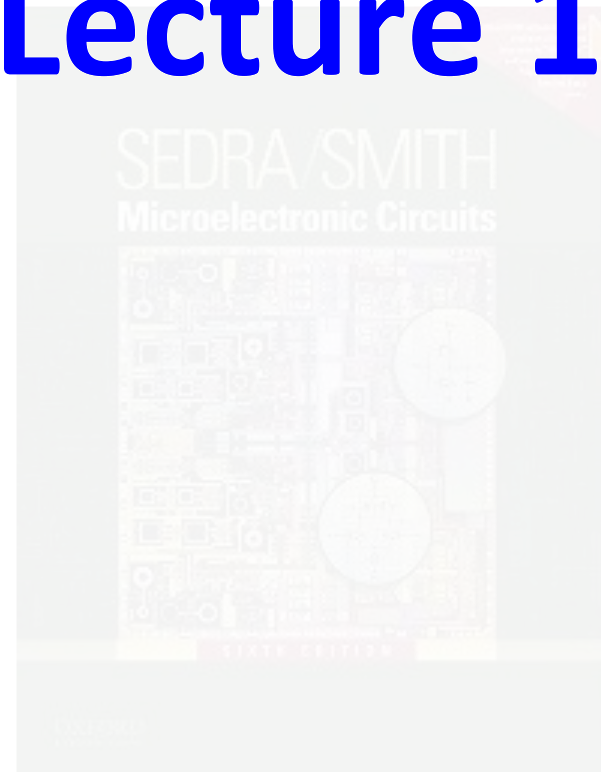
Lecture 13 – 二极管电路 part2



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课程纲要

- 6.1 二极管的结构和工作原理
- 6.1.1 本征半导体、掺杂半导体、PN结基本概念
- 6.1.2 二极管结构及其伏安特性
- 6.1.3 二极管电路模型（包括简化、恒压降和小信号模型）
- 6.1.4 齐纳二极管伏安特性、主要参数及其应用电路
- 6.2 二极管应用电路的分析
- 6.2.1 整流电路（包括半波、全波和桥式）
- 6.2.2 限幅和钳位电路
- 6.2.3 电压倍增电路
- 6.2.4 逻辑门

Introduction

- 本章知识点
  - 理想二极管的特性，以及 包含多个二极管的电路的分析和设计，实现有用、有趣的非线性特性；
  - PN结二极管的电路模型及其在电路分析与设计中的应用；
    - ①简化模型（理想模型）；
    - ②指数模型；
    - ③恒压降模型；
    - ④小信号模型；

Introduction

- 应用1：用反向串联的、工作于反向击穿区的zener二极管实现直流恒压
- 应用2：整流电路（日常充电器, ac → dc）
- 其他应用…

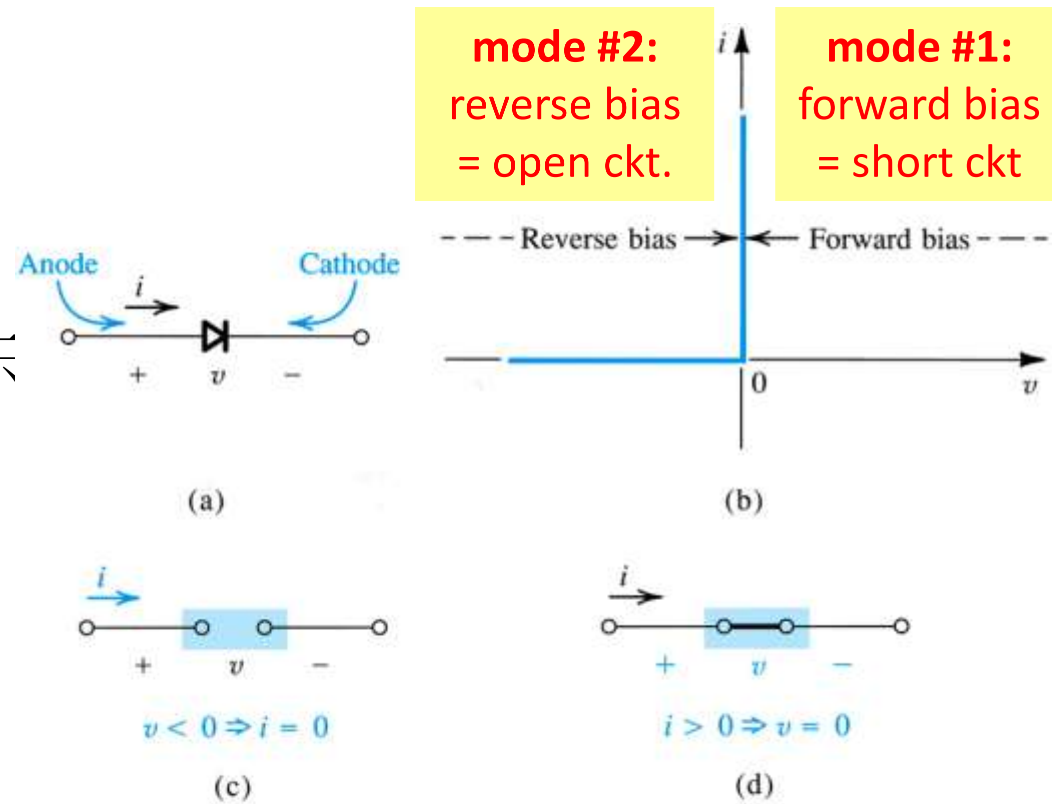
二极管电路的分析方法（理想模型、恒压降模型）

- 假设二极管处于“闭合on”或“打开off”状态，分析电路，再验证是否违背二极管的基本属性，若违背了，则假设错误
  - 开关闭合on，电压为0或$V_{D,on}$，验证电流；电流只能从正流向负；
  - 开关打开off，电流为0，验证电压；电压只能是负端高于正端
- 常用的观察电路特性的三种视角
  - I-V特性，观察电路的输入电压与输入电流关系
  - 输入-输出特性
  - 时域响应特性

4.1.1. 理想二极管的伏安特性

多段直线只要跨过转折点即为非线性

- 理想二极管 – 最基本的非线性元件
  - 两端元件；
  - 元件符号 如右图所示
  - 两种工作模式(状态)
    - on and off
  - I/V：分段线性函数
    - 段内线性；跨段非线性



4.1.1. Current-Voltage Characteristic

- 需要防止
  - ①极大的正向电流（否则器件会烧毁）；
  - ②极大的反向电压（否则进入反向击穿区后电流也会迅速增加）；
- 可通过外部电路来限制

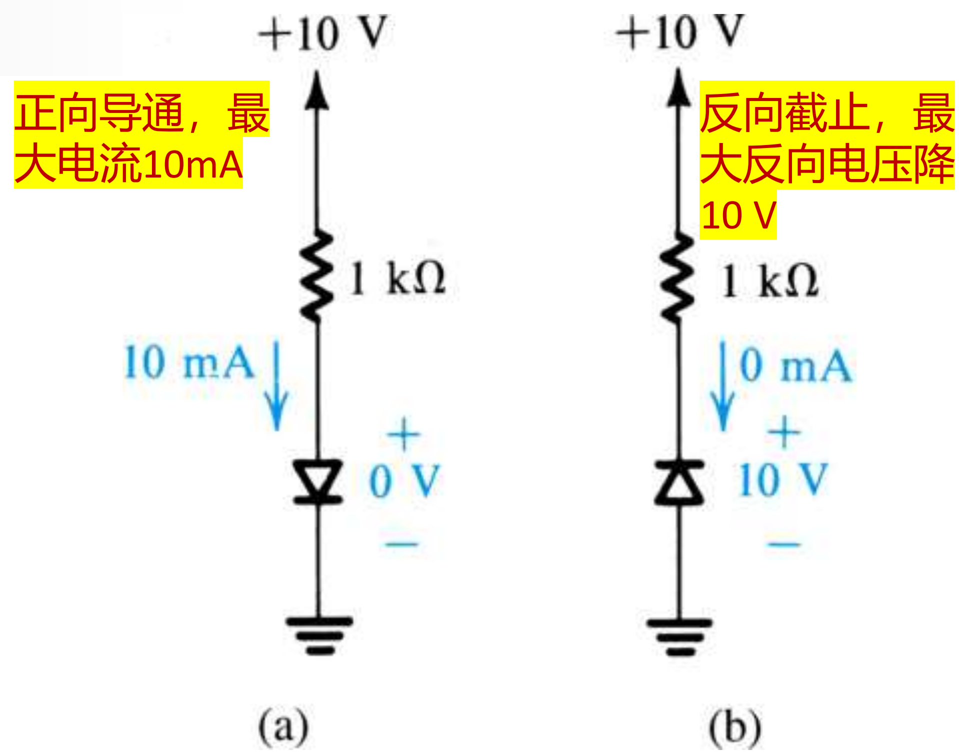


Figure 4.2: The two modes of operation of ideal diodes and the use of an external circuit to limit **(a)** the forward current and **(b)** the reverse voltage.

4.1.2: **A Simple Application – The Rectifier**

最基本的应用：整流器
整流，就是将AC转化为DC

- One fundamental application of this piecewise linear behavior is the rectifier.
- **Q:** What is a **rectifier**?
  - **A:** Circuit which converts AC waves in to DC…ideally with no loss.

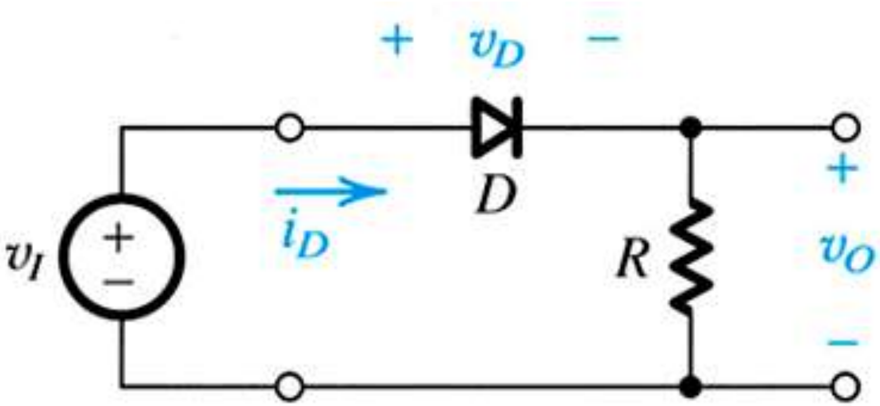


Figure 4.3(a): Rectifier Circuit

时域响应特性

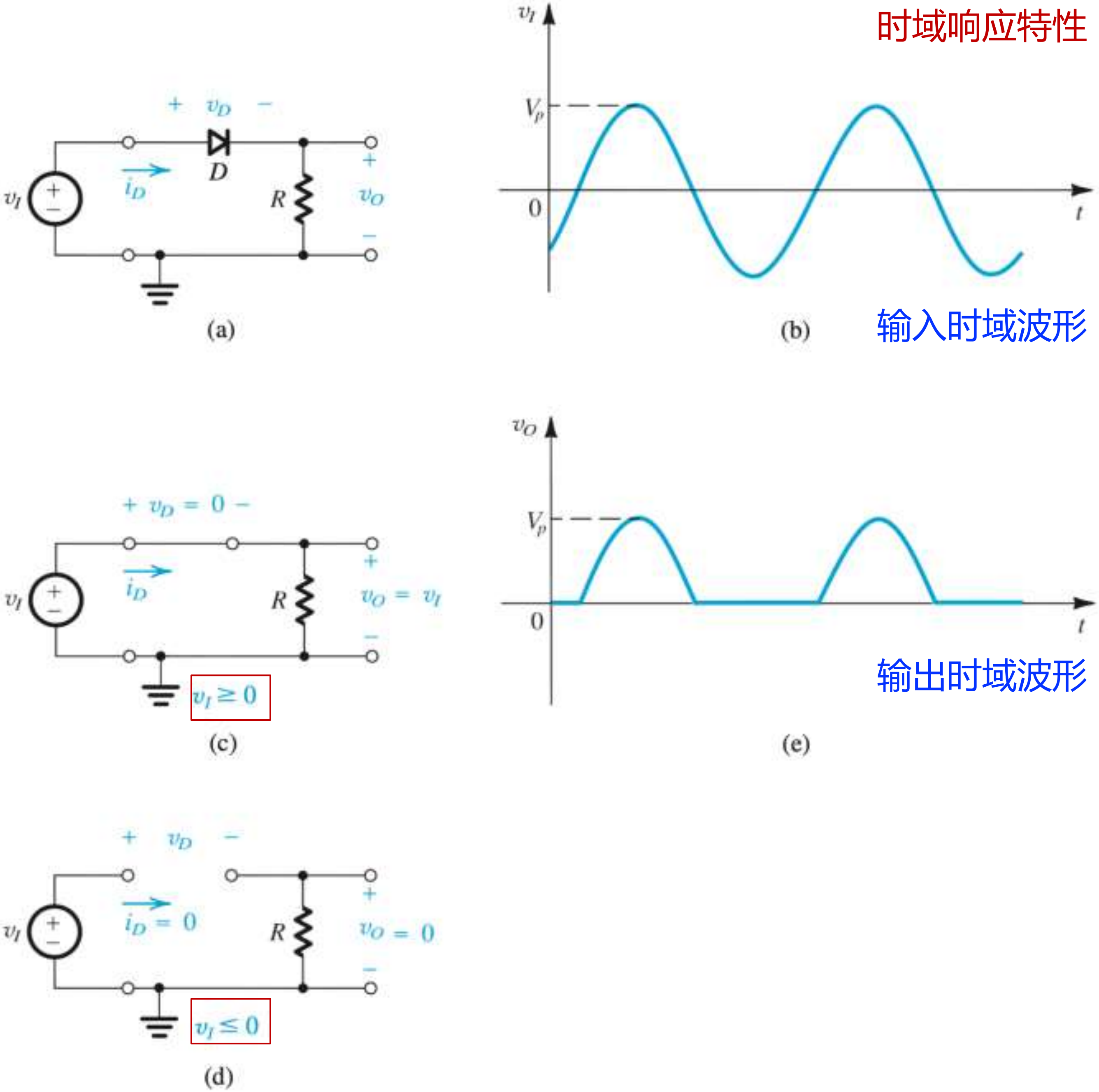
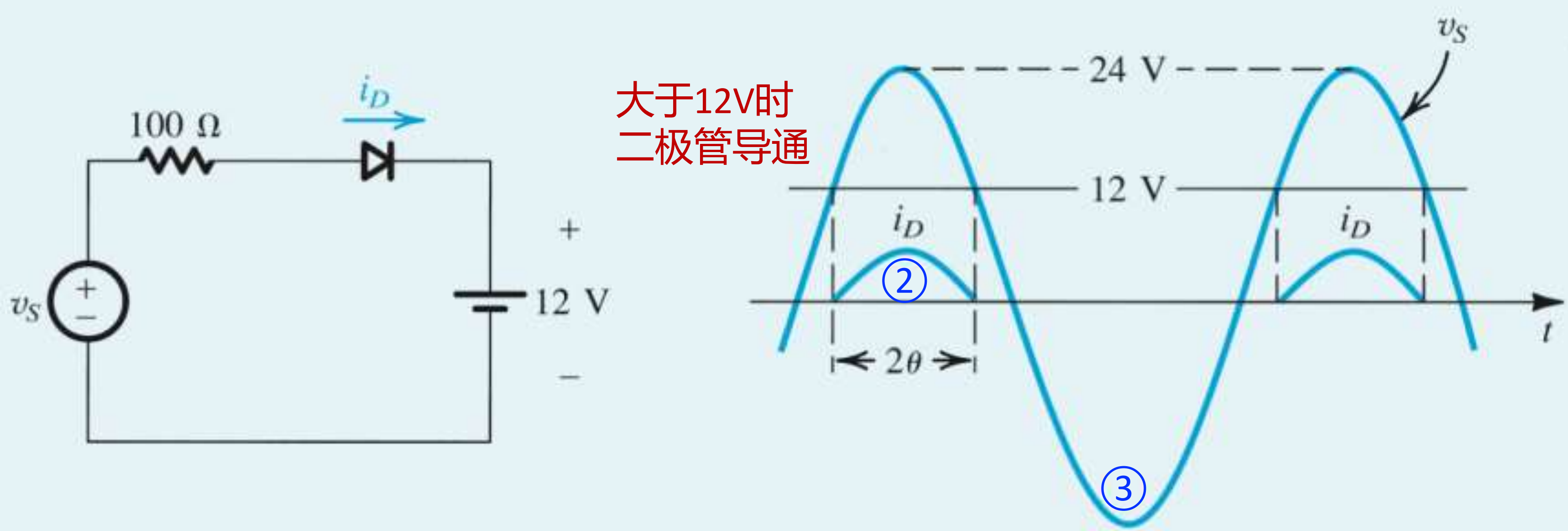


Figure 4.3 **(a)** Rectifier circuit. **(b)** Input waveform. **(c)** Equivalent circuit when $v_I \geq 0$. **(d)** Equivalent circuit when $v_I \leq 0$. **(e)** Output waveform.

Example 4.1

Figure 4.4(a) shows a circuit for charging a 12-V battery. If v_s is a sinusoid with 24-V peak amplitude, find the fraction of each cycle during which the diode conducts. Also, find the peak value of the diode current and the maximum reverse-bias voltage that appears across the diode.



(a) (b)

① $24\cos\theta = 12 \Rightarrow \theta = 60°$

③ 二极管最大反向电压

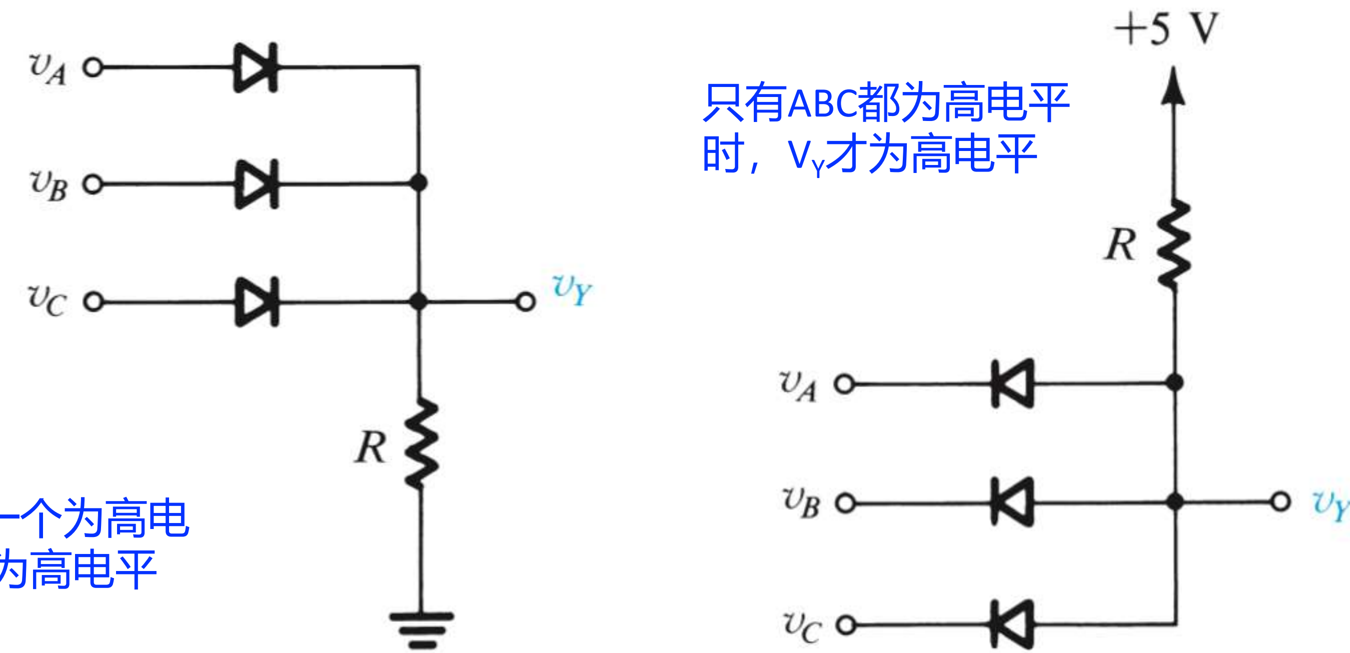
$$24 + 12 = 36\ \text{V}$$

② 二极管峰值电流

$$I_d = \frac{24-12}{100} = 0.12\ \text{A}$$

4.1.3. **Another Application, Diode Logic Gates**

另一应用：逻辑门（实际上很少用）



ABC任意一个为高电平，V_Y即为高电平

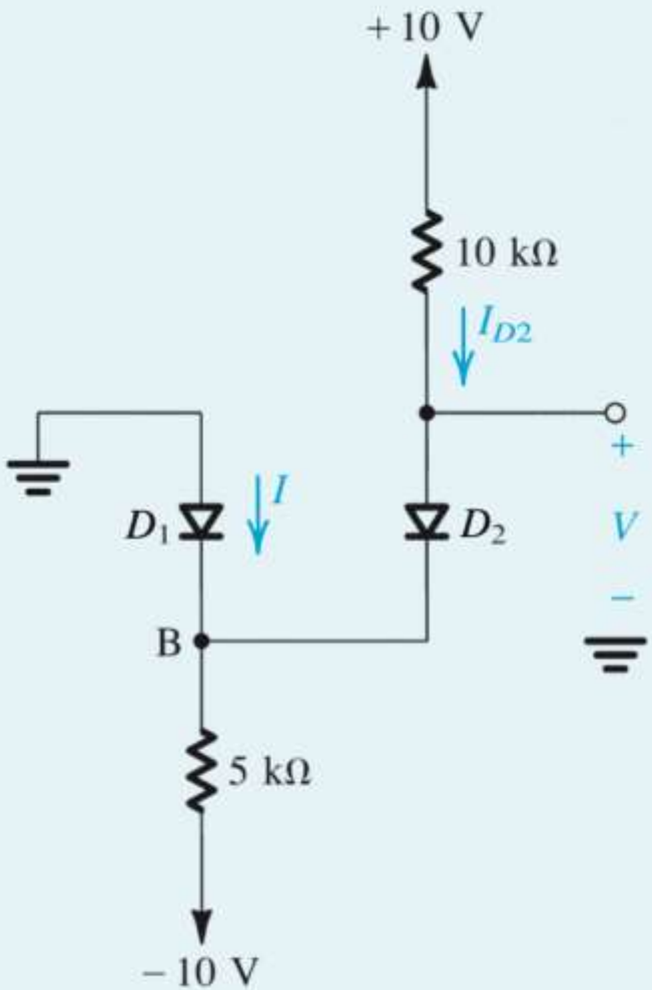
(a) 逻辑“或”　　　(b) 逻辑“与”

Figure 4.5 Diode logic gates: **(a)** OR gate; **(b)** AND gate (in a positive-logic system).

