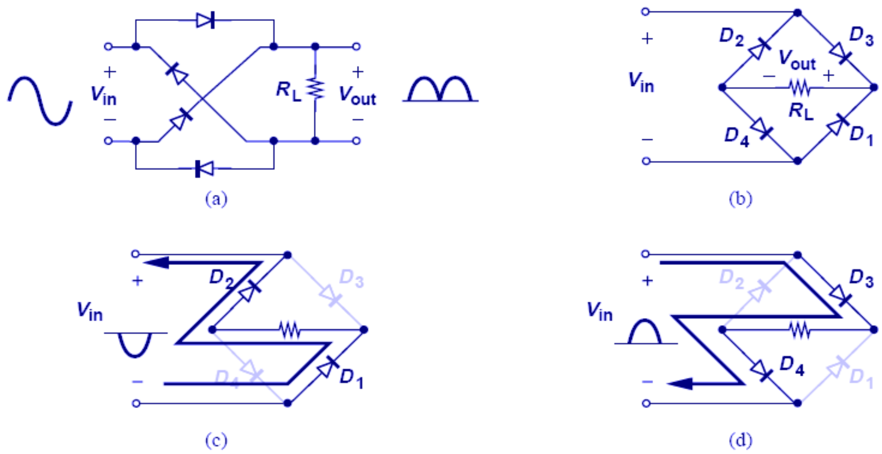
- A full-wave rectifier passes both the negative and positive half cycles of the input, while inverting the negative half of the input.
- As proved later, a full-wave rectifier reduces the ripple by a factor of two.

The Evolution of Full-Wave Rectifier



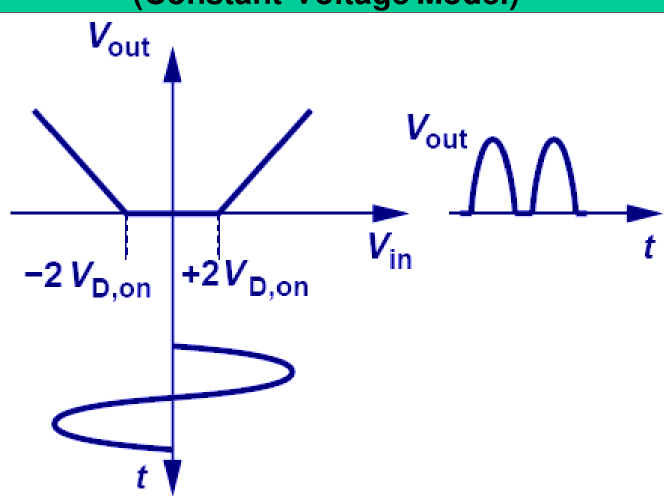
- Figures (e) and (f) show the topology that inverts the negative half cycle of the input.

Full-Wave Rectifier: Bridge Rectifier



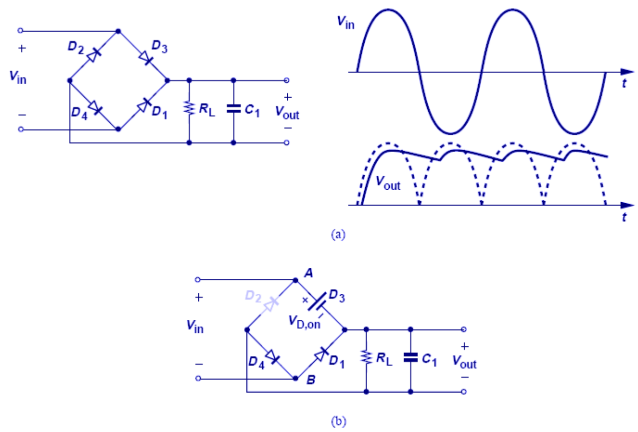
- The figure above shows a full-wave rectifier, where D1 and D2 pass/invert the negative half cycle of input and D3 and D4 pass the positive half cycle.