Example 4.2

假设on或off后，电位会被确定，然后计算电流，看方向

Assuming the diodes to be ideal, find the values of I and V in the circuits of Fig. 4.6.



(a)

Figure 4.6 Circuits for Example 4.2.

①假设D1和D2都on

②分析

$$V_B = 0 \text{ and } V = 0$$

$$I_{D2} = \frac{10-0}{10} = 1 \text{ mA}$$

$$I + 1 = \frac{0-(-10)}{5}$$ 在节点B处

$$\Downarrow$$

$$I = 1 \text{ mA}$$

③验证，电流从正流向负，合理

Example 4.2

Assuming the diodes to be ideal, find the values of I and V in the circuits of Fig. 4.6.

①假设D1和D2都on

②分析

$$V_B = 0 \text{ and } V = 0$$

$$I_{D2} = \frac{10 - 0}{5} = 2 \text{ mA}$$

$$I + 2 = \frac{0 - (-10)}{10} \Rightarrow I = -1 \text{ mA}$$

③验证，电流从负流向正，不合理

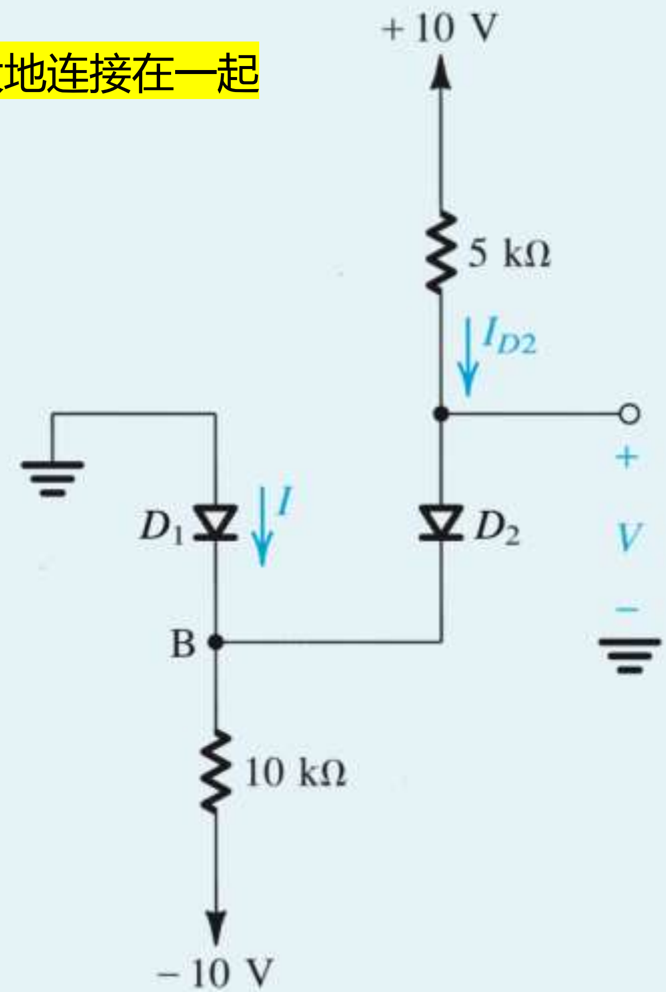
④重新假设D1off，D2 on

$$I_{D2} = \frac{10 - (-10)}{15} = 1.33 \text{ mA}$$

$$V_B = -10 + 10 \times 1.33 = +3.3 \text{ V}$$

⑤验证，反向偏置，负端电压大于正端电压，合理

大地连接在一起



(b)

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4.2. PN结二极管的特性

大多数的二极管都用PN结来实现

正向导通，反向截止，Breakdown恒压

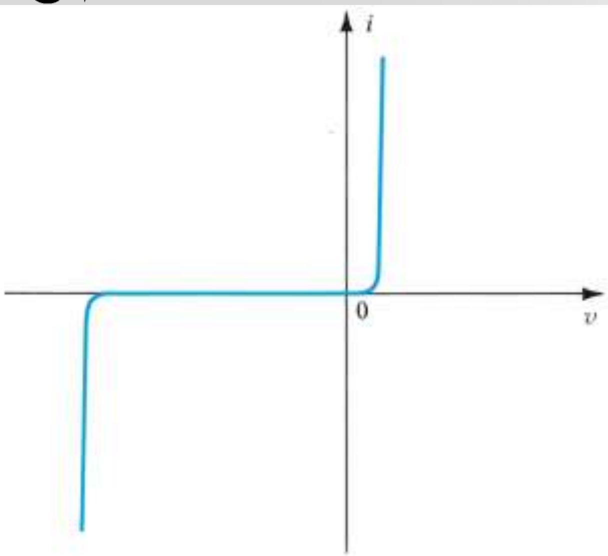
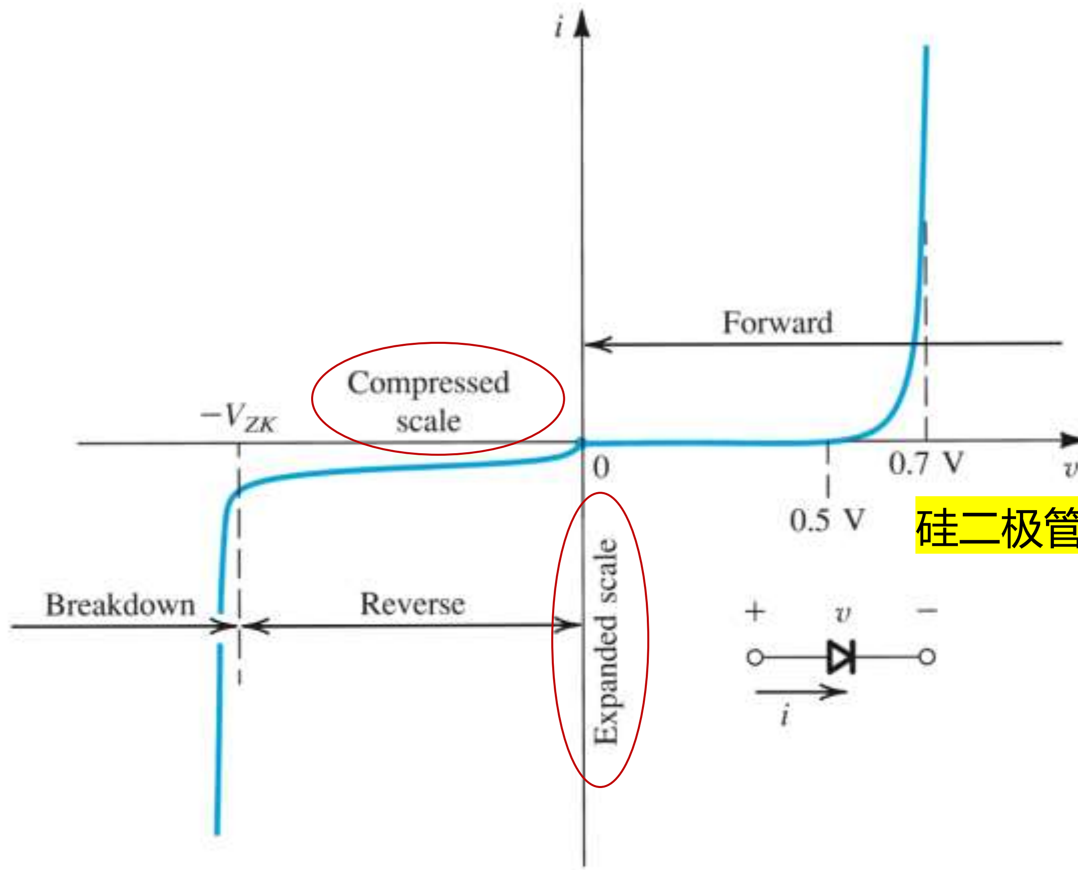


Figure 4.7 The i–v characteristic of a silicon junction diode.



硅二极管0.7V升

Figure 4.8 The diode i–v relationship with some scales expanded and others compressed in order to reveal details.

4.2.1. The Forward-Bias Region正向偏置区域

- The forward-bias region of operation is entered when $v > 0$.
- I-V relationship is closely approximated by equations to right.

(4.3) is a simplification suitable for large v

$$\text{(eq4.1)}\ \underbrace{i = I_S(e^{v/V_T} - 1)}_{I_S = \text{ constant for diode at given temperature (aka. saturation current)}}$$

$$\text{(eq4.2)}\ \underbrace{V_T = \frac{kT}{q}}_{\substack{V_T = \text{ thermal voltage} \\ k = \text{ Boltzmann's constant (8.62E-5 eV/K)} \\ q = \text{ magnitude of electron charge (1.6E-19 C)}}} = \underbrace{\mathbf{26}\ \text{mV}}_{\text{at room temperature}}$$

$$\text{(eq4.3)}\ \underbrace{i = I_S e^{v/V_T}}_{I_S = \text{ constant for diode at given temperature (aka. saturation current)}}$$

对于较大的正向电压v，该式更简单

4.2.1. The Forward-Bias Region

$$\text{(eq4.3)}\ i = I_S e^{v/V_T}$$

根据电压求电流

- Equation (4.3) may be reversed to yield (4.4).
- This relationship applies over as many as seven decades of current.

I_S = constant for diode at given temperature (aka. saturation current)

$$\text{(eq4.4)}\ \boxed{v = V_T \ln\left(\frac{i}{I_S}\right)}$$

根据电流求电压

4.2.1. The Forward-Bias Region

分析电压变化对电流的影响，或反之

- **Q:** What is the relative effect of current flow (i) on forward biasing voltage (v)?
- **A:** Very small.
  - 10x change in i, effects 60mV change in v.

(eq4.3) $i = I_S e^{v/V_T}$

⇩

在0.7V附近，1/10扔掉是合理的，所以看似不变但电流迅速增大

正向电压变化 **60 mV**， 电流变化 **10倍**

$$\overbrace{I_1 = I_S e^{V_1/V_T} \text{ and } I_2 = I_S e^{V_2/V_T}}^{\text{step \#1: consider two cases (\#1 and \#2)}}$$

$$\overbrace{\frac{I_2}{I_1} = \frac{\cancel{I_S} e^{V_2/V_T}}{\cancel{I_S} e^{V_1/V_T}}}^{\text{step \#2: divide } I_2 \text{ by } I_1}$$

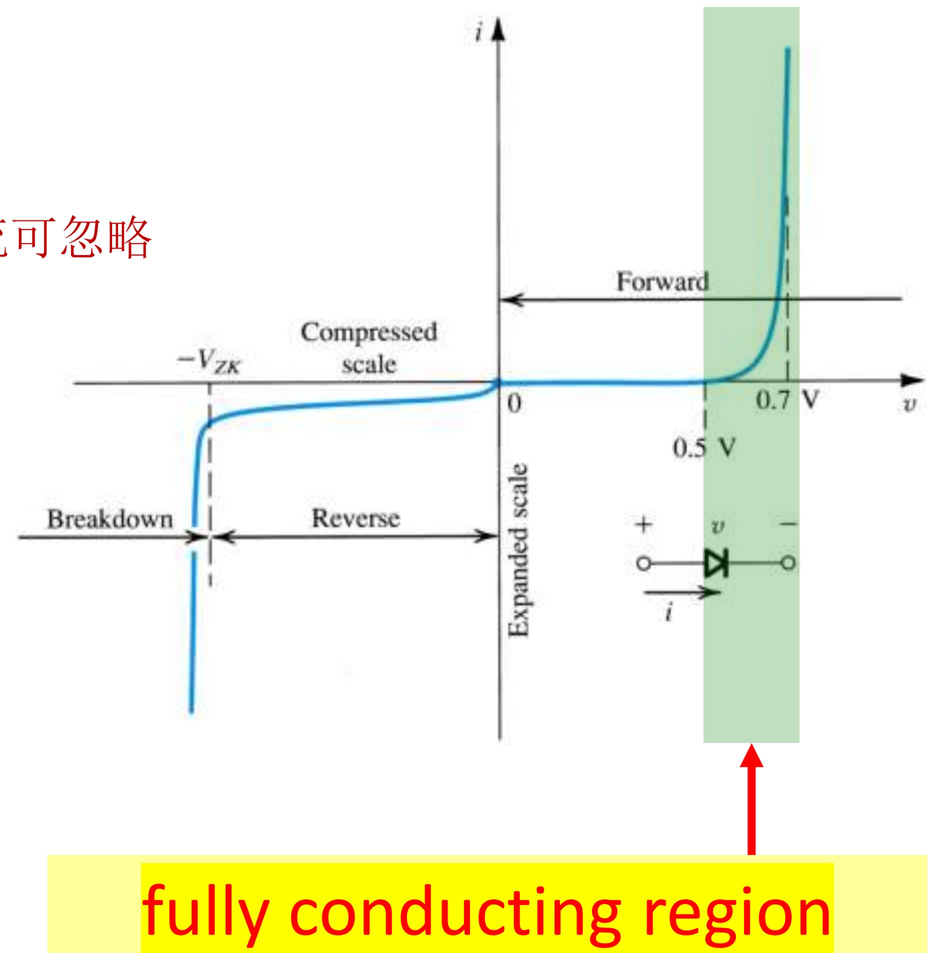
$$\overbrace{\frac{I_2}{I_1} = e^{(V_2 - V_1)/V_T}}^{\text{step \#3: combine two exponentials}}$$

$$\overbrace{V_2 - V_1 = V_T \ln\left(I_2 / I_1\right)}^{\text{step \#4: invert this expression}}$$

$$\overbrace{V_2 - V_1 = \underbrace{2.3 V_T \log\left(I_2 / I_1\right)}_{60mV \approx 2.3 V_T \log(10/1)}}^{\text{step \#5: convert to log base 10}}$$

4.2.1: The Forward-Bias Region

- **cut-in voltage** – is voltage, below which, minimal current flows 小于0.5V时，电流可忽略
  - approximately 0.5V
- **fully conducting region** – is region in which R_{diode} is approximately equal 0
  - between 0.6 and 0.8V



Q：0.6~0.8V 电压对应多少倍的电流变化？

Example 4.3

A silicon diode said to be a 1-mA device displays a forward voltage of 0.7 V at a current of 1 mA. Evaluate the junction scaling constant I_S. What scaling constants would apply for a 1-A diode of the same manufacture that conducts 1 A at 0.7 V?

并联1000个，面积1000倍

① $i = I_S e^{v/V_T}$ $\Rightarrow$ $I_S = 10^{-3} e^{-700/25} = 6.9 \times 10^{-16}$ A

② 1000个 1-mA device并联，可构成一个 1-A device，所以 $I_S = 6.9 \times 10^{-13}$ A

温度特性

温度越高，Is越大，所以曲线向左移动

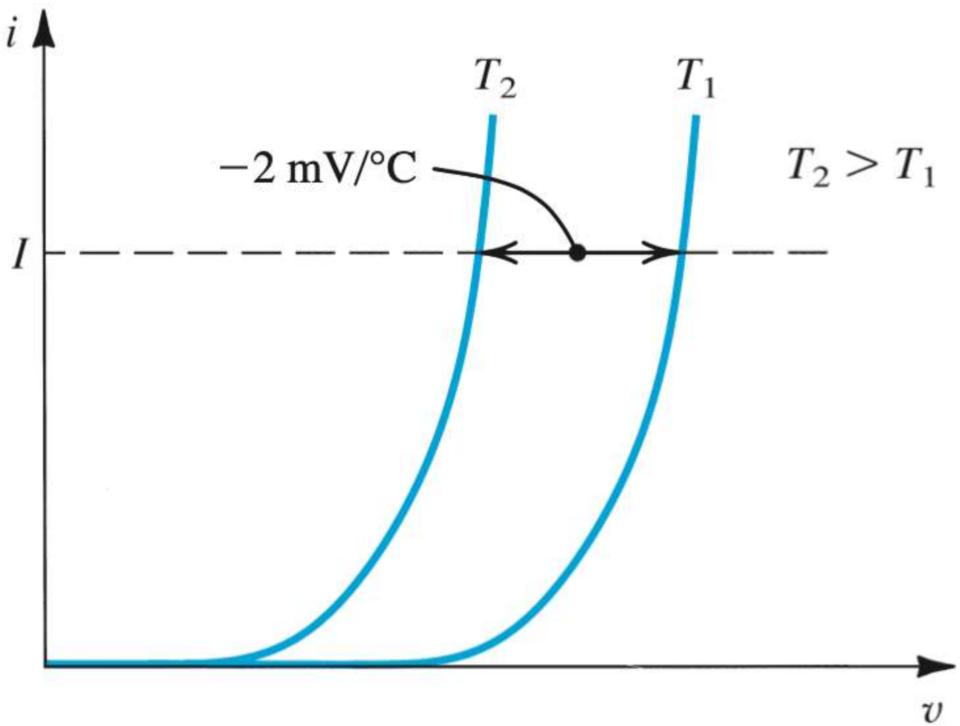


Figure 4.9 Temperature dependence of the diode forward characteristic. At a constant current, the voltage drop decreases by approximately 2 mV for every 1°C increase in temperature.