Input/Output Characteristics of a Full-Wave Rectifier (Constant-Voltage Model)



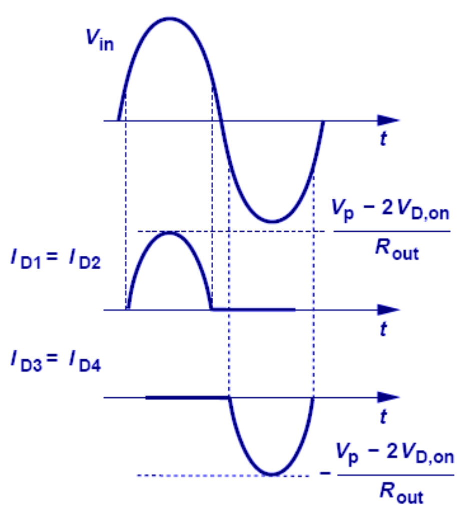
- The dead-zone around V_{in} arises because V_{in} must exceed 2 $V_{D,ON}$ to turn on the bridge.

Complete Full-Wave Rectifier

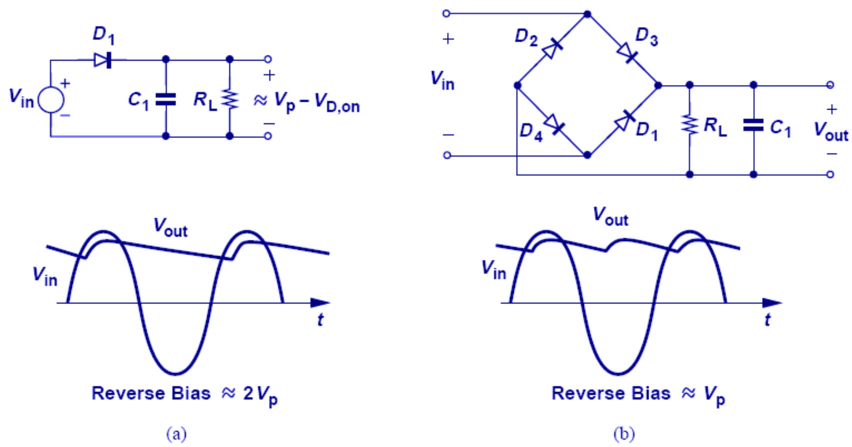


- Since C1 only gets ½ of period to discharge, ripple voltage is decreased by a factor of 2. Also (b) shows that each diode is subjected to approximately one Vp reverse bias drop (versus 2Vp in half-wave rectifier).

Current Carried by Each Diode in the Full-Wave Rectifier

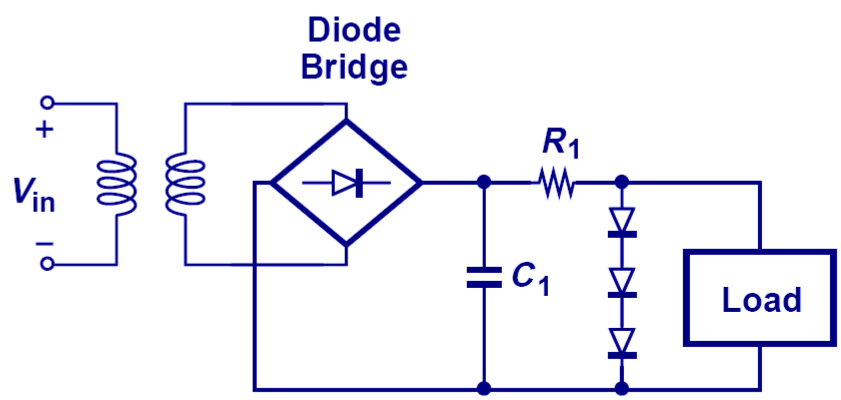


Summary of Half and Full-Wave Rectifiers



- Full-wave rectifier is more suited to adapter and charger applications.

Voltage Regulator



- The ripple created by the rectifier can be unacceptable to sensitive load; therefore, a regulator is required to obtain a very stable output.
- Three diodes operate as a primitive regulator.

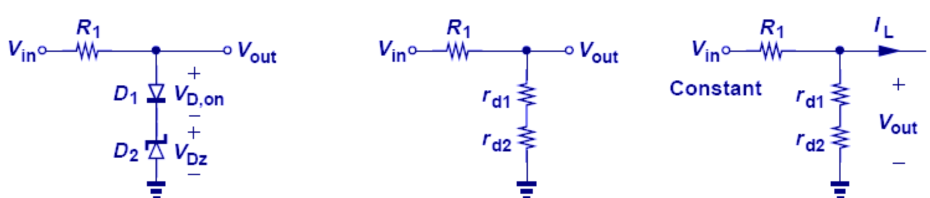
Voltage Regulation With Zener Diode

(a) (b)

$$V_{out} = \frac{r_D}{r_D + R_1} V_{in}$$

- **Voltage regulation can be accomplished with Zener diode. Since rd is small, large change in the input will not be reflected at the output.**

Line Regulation VS. Load Regulation



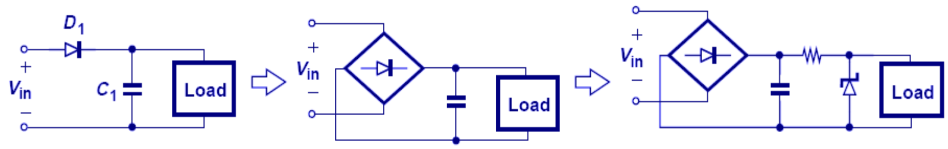
(a) (b) (c)

$$\frac{V_{out}}{V_{in}} = \frac{r_{D1} + r_{D2}}{r_{D1} + r_{D2} + R_1}$$

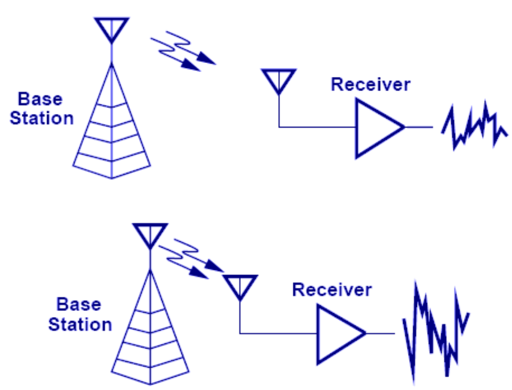
$$\left|\frac{V_{out}}{I_L}\right| = (r_{D1} + r_{D2}) \parallel R_1$$

- **Line regulation is the suppression of change in Vout due to change in Vin (b).**
- **Load regulation is the suppression of change in Vout due to change in load current (c).**