4.2.2. The Reverse-Bias Region 反向偏置区域

- The reverse-bias region of operation is entered when $v < 0$.
- *I-V* relationship, for negative voltages with $|v| > V_T$ (26*mV*), is closely approximated by equations to right.

$$i = I_S(e^{v/V_T} - 1)$$

$$\Downarrow$$

$$i \simeq -I_S$$ 理论值

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4.2.2. **The Reverse-Bias Region**

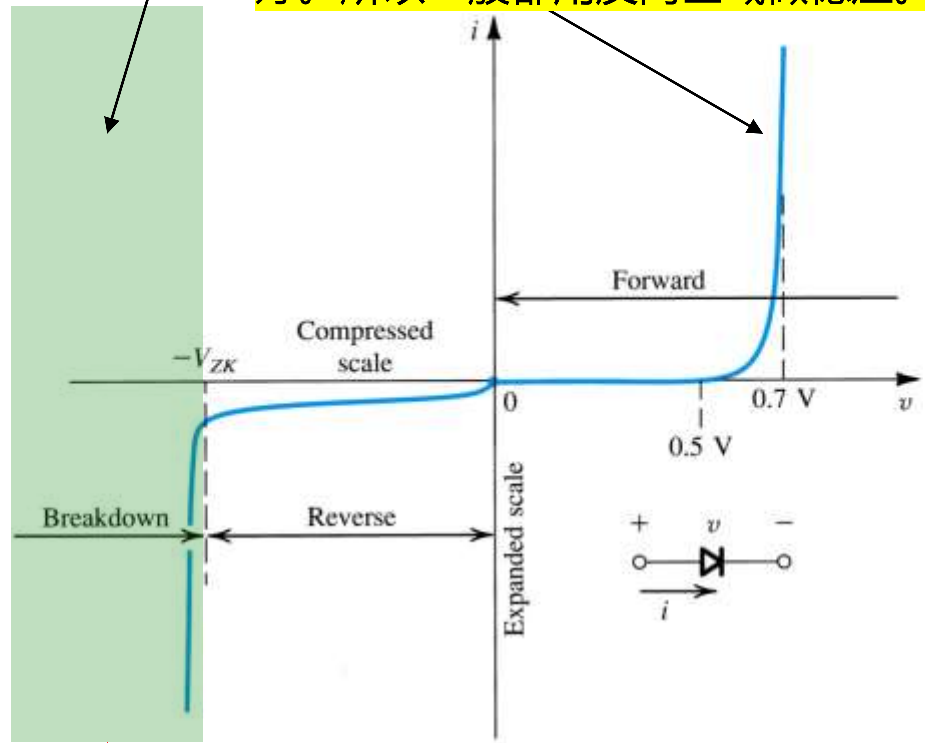
- A “real” diode exhibits reverse-bias current, although small, much larger than I_S. 实际值
  - 10^{-9} vs. 10^{-14} *Amps*
- A large part of this reverse current is attributed to leakage effects.

4.2.3. The Breakdown Region 反向击穿区

稳压器：电压基本保持不变，当①负载有变化时；②供电电压有变化时
二极管两个区域都可以用作稳压器

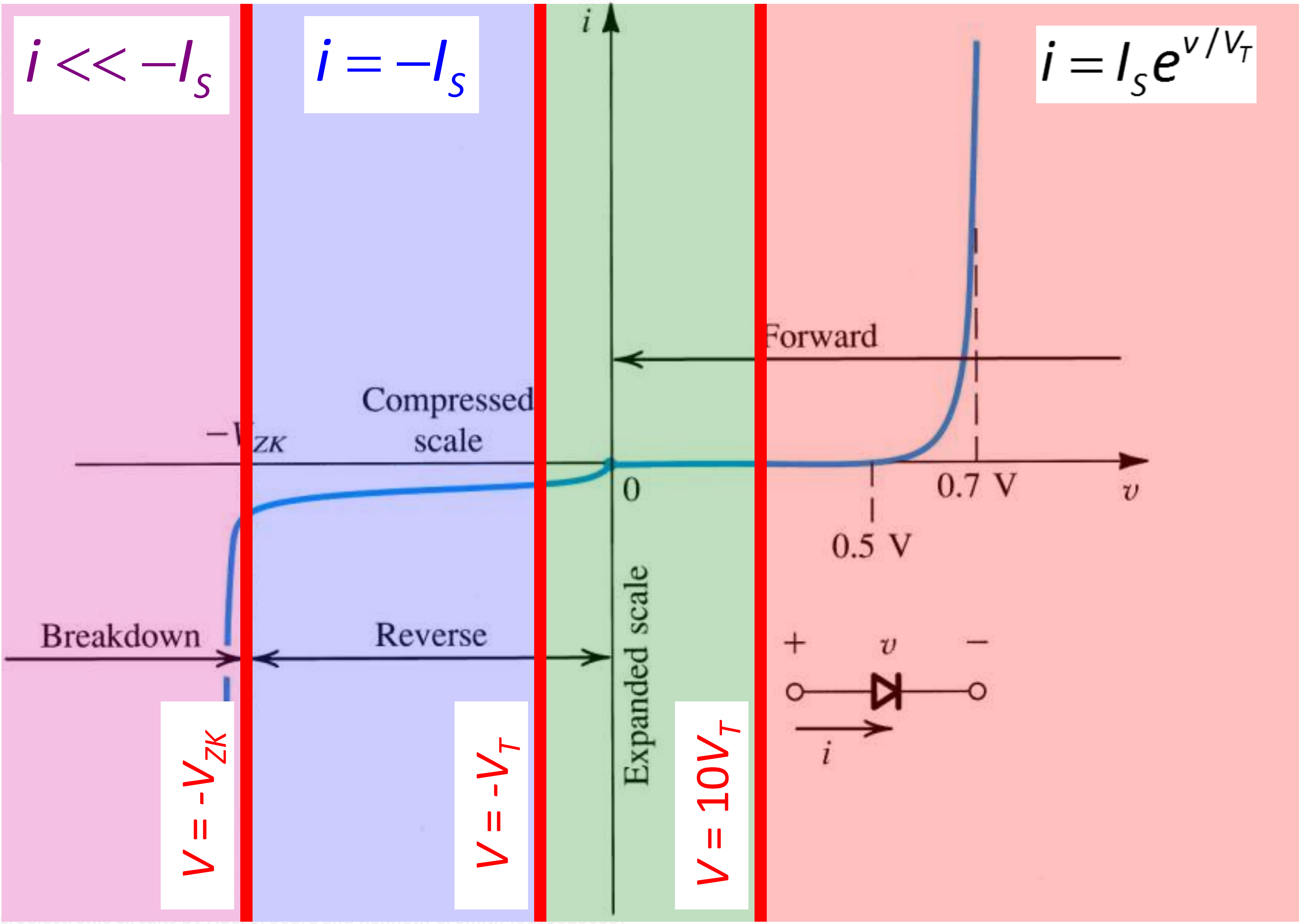
稳压器，电压稳定，输入和负载电压变化时，电压仍要稳定。
同样电流变化范围，电压变化小就越好。所以一般都用反向区域做稳压。

- The breakdown region of operation is entered when $v < V_{ZK}$.
  - **Zener-Knee Voltage (V_{ZK})**
- This is normally non-destructive. 非破坏性的
- 电压基本不变，也可用作 **voltage regulator** (稳压器)



breakdown region

$$i = I_S(e^{v/V_T} - 1)$$



$i << -I_S$
$i = -I_S$
$i = I_S e^{v/V_T}$
i
Forward
Compressed scale
$-V_{ZK}$
0
0.7 V
v
0.5 V
Breakdown
Reverse
Expanded scale
+
v
−
i
$V = -V_{ZK}$
$V = -V_T$
$V = 10V_T$

4.3. Modeling the Diode Forward Characteristic

- The previous slides define a robust set of diode models.
- Upcoming slides, however, discuss simplified diode models better suited for use in circuit analyses:
  - exponential model
  - constant voltage-drop model
  - ideal diode model
  - small-signal (linearization) model

4.3.1. The Exponential Model

- **exponential diode model**
  - most accurate 指数模型~最为精确，但最难分析
  - most difficult to employ in circuit analysis
    - due to nonlinear nature

$$\underbrace{\text{(eq4.6)} \quad I_D = I_S e^{V_D / V_T}}_{\substack{V_D = \text{voltage across diode} \\ I_D = \text{current through diode}}}$$

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4.3.1. The Exponential Model

- **Q:** How does one solve for I_D in circuit to right?
  - $V_{DD} = 5V$
  - $R = 1kOhm$
  - $I_D = 1mA$ @ $0.7V$
- **A:** Two methods exist…
  - **graphical method 图解法（方法2）**
  - **iterative method 迭代法（方法3）**

①二极管的电压电流约束关系：

$$I_D = I_S e^{V_D/V_T}$$

②外部电路分析

$$I_D = \frac{V_{DD} - V_D}{R}$$

两个未知数，两个方程，可解，但要解超越方程（方法1）

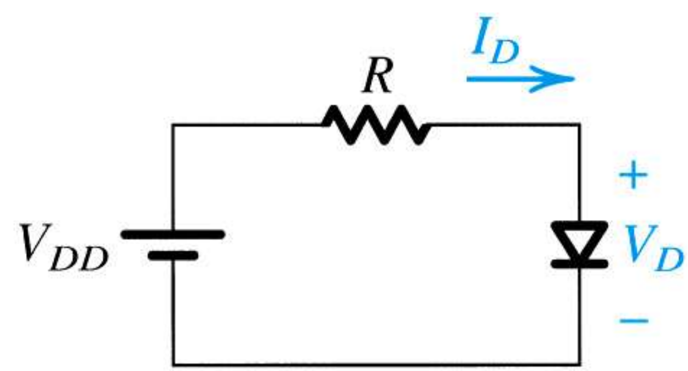

Figure 4.10: A simple circuit used to illustrate the analysis of circuits in which the diode is forward conducting.

4.3.2. **Graphical Analysis Using Exponential Model**

图解法是求解非线性方程的经典方法

- **step #1:** Plot the relationships of (4.6) and (4.7) on single graph
- **step #2:** Find intersection of the two…
  - **load line** and diode characteristic intersect at **operating point**

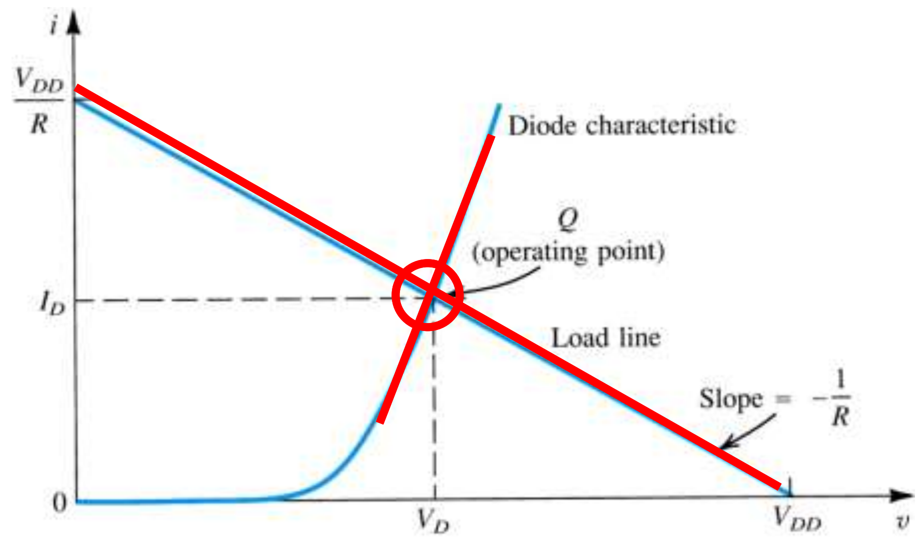

Figure 4.11: Graphical analysis of the circuit in Fig. 4.10 using the exponential diode model.

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4.3.2. **Graphical Analysis Using Exponential Model**

- **Pro's 优点**
  - Intuitive
- **Con's 缺点**
  - Poor Precision
  - Not Practical for Complex Analyses
    - multiple lines required

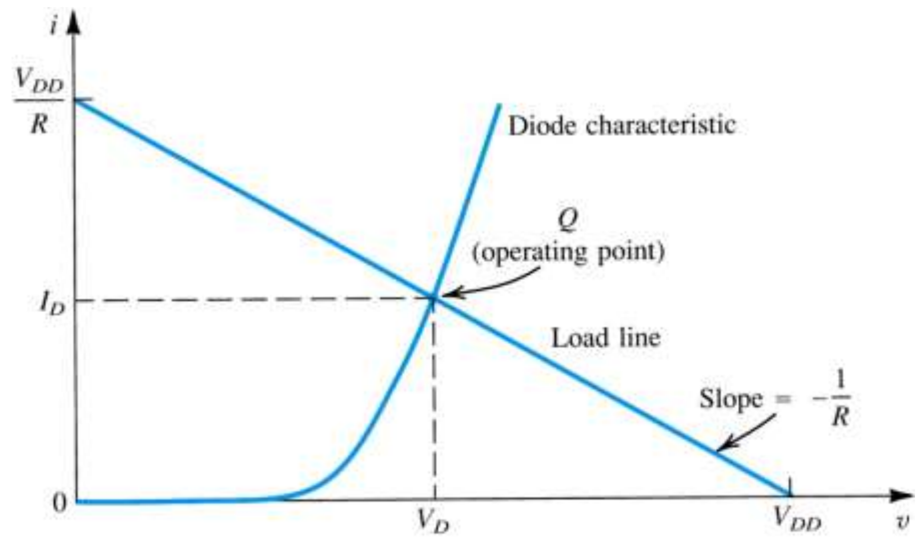
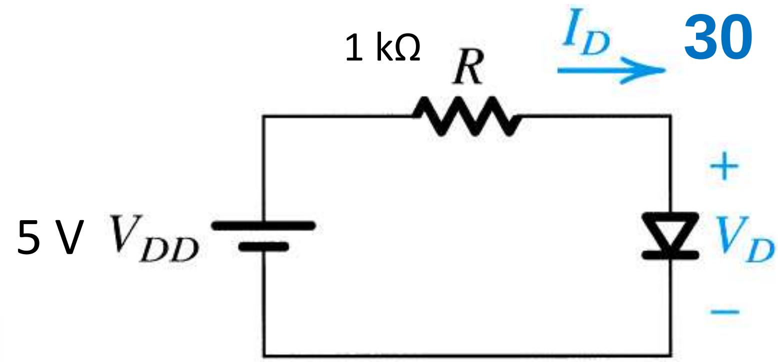


Figure 4.11: Graphical analysis of the circuit in Fig. 4.10 using the exponential diode model.

4.3.3. Iterative Analysis Using Exponential Method



- **step #1:** Start with initial guess of V_D.
  - $V_D^{(0)}$: assume that $V_D = 0.7$ V
- **step #2:** Use nodal / mesh analysis to solve I_D. $I_D = \frac{V_{DD} - V_D}{R}$ = 4.3 mA
- **step #3:** Use exponential model to update V_D.
  4.3mA比1mA大，电压要相应增加
  $$V_2 = V_1 + 0.06 \log \frac{I_2}{I_1}$$
  - $V_D^{(1)} = \mathbf{f}(V_D^{(0)})$
  $V_1 = 0.7$ V, $I_1 = 1$ mA, and $I_2 = 4.3$ mA results in $V_2 = 0.738$ V.
- **step #4:** Repeat these steps until $V_D^{(k+1)} = V_D^{(k)}$.
  - Upon convergence, the new and old values of V_D will match.

$$I_D = \frac{5 - 0.738}{1} = 4.262 \text{ mA}$$
$$V_2 = 0.738 + 0.06 \log \left[\frac{4.262}{4.3}\right] = 0.738 \text{ V}$$

Example 4.4

Determine the current I_D and the diode voltage V_D for the circuit in Fig. 4.10 with $V_{DD} = 5$ V and $R = 1$ kΩ. Assume that the diode has a current of 1 mA at a voltage of 0.7 V.

4.3.3. Iterative Analysis Using Exponential Method

- **Pro's**
  - High Precision
- **Con's**
  - Not Intuitive
  - Not Practical for Complex Analyses
    - 10+ iterations may be required
- 可见，采用指数模型，不管是图解法还是迭代法，虽然精度高，但效率低；

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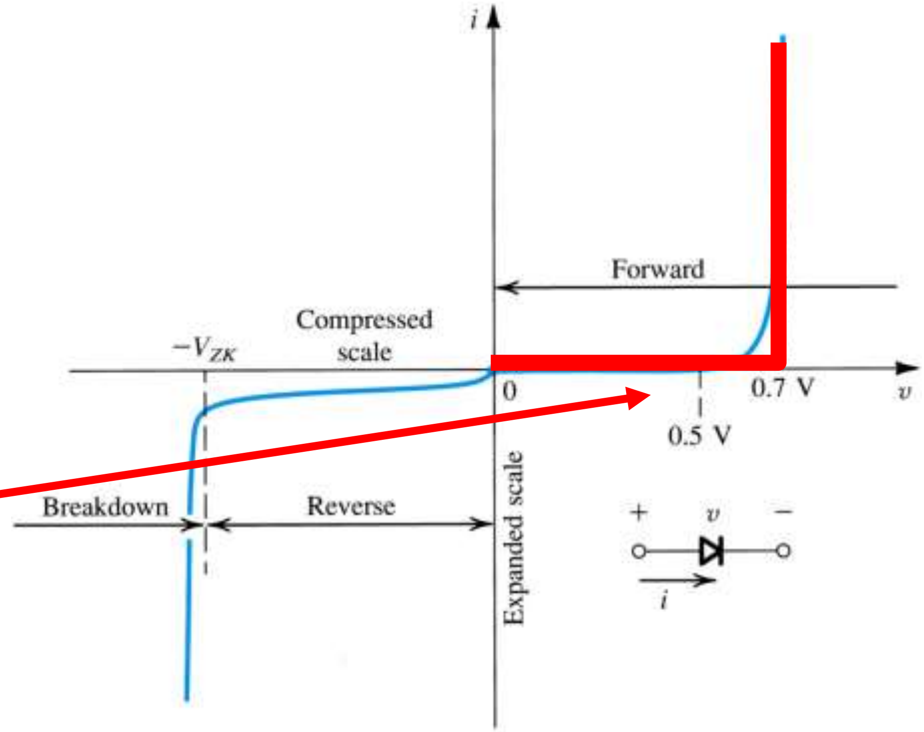
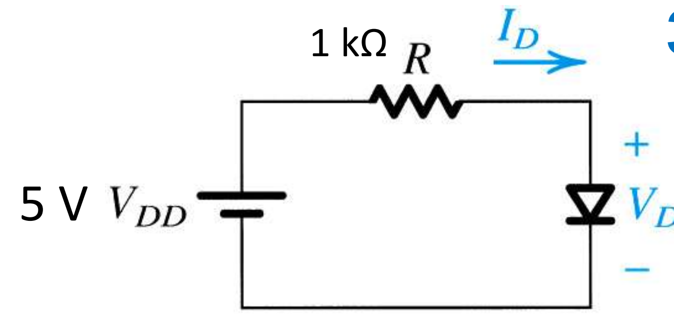
4.3. Modeling the Diode Forward Characteristic

需要一个能快速分析二极管电路的方法：恒压降模型

- **Q:** How can one analyze these diode-based circuits more efficiently?
- **A:** Find a simpler model.
  - One example is assume that voltage drop across the diode is constant.