Evolution of AC-DC Converter

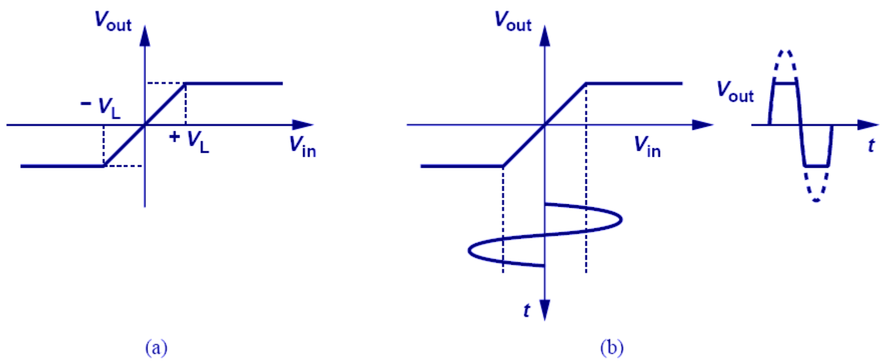


Limiting Circuits



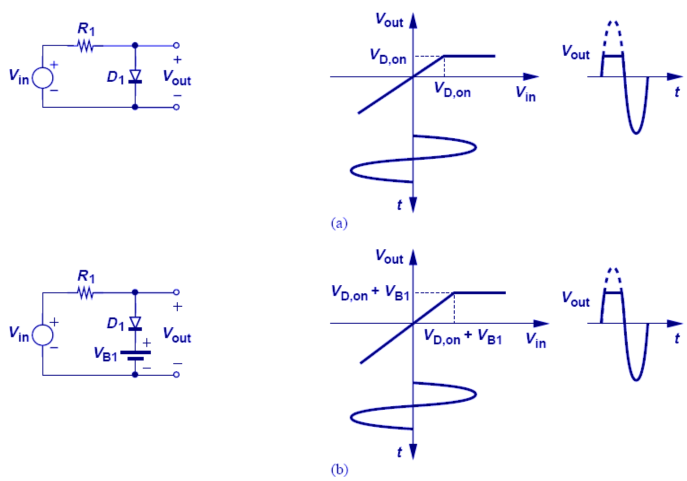
- The motivation of having limiting circuits is to keep the signal below a threshold so it will not saturate the entire circuitry.
- When a receiver is close to a base station, signals are large and limiting circuits may be required.

Input/Output Characteristics



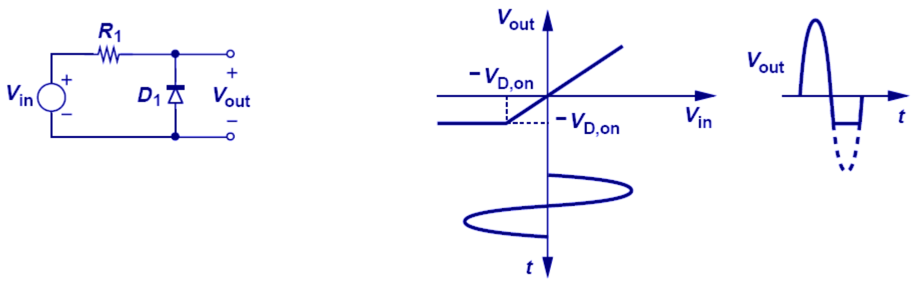
➢ **Note the clipping of the output voltage.**

Limiting Circuit Using a Diode: Positive Cycle Clipping

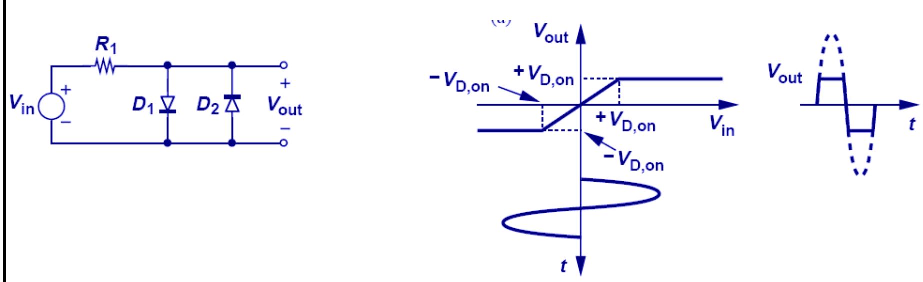


➢ **As was studied in the past, the combination of resistor-diode creates limiting effect.**

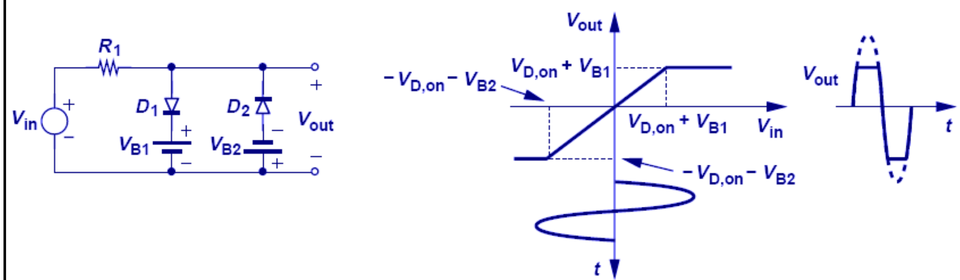
Limiting Circuit Using a Diode: Negative Cycle Clipping