4.3.5. The Constant Voltage-Drop Model



- The **constant voltage-drop diode model** assumes that the slope of I_D vs. V_D is vertical *@ 0.7V*
- **Q:** How does example 4.4 solution change if CVDM is used?
  - **A:** 4.262*mA* to 4.3*mA*

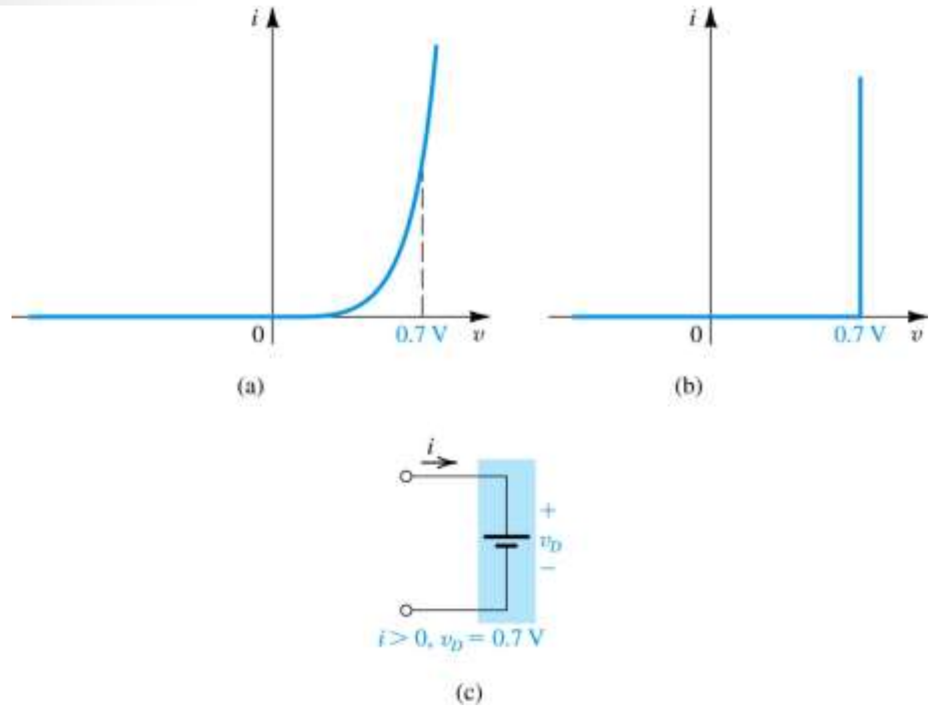
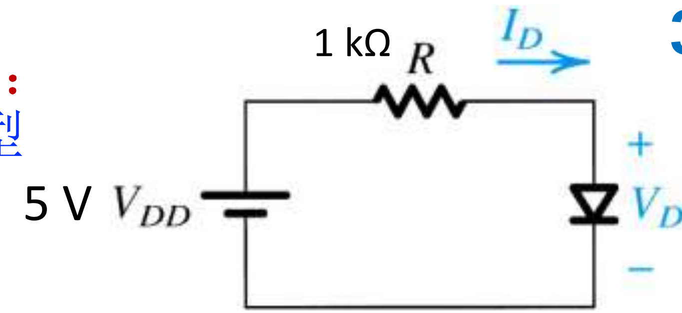


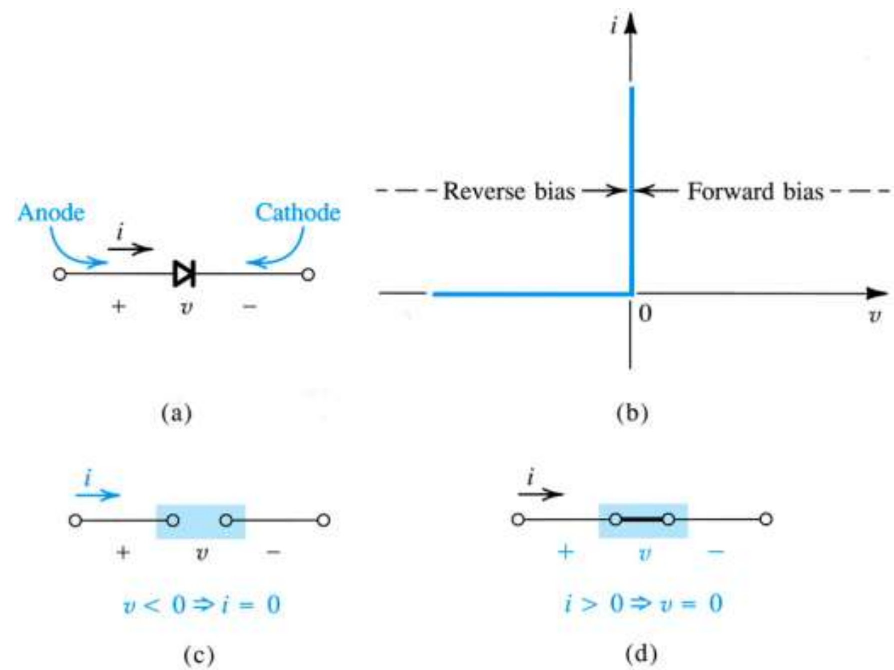
Figure 4.12: Development of the diode constant-voltage-drop model: **(a)** the…

4.3.6. **Ideal Diode Model**

更简单的模型：
理想模型



- The **ideal diode model** assumes that the slope of I_D vs. V_D is vertical *@ 0V*
- **Q:** How does example 4.4 solution change if ideal model is used?
  - **A:** 4.262*mA* to 5*mA*



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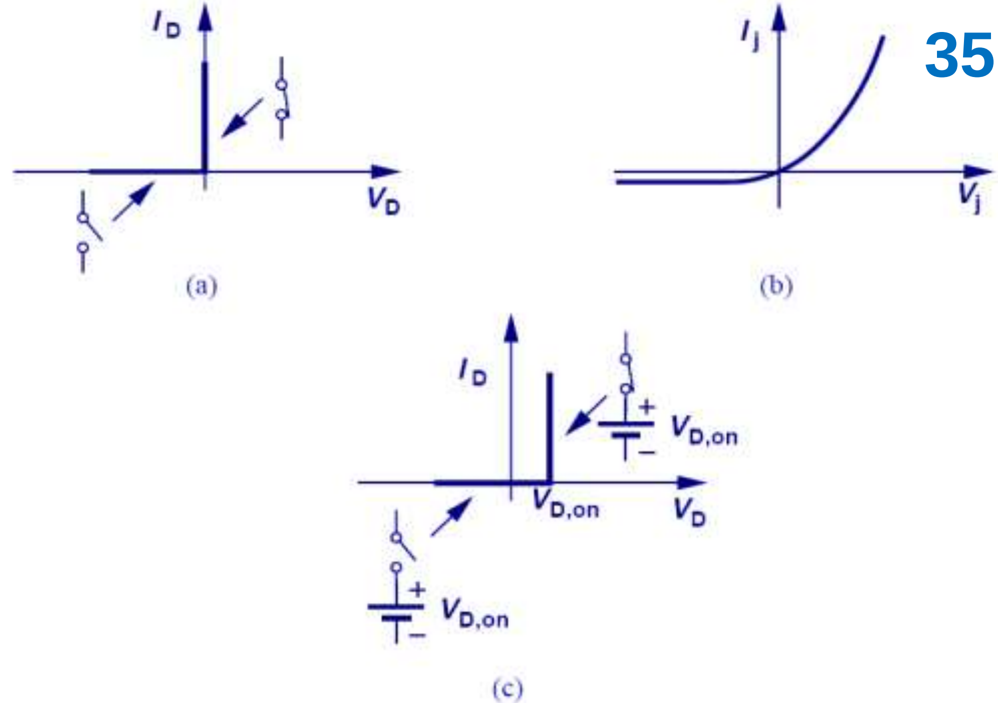
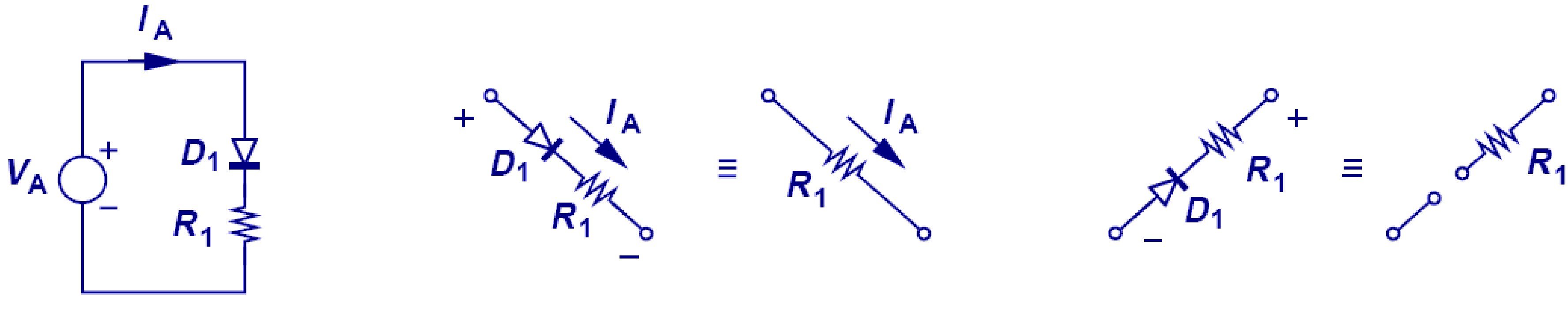
When to use these models?



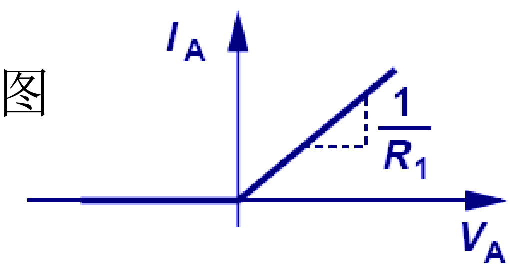
- **exponential model**
  - low voltages
  - less complex circuits
  - emphasis on accuracy over practicality
- **constant voltage-drop mode**:
  - medium voltages = 0.7*V*
  - more complex circuits
  - emphasis on practicality over accuracy
  - 大部分情况适用 **70-80%**
- **ideal diode model**
  - high voltages >> 0.7*V*
  - very complex circuits
  - cases where a difference in voltage by 0.7*V* is negligible
  - 一般用于快速判断二极管状态
- **small-signal model**
  - this is next…

常规电路特性图：①I/V；②输入输出；③时域图

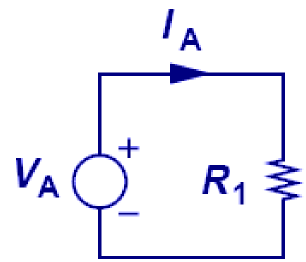


(a) (b) (c)

①I/V特性图



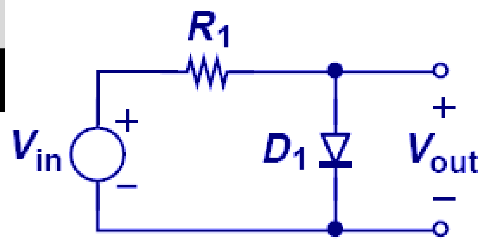
(d)



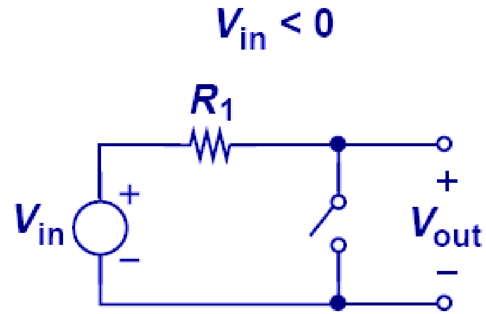
(e)

- 分析二极管电路的一个原则：二极管刚要开启时（about to turn on）,I_D=0，V_D=$V_{D,on}$(0或0.7V，视采用何种模型而定)；V_A从-∞到+∞，必有一点电压为使二极管刚要开启的电压

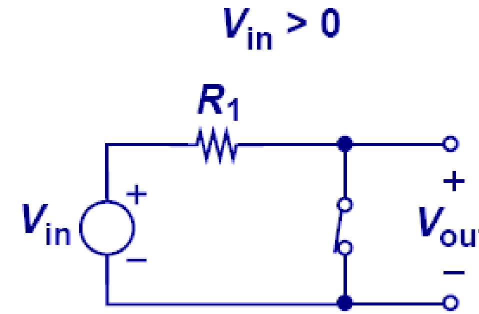
Input/Output Characteristics



(a)

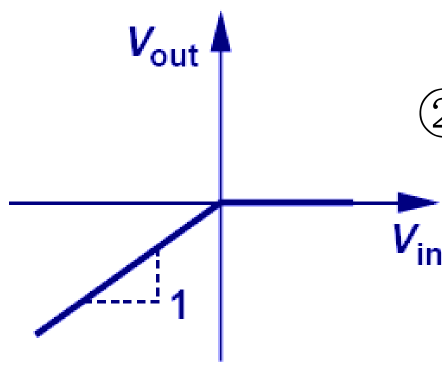


(b)



(c)

绘图方法：
①Vin从-∞开始增加→曲线1；
②Vin从+∞开始减小→曲线2；
③曲线1和曲线2的相交点如何确定？A. 直接延长相交；B. 分析二极管刚要开启的临界点



(d)

②输入输出特性图

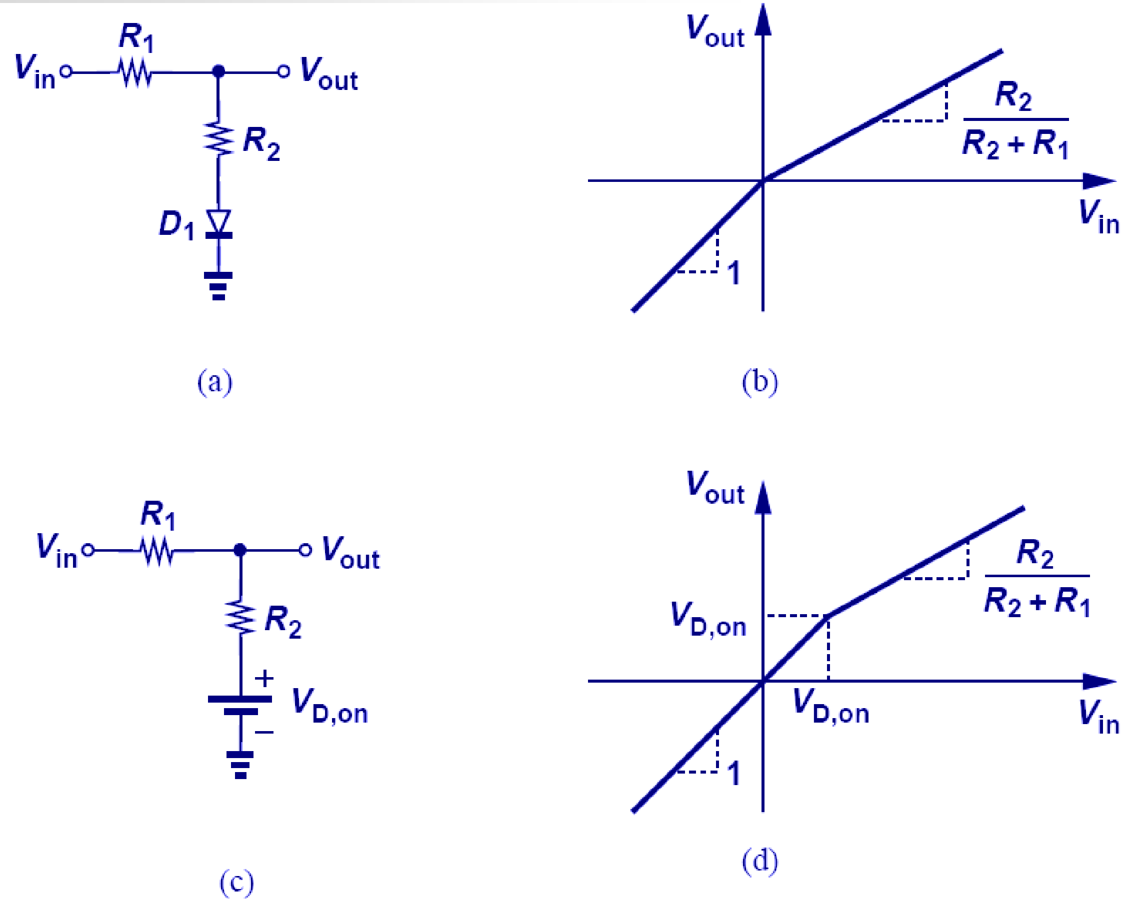
负无穷画，正无穷画，两者相交即可

- 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 $V_{out} = 0$.

Input/Output Characteristics with Ideal and Constant-Voltage Models

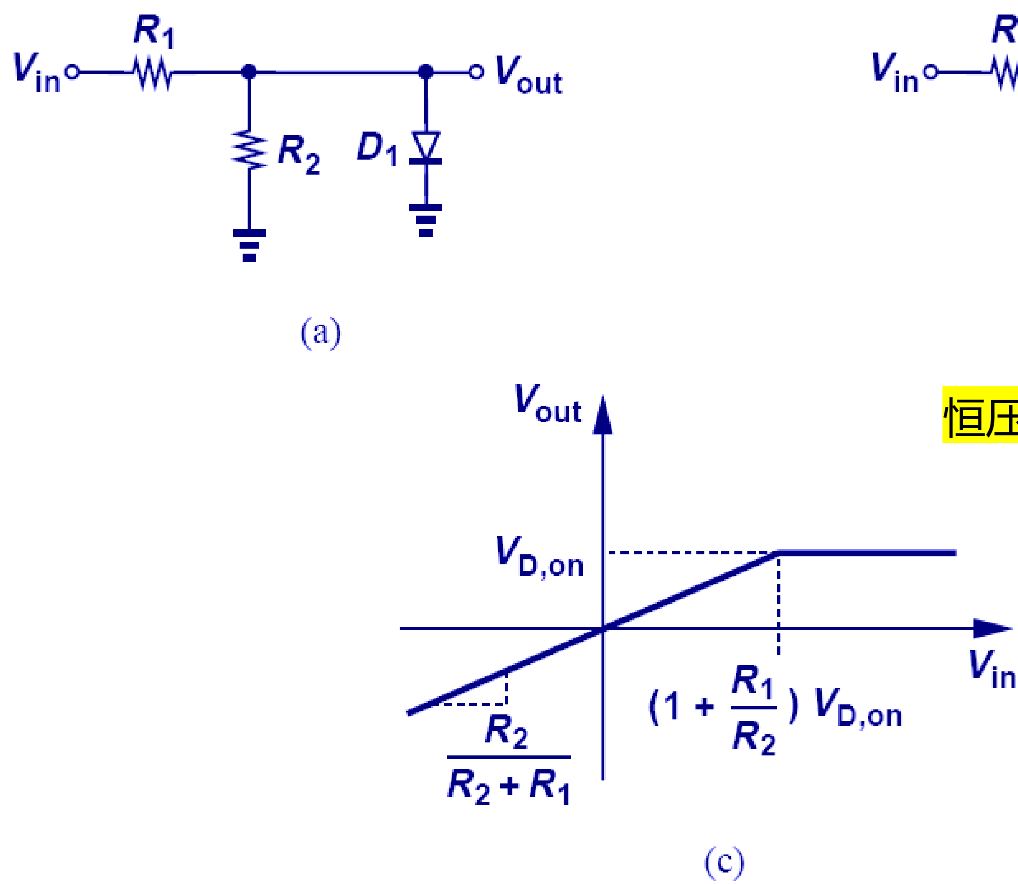
理想模型

恒压降模型



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

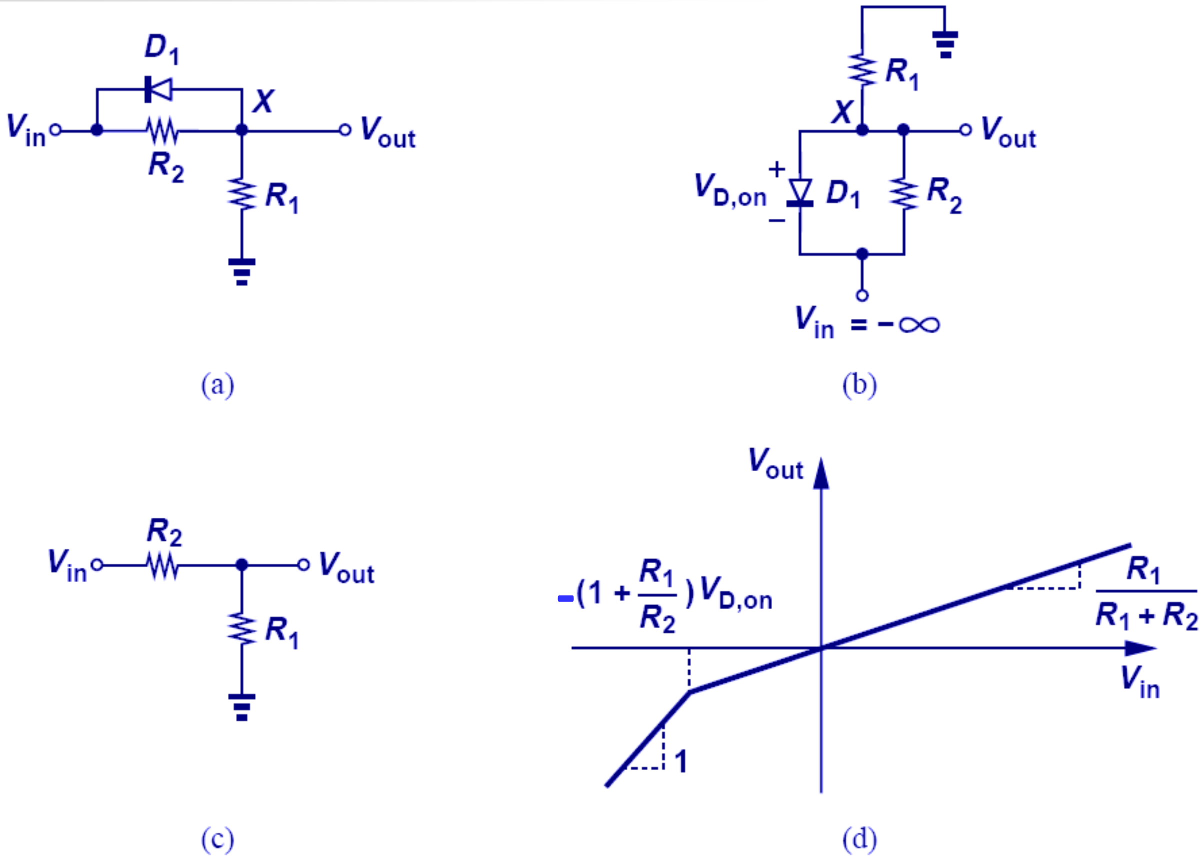
Input/Output Characteristics with a Constant-Voltage Model



恒压降模型是要消耗电压

- 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

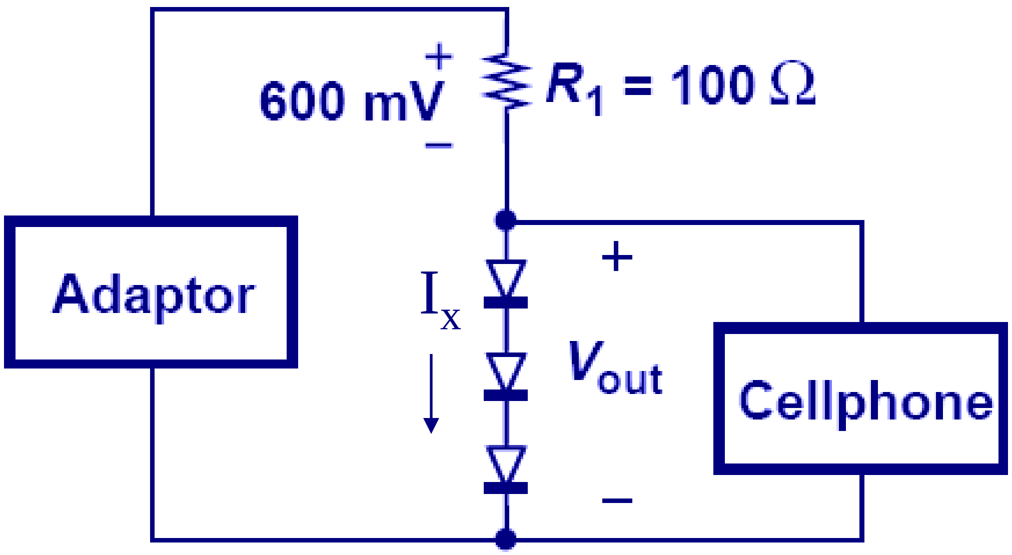


- In this example, since V_{in} is connected to the cathode, the diode conducts when V_{in} is very negative.
- The break point where the slope changes is when the current across R_1 is equal to the current across R_2.

Cell Phone Adapter
手机适配器（稳压器）

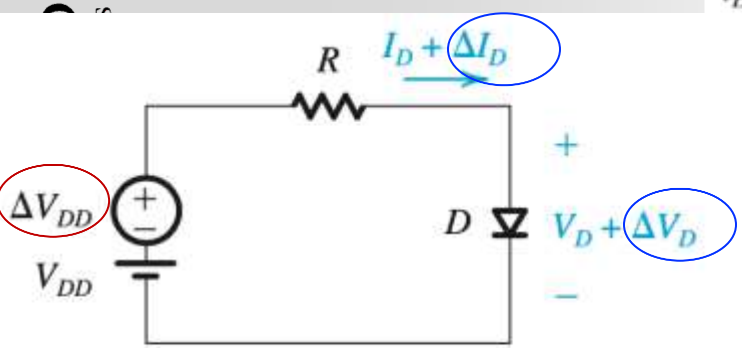
小信号模型的动机：
有效分析微量变化的响应

稳压器：电压基本保持不变，当①负载有变化时；②供电电压有变化时



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

- $V_{out} = 3\ V_{D,on}$ is used to charge cell phones.
- However, if I_x changes, iterative method is often needed to obtain a solution, thus motivating a simpler technique.（充电器输入电压有微量波动时，如何有效分析v_{out}的变化量）



当V_{DD}有微小变化ΔV_{DD}时，分析二极管ΔV_D和ΔI_D之间的关系

① $v_D(t) = V_D + v_d(t)$

② $i_D(t) = I_S e^{(V_D+v_d)/V_T}$

黑色曲线上A点和B点之间

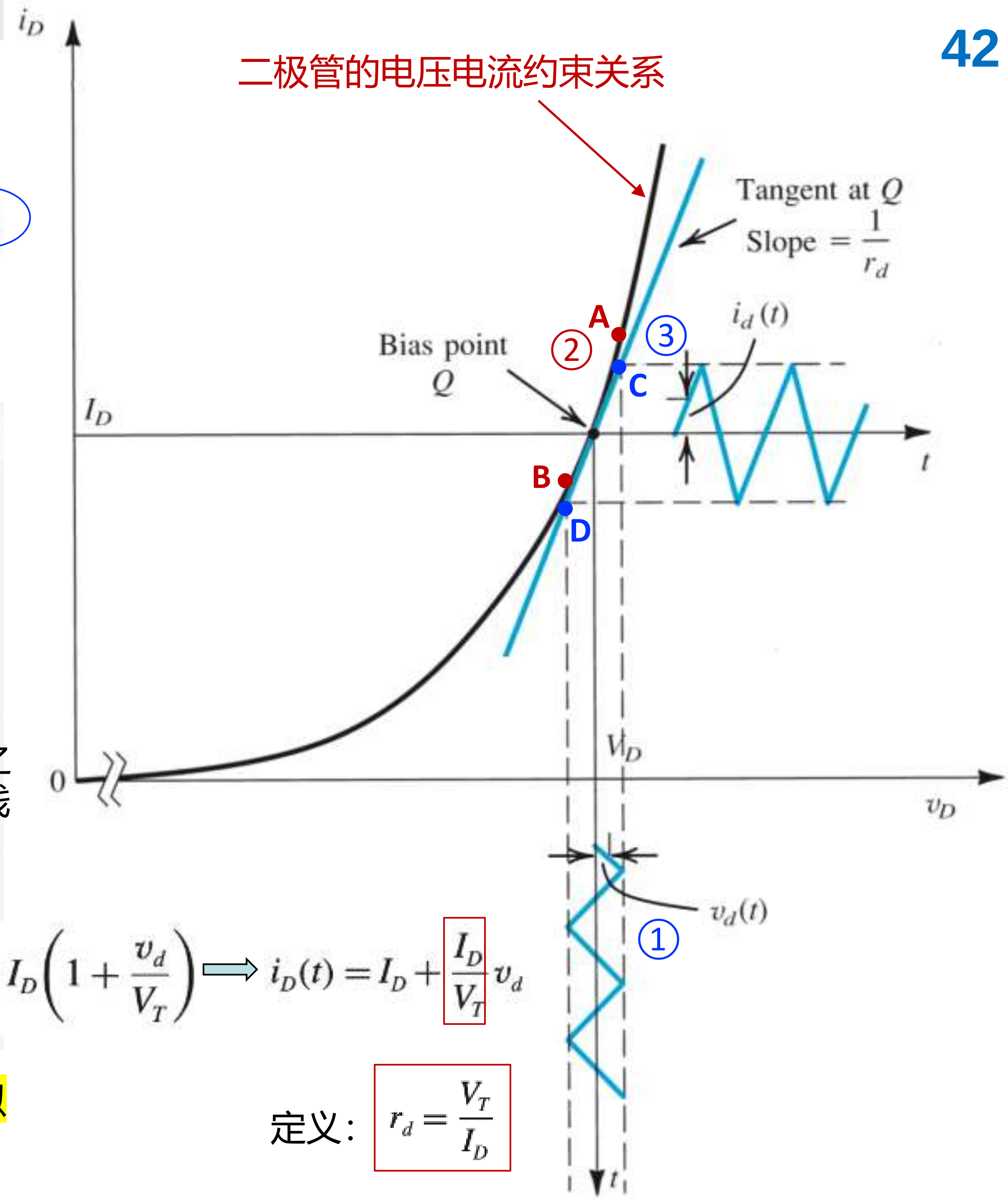
③ 可以用蓝色曲线上的C点和D点之间来近似，如何近似？（Q点作切线，线性化）什么情况下可以近似？

$$i_D(t) = I_D e^{v_d/V_T}$$

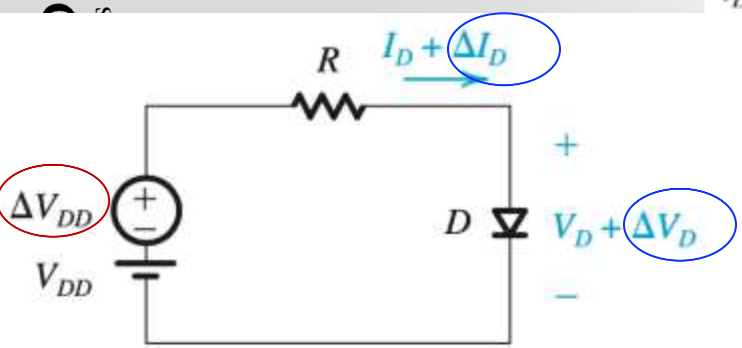
近似前提：$\frac{v_d}{V_T} \ll 1$

$$i_D(t) \simeq I_D\left(1+\frac{v_d}{V_T}\right) \Longrightarrow i_D(t) = I_D + \boxed{\frac{I_D}{V_T}} v_d$$

一般来说，当$v_d < (1/5)V_T$时，可近似，即**v_d < 5mV** 时可近似



定义：$\boxed{r_d = \frac{V_T}{I_D}}$



$$i_D(t) = I_D + \boxed{\frac{I_D}{V_T}} v_d \qquad \boxed{r_d = \frac{V_T}{I_D}}$$

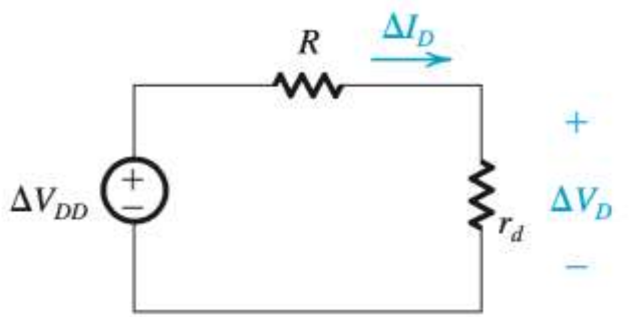
有微小变化量时的分析方法：因为输入总量是直流和小信号变化量的线性叠加，所以

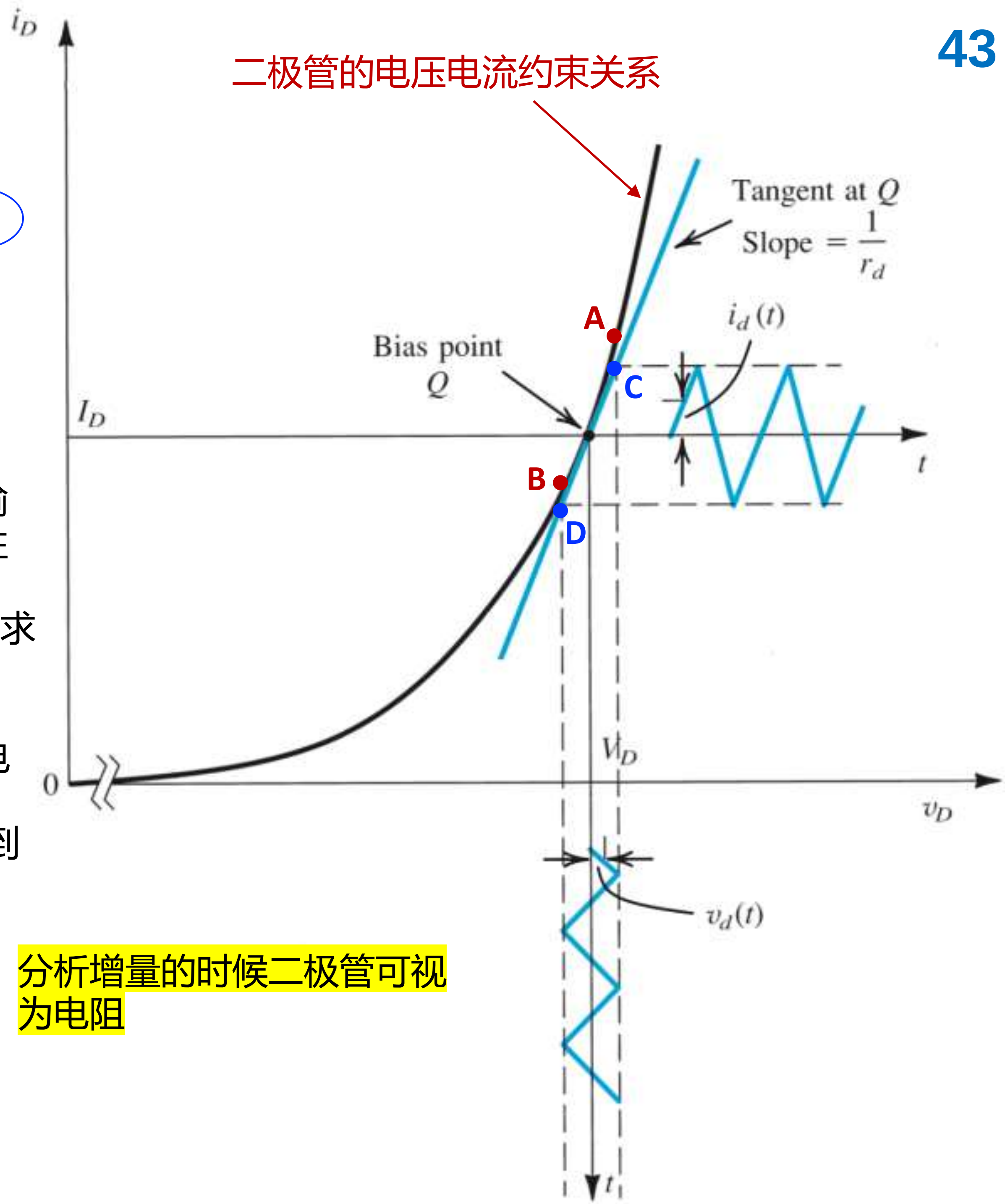
①先做直流分析（turn off ΔV_{DD}），求出I_D

②根据I_D计算出小信号参数r_d

③再做小信号分析（turn off V_{DD}）电阻不变，**二极管用小信号模型r_d代替**

④最后将直流和小信号相叠加，得到完整的时域信号





分析增量的时候二极管可视为电阻

Consider the circuit shown in Fig. 4.16(a) for the case in which $R = 10\,\mathrm{k}\Omega$. The power supply V^+ has a dc value of 10 V on which is superimposed a 60-Hz sinusoid of 1-V peak amplitude. (This "signal" component of the power-supply voltage is an imperfection in the power-supply design. It is known as the **power-supply ripple**. More on this later.) Calculate both the dc voltage of the diode and the amplitude of the sine-wave signal appearing across it. Assume the diode to have a 0.7-V drop at 1-mA current.

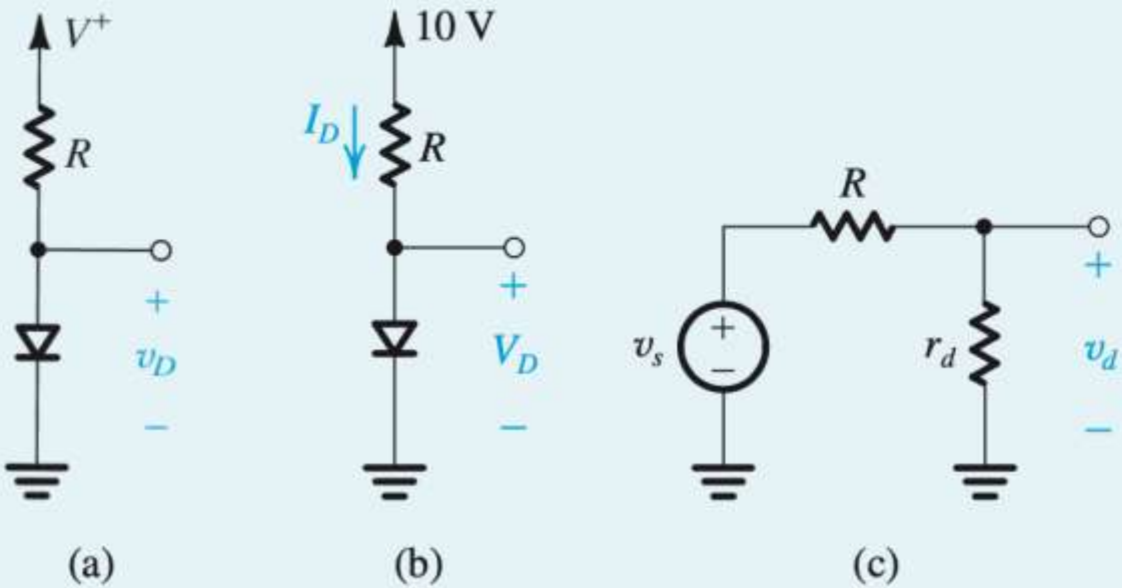


Figure 4.16 **(a)** Circuit for Example 4.5. **(b)** Circuit for calculating the dc operating point. **(c)** Small-signal equivalent circuit.

①直流分析 $V_D \simeq 0.7\ \mathrm{V}$ $\quad I_D = \dfrac{10-0.7}{10} = 0.93\ \mathrm{mA}$

Example 4.5

Consider the circuit shown in Fig. 4.16(a) for the case in which $R = 10\,k\Omega$. The power supply V^+ has a dc value of 10 V on which is superimposed a 60-Hz sinusoid of 1-V peak amplitude. (This "signal" component of the power-supply voltage is an imperfection in the power-supply design. It is known as the **power-supply ripple**. More on this later.) Calculate both the dc voltage of the diode and the amplitude of the sine-wave signal appearing across it. Assume the diode to have a 0.7-V drop at 1-mA current.