Limiting Circuit Using a Diode: Positive and Negative Cycle Clipping

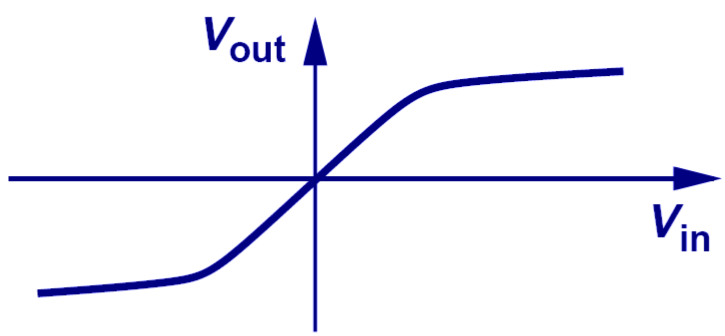


General Voltage Limiting Circuit



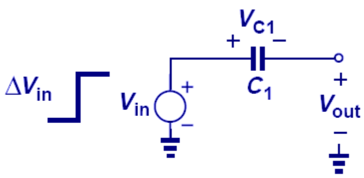
- Two batteries in series with the antiparalle diodes control the limiting voltages.

Non-idealities in Limiting Circuits

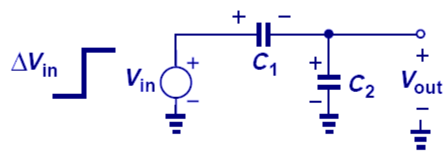


- The clipping region is not exactly flat since as Vin increases, the currents through diodes change, and so does the voltage drop.

Capacitive Divider



(a)

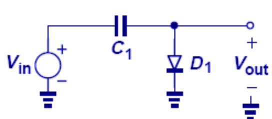


(b)

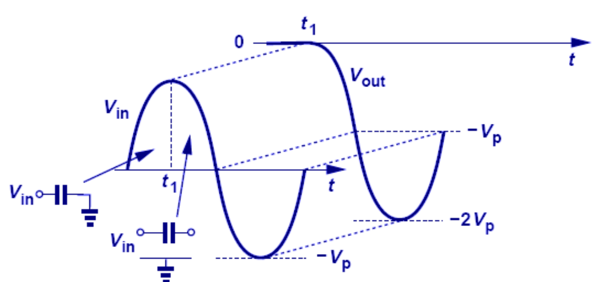
$$\Delta V_{out} = \Delta V_{in}$$

$$\Delta V_{out} = \frac{C_1}{C_1 + C_2} \Delta V_{in}$$

Waveform Shifter: Peak at -2Vp



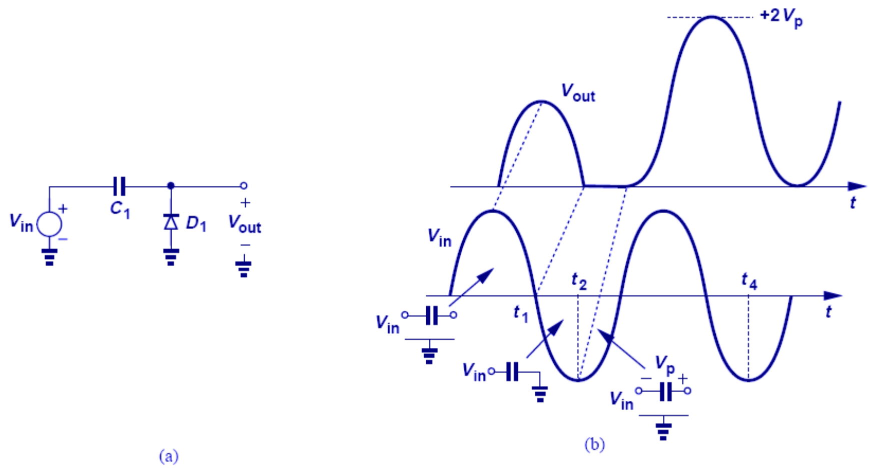
(a)



(b)

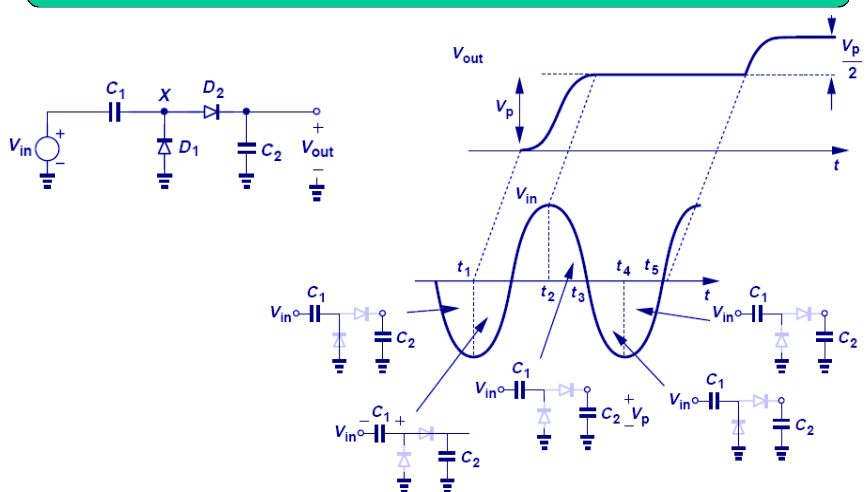
- As Vin increases, D1 turns on and Vout is zero.
- As Vin decreases, D1 turns off, and Vout drops with Vin from zero. The lowest Vout can go is -2Vp, doubling the voltage.

Waveform Shifter: Peak at 2Vp



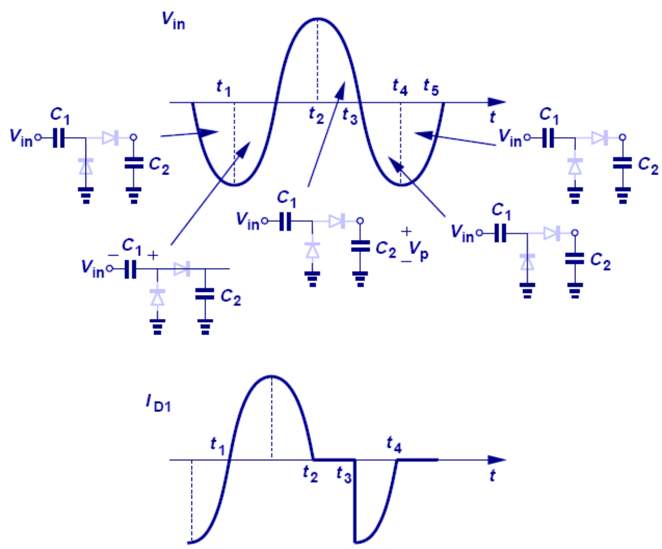
- Similarly, when the terminals of the diode are switched, a voltage doubler with peak value at 2Vp can be conceived.

Voltage Doubler

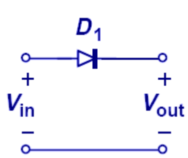


- The output increases by V_p, $V_{p/2}$, $V_{p/4}$, etc in each input cycle, eventually settling to $2\,V_p$.