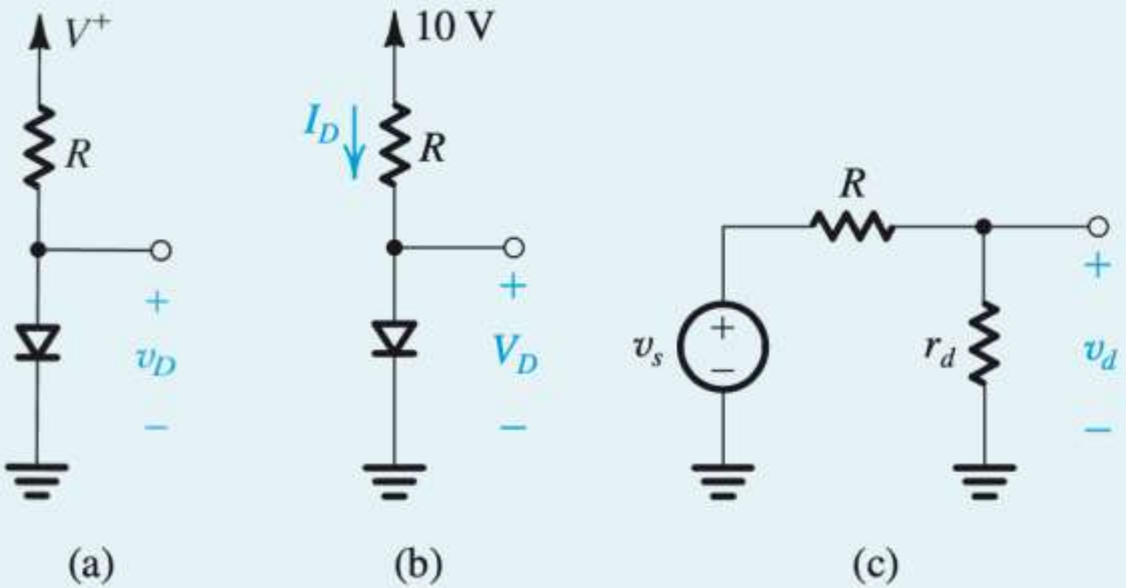


Figure 4.16 **(a)** Circuit for Example 4.5. **(b)** Circuit for calculating the dc operating point. **(c)** Small-signal equivalent circuit.

②计算小信号参数

$$r_d = \frac{V_T}{I_D} = \frac{25}{0.93} = 26.9\ \Omega$$

* Sedra 的教材为了计算简单，将26 mV 近似成 25 mV

Example 4.5

Consider the circuit shown in Fig. 4.16(a) for the case in which $R = 10\,\mathrm{k\Omega}$. The power supply V^+ has a dc value of 10 V on which is superimposed a 60-Hz sinusoid of 1-V peak amplitude. (This "signal" component of the power-supply voltage is an imperfection in the power-supply design. It is known as the **power-supply ripple**. More on this later.) Calculate both the dc voltage of the diode and the amplitude of the sine-wave signal appearing across it. Assume the diode to have a 0.7-V drop at 1-mA current.

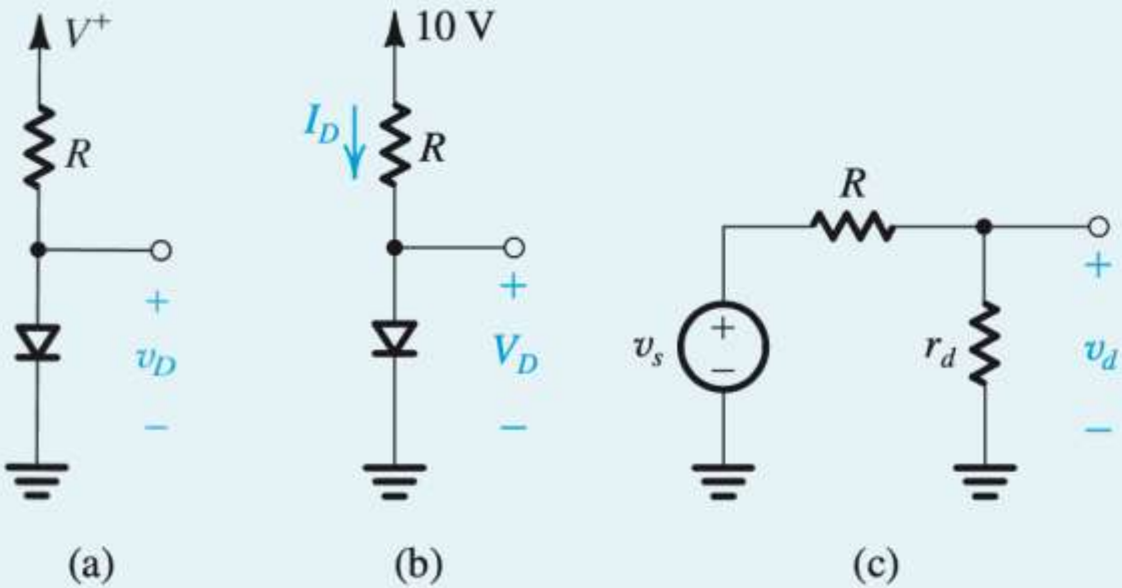
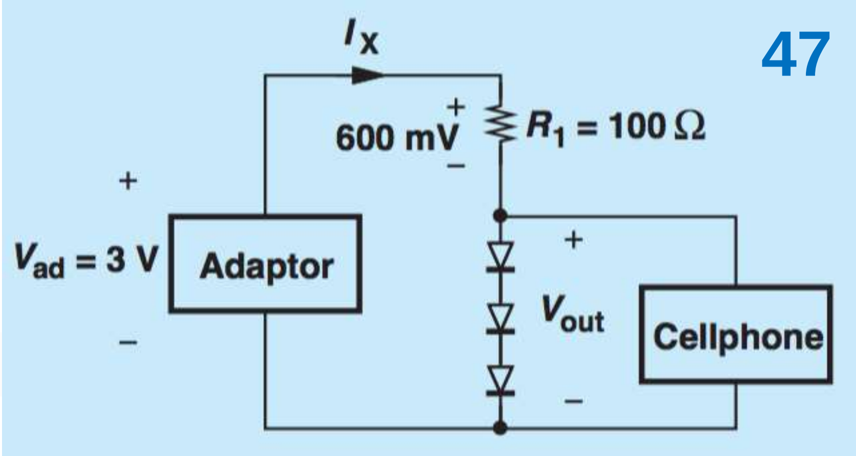


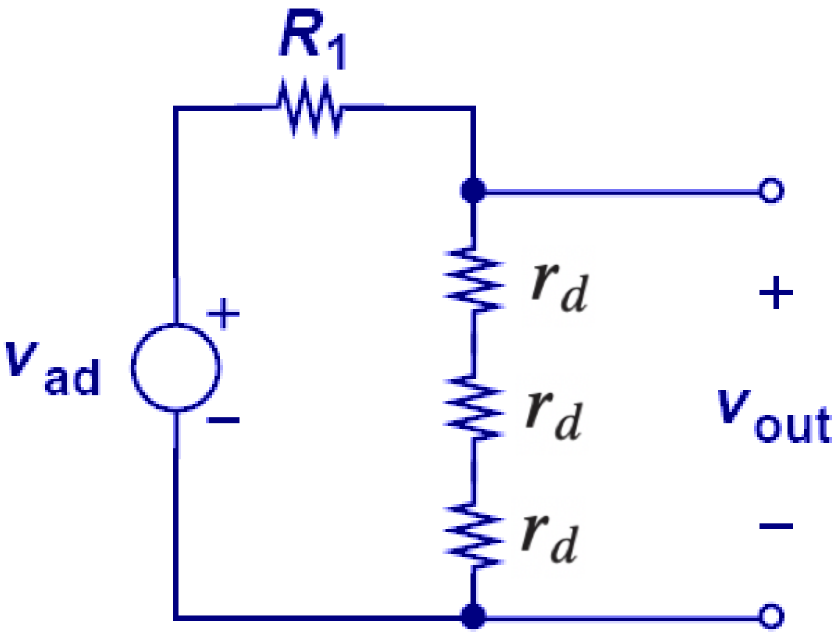
Figure 4.16 **(a)** Circuit for Example 4.5. **(b)** Circuit for calculating the dc operating point. **(c)** Small-signal equivalent circuit.

③小信号分析（等效电路参见图c）

$$v_d(\text{peak}) = \hat{V}_s \frac{r_d}{R + r_d} = 1 \frac{0.0269}{10 + 0.0269} = 2.68\ \text{mV}$$

Adapter Example Revisited





假设 $V_D = 800$ mV

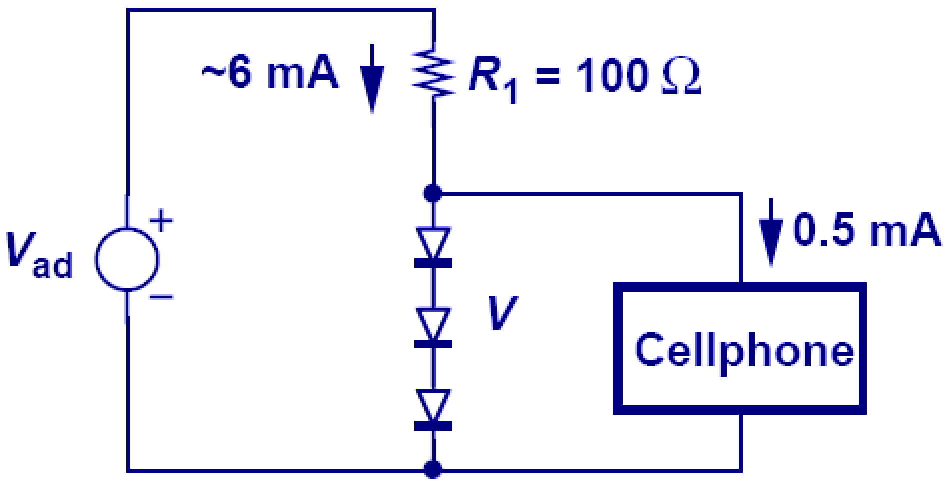
$$r_d = (26\,\mathrm{mV})/(6\,\mathrm{mA}) = 4.33\ \Omega$$

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

输入电压变化100mV~输出变化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



小信号分析需验证近似前提是否成立
每个二极管上电压变化约2.2mV，小于25mV，小信号近似适用

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

注意验证

假设 6 mA 不变

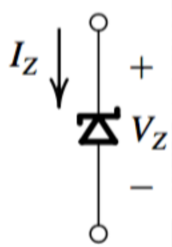
- 当不接入手机时，二极管上流过的电流为 6 mA
- 当接入手机后，手机分流走0.5mA，二极管上流过的电流变为 5.5 mA，请问给三个二极管串联的总电压变化多少？

- 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.

4.4. Operation in the Reverse Breakdown Region – Zener Diodes 反向截止区作为稳压器，齐纳二极管

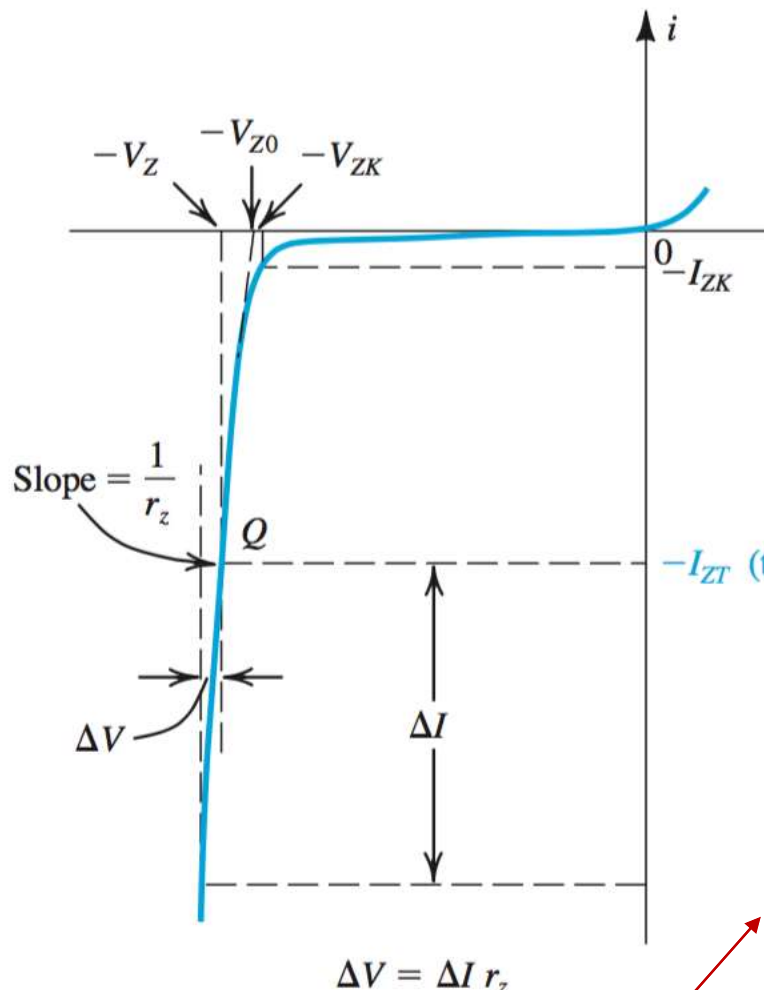
齐纳二极管稳压器**已基本不用**，现在实用的稳压器（voltage regulator）都用 IC 实现

- Under certain circumstances, diodes may be intentionally used in the reverse breakdown region.
- These are referred to as **Zener Diodes**.

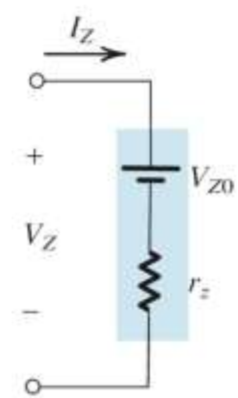


齐纳二极管的符号

- V_{ZK}，I_{ZK}，反向截止区的起始点
- V_Z，I_{ZT}，工作点
- V_{Z0}，线性化与横坐标的交点



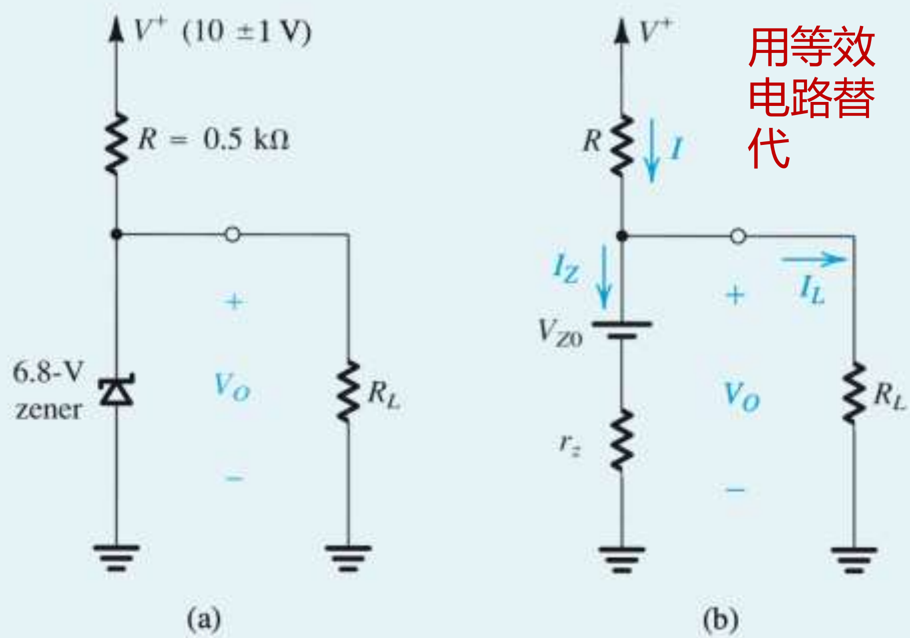
等效电路，用电路描述线性化区域：



Example 4.7

The 6.8-V zener diode in the circuit of Fig. 4.21(a) is specified to have $V_Z = 6.8$ V at $I_Z = 5$ mA, $r_z = 20\ \Omega$, and $I_{ZK} = 0.2$ mA. The supply voltage V^+ is nominally 10 V but can vary by ±1 V.

(a) Find V_O with no load and with V^+ at its nominal value.
(b) Find the change in V_O resulting from the ±1-V change in V^+. Note that $(\Delta V_O/\Delta V^+)$, usually expressed in mV/V, is known as **line regulation**.
(c) Find the change in V_O resulting from connecting a load resistance R_L that draws a current $I_L = 1$ mA, and hence find the **load regulation** $(\Delta V_O/\Delta I_L)$ in mV/mA.
(d) Find the change in V_O when $R_L = 2$ kΩ.
(e) Find the value of V_O when $R_L = 0.5$ kΩ.
(f) What is the minimum value of R_L for which the diode still operates in the breakdown region?



用等效电路替代

第一步，求V_{Z0}

已知直线斜率，某一点坐标，求与x轴的交点

$V_Z = 6.8$ V, $I_Z = 5$ mA, and $r_z = 20\ \Omega$ $\Longrightarrow$ $V_{Z0} = 6.7$ V.

(a) 不接负载时

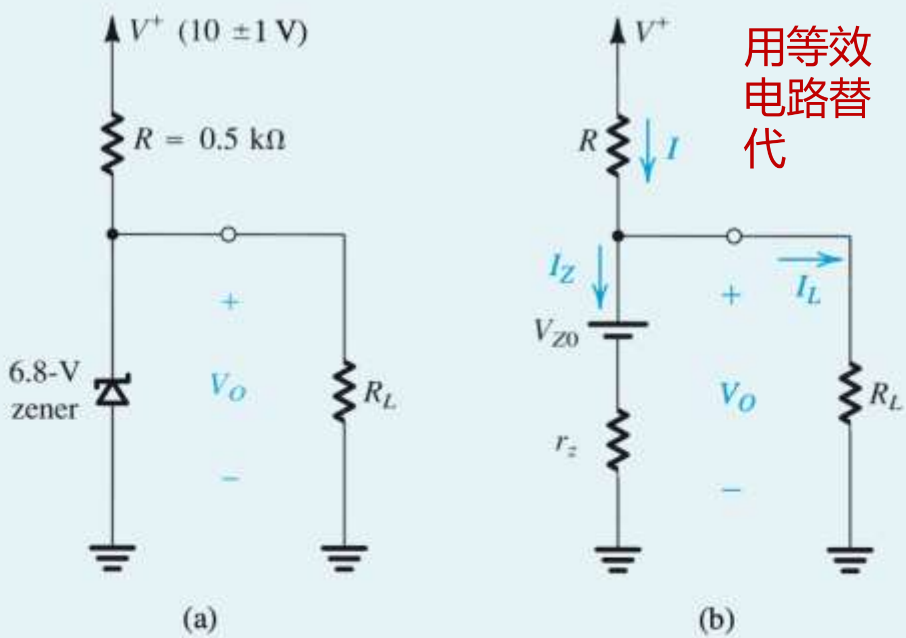
$$I_Z = I = \frac{V^+ - V_{Z0}}{R + r_z} = \frac{10 - 6.7}{0.5 + 0.02} = 6.35 \text{ mA}$$

$$V_O = V_{Z0} + I_Z r_z = 6.7 + 6.35 \times 0.02 = 6.83 \text{ V}$$

Example 4.7

The 6.8-V zener diode in the circuit of Fig. 4.21(a) is specified to have $V_Z = 6.8$ V at $I_Z = 5$ mA, $r_z = 20\ \Omega$, and $I_{ZK} = 0.2$ mA. The supply voltage V^+ is nominally 10 V but can vary by ±1 V.

(a) Find V_O with no load and with V^+ at its nominal value.
(b) Find the change in V_O resulting from the ±1-V change in V^+. Note that $(\Delta V_O/\Delta V^+)$, usually expressed in mV/V, is known as **line regulation**.
(c) Find the change in V_O resulting from connecting a load resistance R_L that draws a current $I_L = 1$ mA, and hence find the **load regulation** $(\Delta V_O/\Delta I_L)$ in mV/mA.
(d) Find the change in V_O when $R_L = 2$ kΩ.
(e) Find the value of V_O when $R_L = 0.5$ kΩ.
(f) What is the minimum value of R_L for which the diode still operates in the breakdown region?