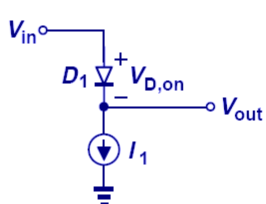
Current thru D_1 in Voltage Doubler

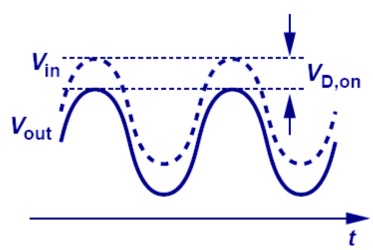


Another Application: Voltage Shifter



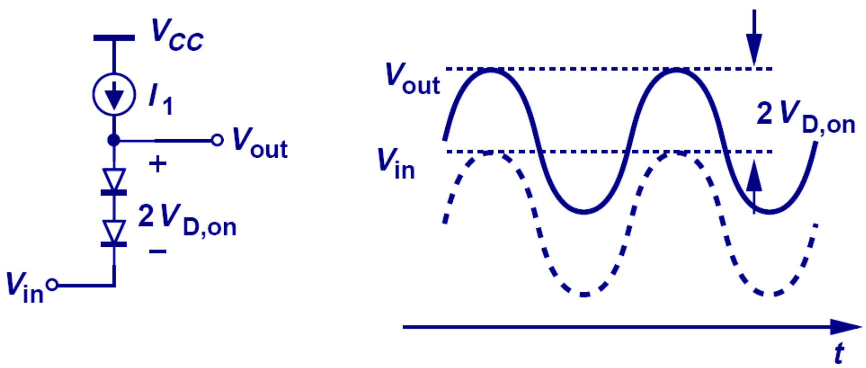
(a)



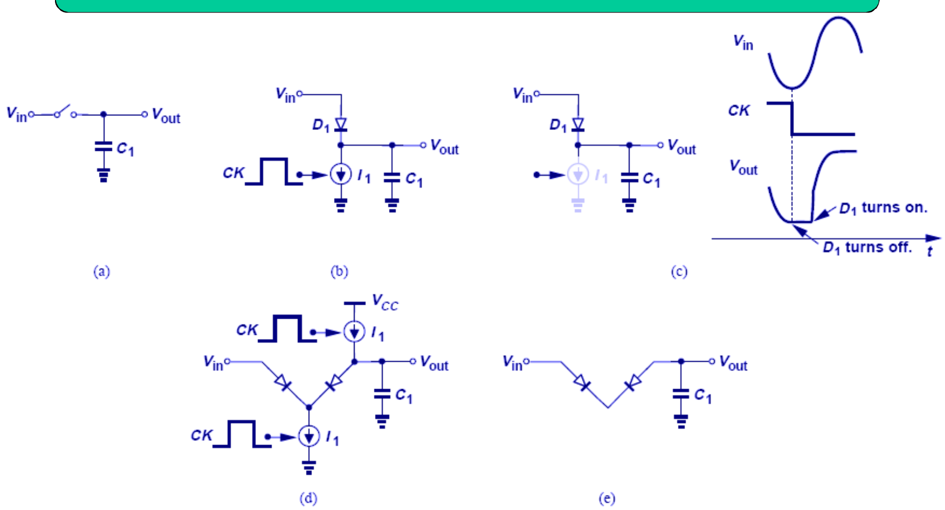


(b)

Voltage Shifter ($2V_{D,ON}$)

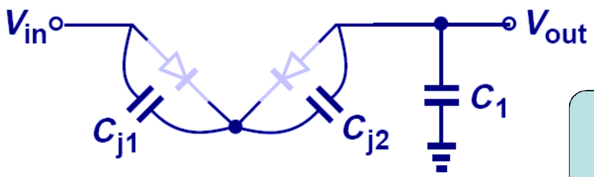


Diode as Electronic Switch



- Diode as a switch finds application in logic circuits and data converters.

Junction Feedthrough



$$\Delta V_{out} = \frac{C_j/2}{C_j/2 + C_1} \Delta V_{in}$$

- **For the circuit shown in part e) of the previous slide, a small feedthrough from input to output via the junction capacitors exists even if the diodes are reverse biased**
- **Therefore, C1 has to be large enough to minimize this feedthrough.**