用等效电路替代

(b) 供电电压变化时

$$\Delta V_O = \Delta V^+ \frac{r_z}{R + r_z}$$

$$= \pm 1 \times \frac{20}{500 + 20} = \pm 38.5 \text{ mV}$$

(c) 负载变化时

$$\Delta V_O = r_z \Delta I_Z$$

$$= 20 \times -1 = -20 \text{ mV}$$

【例 1.2.2】 在图 1.2.11 所示稳压管稳压电路中，已知稳压管的稳定电压 $U_Z = 6$ V，最小稳定电流 $I_{Zmin} = 5$ mA，最大稳定电流 $I_{Zmax} = 25$ mA；负载电阻 $R_L = 600\ \Omega$ 电阻。求解限流电阻 R 的取值范围。

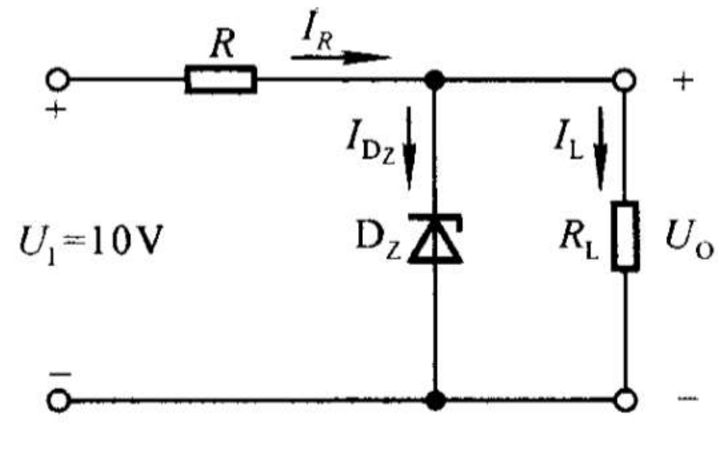


图 1.2.11 稳压管稳压电路

解：从图 1.2.11 所示电路可知，R 上电流 I_R 等于稳压管中电流 I_{D_Z} 和负载电流 I_L 之和，即 $I_R = I_{D_Z} + I_L$。其中 $I_{D_Z} = (5 \sim 25)$ mA，$I_L = U_Z/R_L = (6/600)$ A $= 0.01$ A $= 10$ mA，所以 $I_R = (15 \sim 35)$ mA。

R 上电压 $U_R = U_I - U_Z = (10 - 6)$ V $= 4$ V，因此

$$R_{max} = \frac{U_R}{I_{Rmin}} = \left(\frac{4}{15 \times 10^{-3}}\right)\Omega \approx 227\ \Omega$$

$$R_{min} = \frac{U_R}{I_{Rmax}} = \left(\frac{4}{35 \times 10^{-3}}\right)\Omega \approx 114\ \Omega$$

限流电阻 R 的取值范围为 $114 \sim 227\ \Omega$。

4.5. Rectifier Circuits 整流电路

- One important application of diode is the **rectifier** –
  - Electrical device which converts alternating current (AC) to direct current (DC)
- One important application of rectifier is dc power supply.

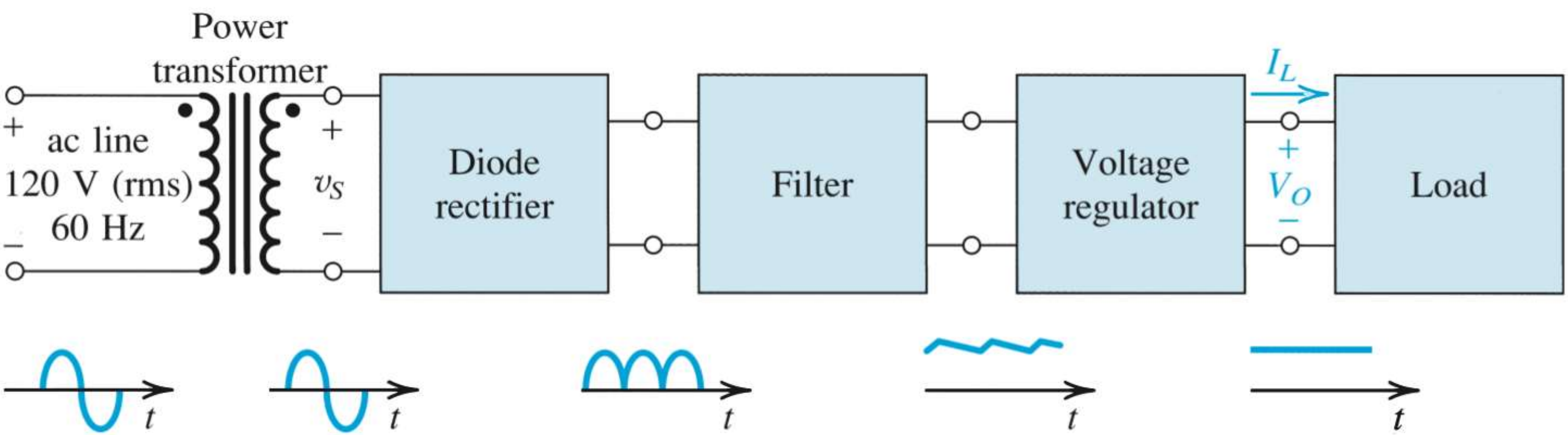


Figure 4.22 Block diagram of a dc power supply.

step #1: increase / decrease rms magnitude of AC wave via power transformer

step #2: convert full-wave AC to half-wave DC (still time-varying and periodic)

step #3: 滤去高频分量，使曲线更光滑

step #4: employ voltage regulator to eliminate ripple

step #5: supply dc load

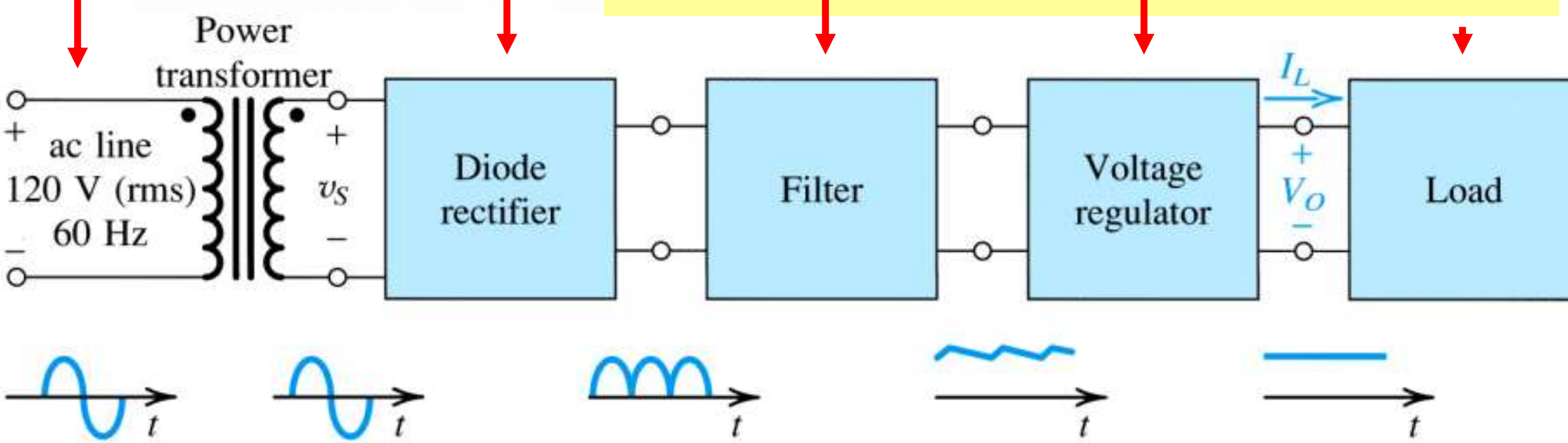


Figure 4.20: Block diagram of a dc power supply

4.5.1. The Half-Wave Rectifier 半波整流

- **half-wave rectifier** – utilizes only alternate half-cycles of the input sinusoid
  - Constant voltage drop diode model is employed.

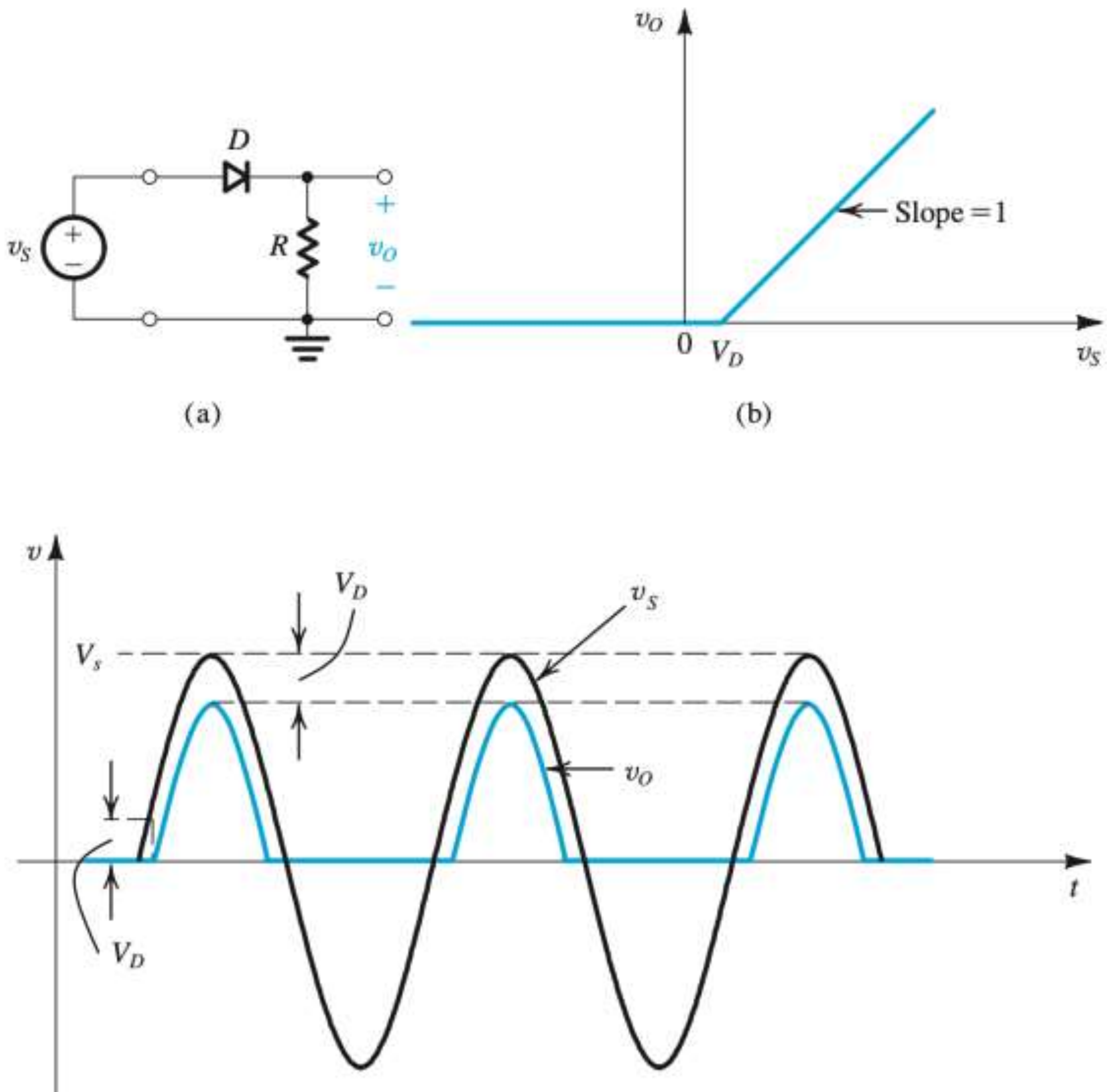


Figure 4.21: (a) Half-wave rectifier **(b)** Transfer characteristic of the rectifier circuit **(c)** Input and output waveforms

4.5.1. The Half-Wave Rectifier

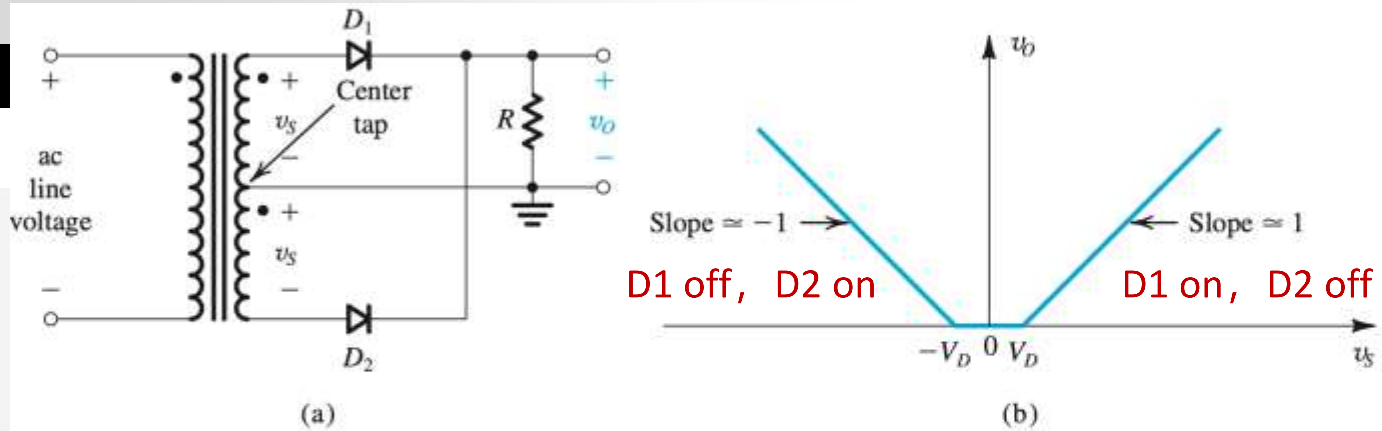
- **current-handling capability** – what is maximum forward current diode is expected to conduct?
- **peak inverse voltage (PIV)** – what is maximum reverse voltage it is expected to block w/o breakdown?
- 需关注两个参数：最大正向电流、最大反向电压

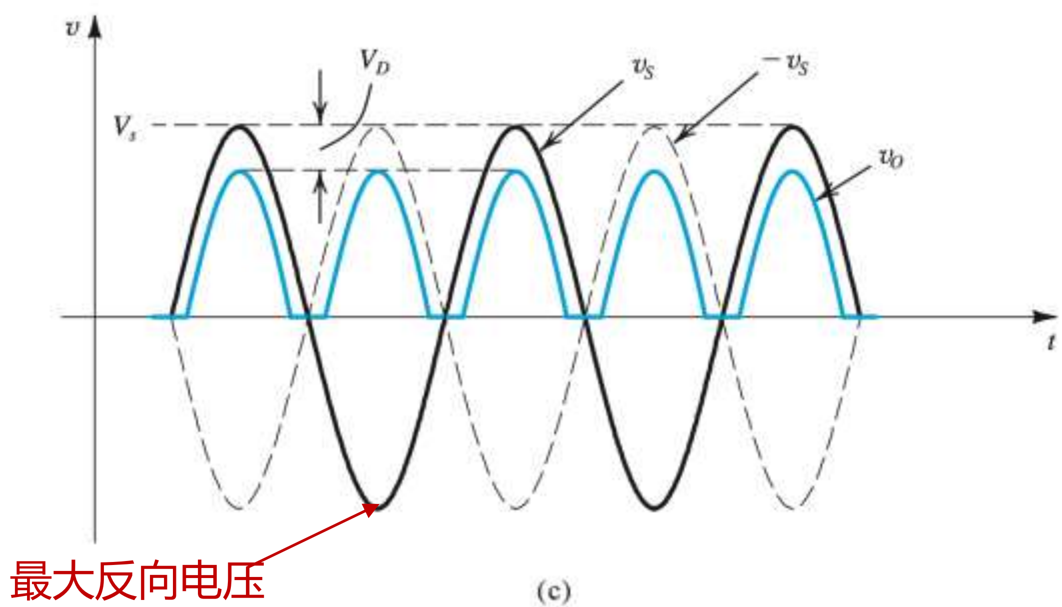
4.5.1. The Half-Wave Rectifier

- **exponential model?** It is possible to use the diode exponential model in describing rectifier operation; however, this requires too much work.
- **small inputs?** Regardless of the model employed, one should note that the rectifier will not operate properly when input voltage is small (< 1*V*).
  - Those cases require a **precision rectifier.**
  - 半波整流电路只适合于输入较大的信号

4.5.2. The Full-Wave Rectifier

全波整流的实现方法之一





4.5.2. The Full-Wave Rectifier

1. 流经负载的电流方向不变
2. 相比半波整流利用率更高
3. 最大反向电压较大

- **Q:** What are most important observation(s) from this operation?
  - **A:** The direction of current flowing across load never changes (both halves of AC wave are rectified). The full-wave rectifier produces a more "energetic" waveform than half-wave.
    - PIV for full-wave = $2V_S - V_D$

4.5.3. The Bridge Rectifier

全波整流的实现方法之二：
桥式整流

- An alternative implementation of the full-wave rectifier is **bridge rectifier.**
  - Shown to right.

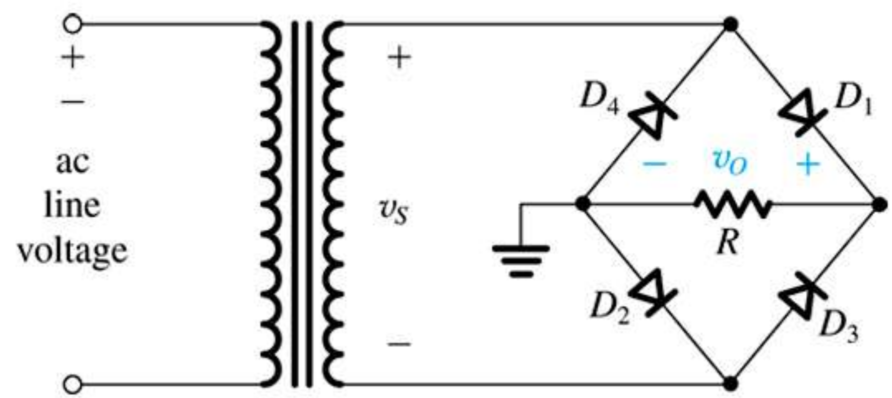


Figure 4.23: The bridge rectifier circuit.

when instantaneous source voltage is **positive**, D_1 and D_2 on while D_3 *and* D_4 off

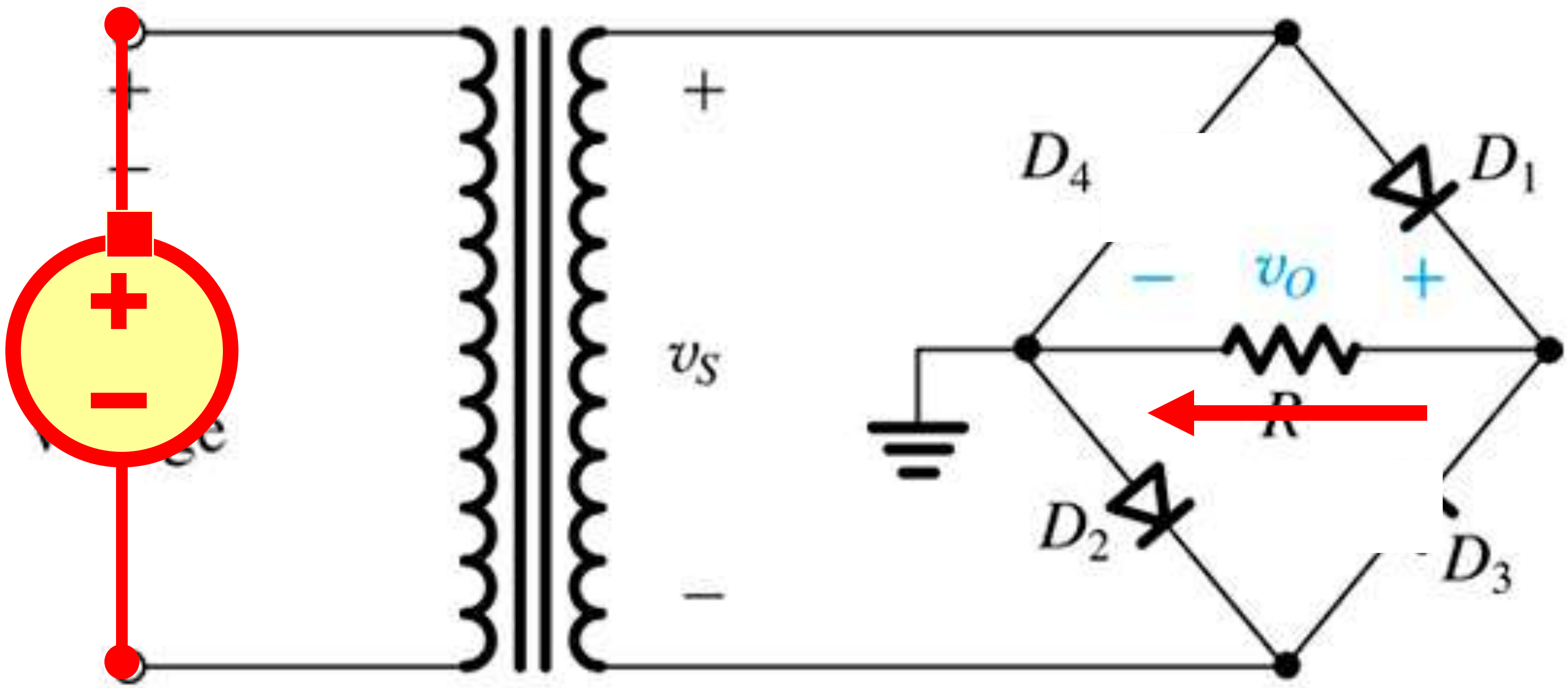


Figure 4.23: The bridge rectifier circuit.

when instantaneous source voltage is **negative**, D_1 and D_2 off while D_3 *and* D_4 on

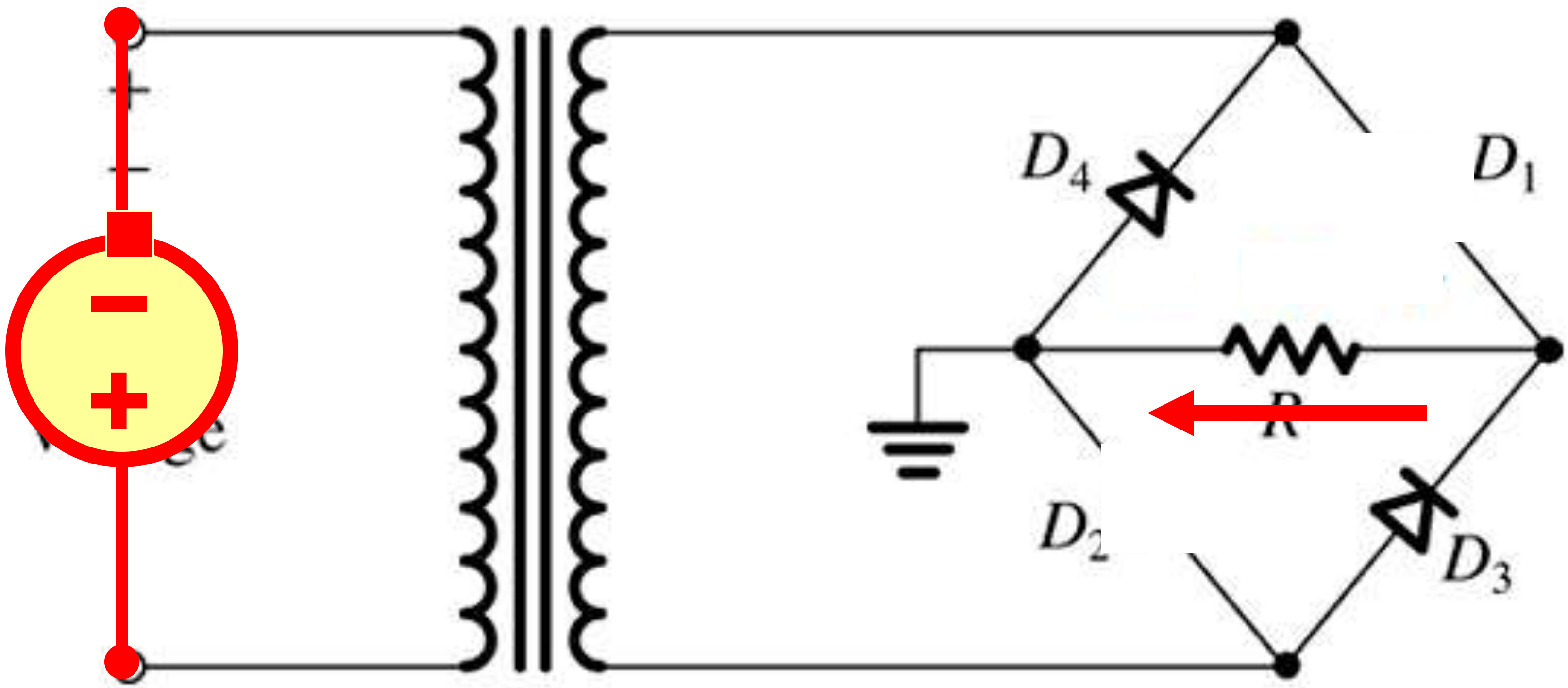
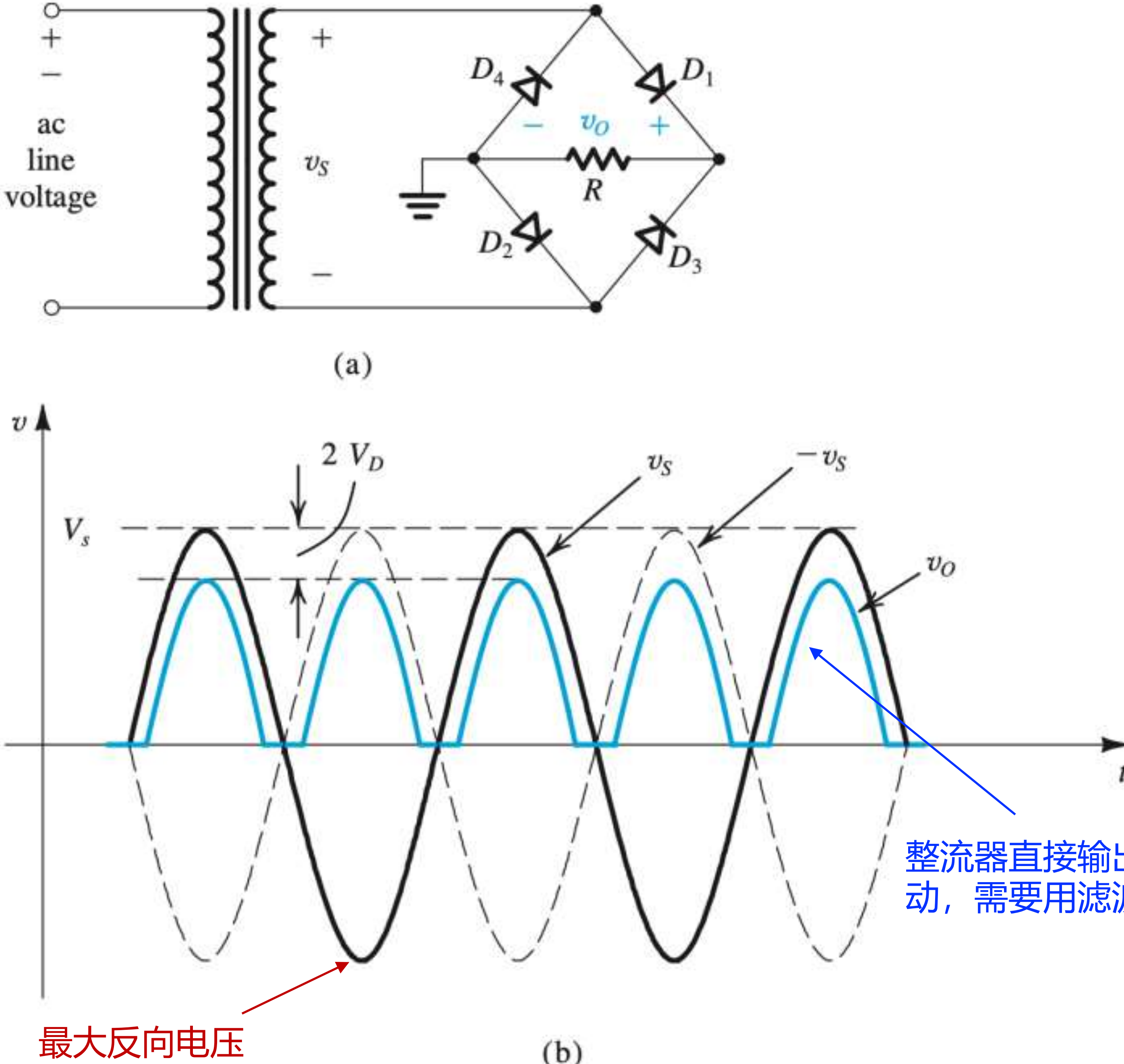


Figure 4.23: The bridge rectifier circuit.



整流器直接输出有较大波
动，需要用滤波器滤除

最大反向电压
被两个二极管分摊

Figure 4.25 The bridge rectifier: **(a)** circuit; **(b)** input and output waveforms.

4.5.3: **The Bridge Rectifier (BR)**

- **Q:** What is the main advantage of BR?
  - **A:** No need for center-tapped transformer.
- **Q:** What is main disadvantage?
  - **A:** Series connection of TWO diodes will reduce output voltage.
- PIV = $V_S - V_D$

1. 无需变压器中间抽头
2. 最大反向电压较小；

- 但，输出电压有两个$V_{D,on}$的压差

4.5.4. The Rectifier with a Filter Capacitor 滤波电容

- Pulsating nature of rectifier output makes unreliable dc supply.
- As such, a **filter capacitor** is employed to remove ripple.

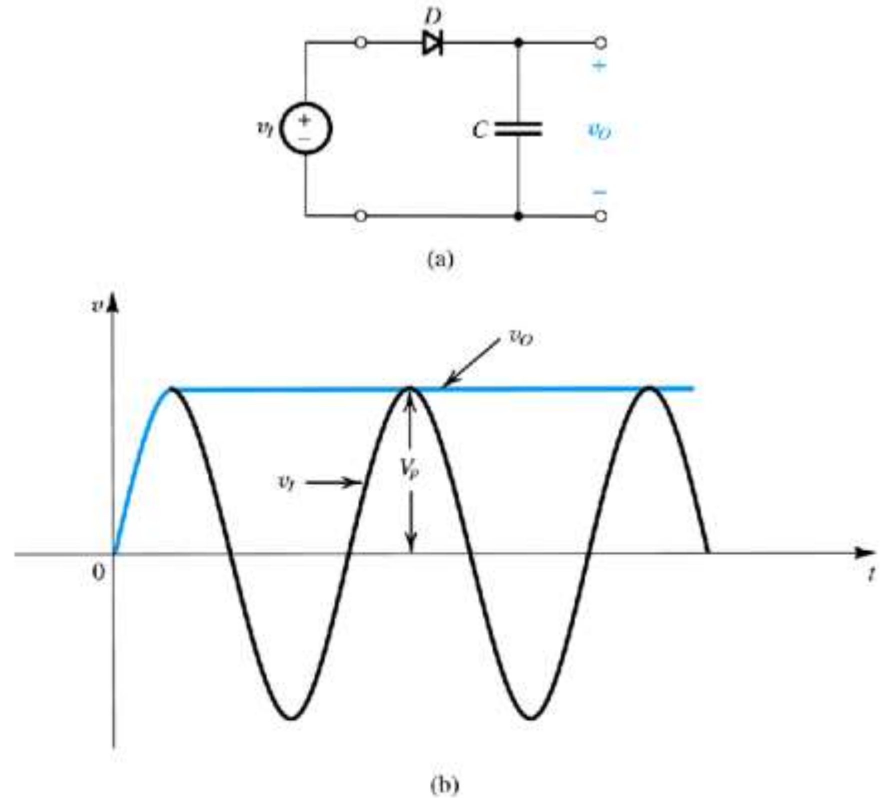


Figure 4.24: (a) A simple circuit used to illustrate the effect of a filter capacitor. **(b)** input and output waveforms assuming an ideal diode.

4.5.4. **The Rectifier with a Filter Capacitor**

- **step #1:** source voltage is positive, diode is forward biased, capacitor charges.
- **step #2:** source voltage is reverse, diode is reverse-biased (blocking), capacitor cannot discharge.
- **step #3:** source voltage is positive, diode is forward biased, capacitor charges (maintains voltage).

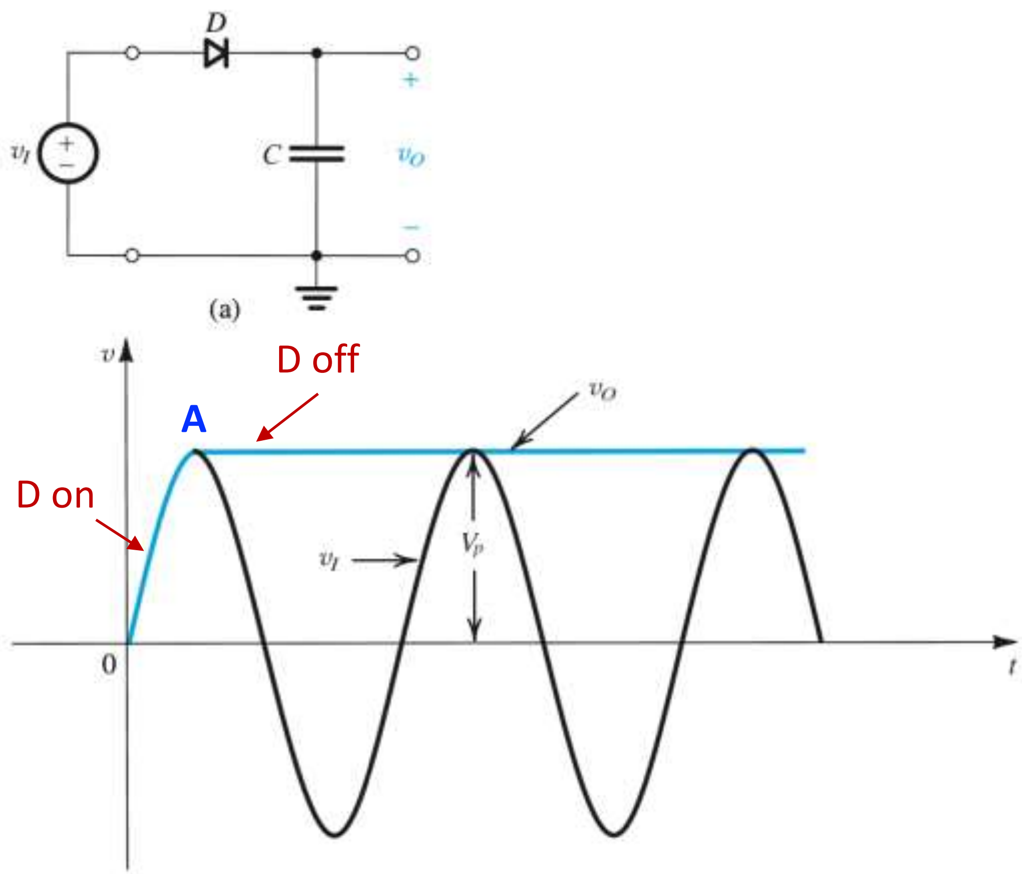


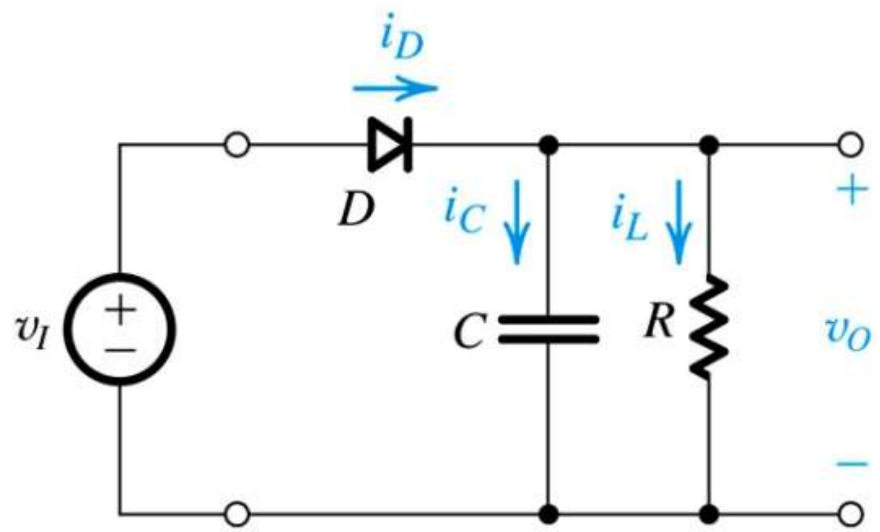
Figure 4.24 (a) A simple circuit used to illustrate the effect…

4.5.4. The Rectifier with a Filter Capacitor

- **Q:** Why is this example unrealistic?
  - **A:** Because for any practical application, the converter would supply a load (which in turn provides a path for capacitor discharging).

4.5.4. **The Rectifier with a Filter Capacitor**

- **Q:** What happens when **load resistor** is placed in parallel with capacitor?
  - **A:** One must now consider the discharging of capacitor across load.

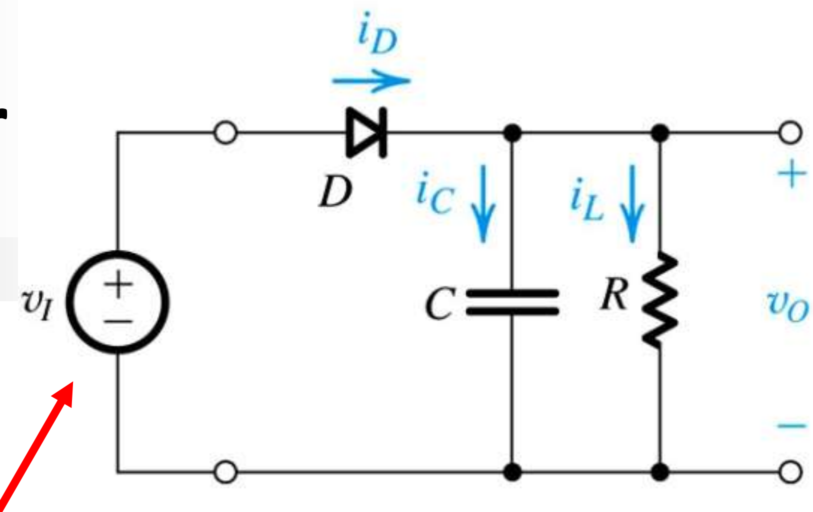


4.5.4. **The Rectifier with a Filter Capacitor**

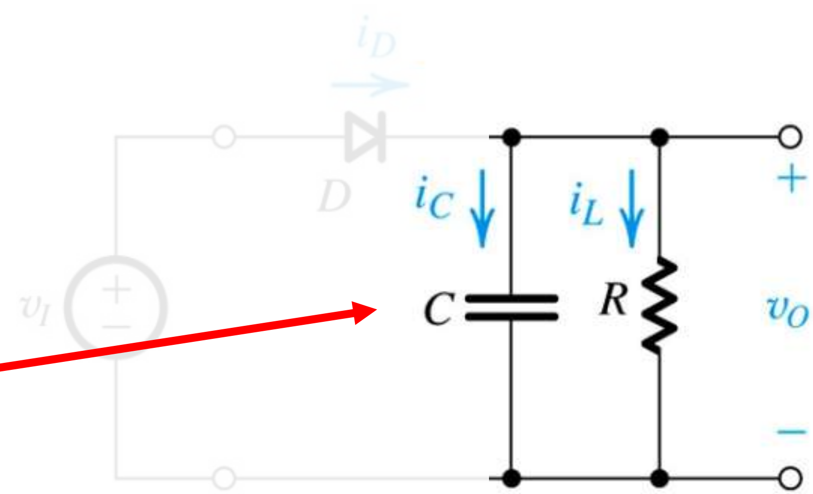
- The textbook outlines how **Laplace Transform** may be used to define behavior below.

$$\overbrace{v_O(t) = v_I(t) - v_D}^{\text{output voltage for state \#1}}$$

$$\underbrace{v_O(t) = V_{peak}e^{-\frac{t}{RC}}}_{\text{output voltage for state \#2}}$$



circuit state #1



circuit state #2

output voltage for state #1

$$v_O(t) = v_I(t)$$

$$v_O(t) = V_{peak} e^{-\frac{t}{RC}}$$

output voltage for state #2

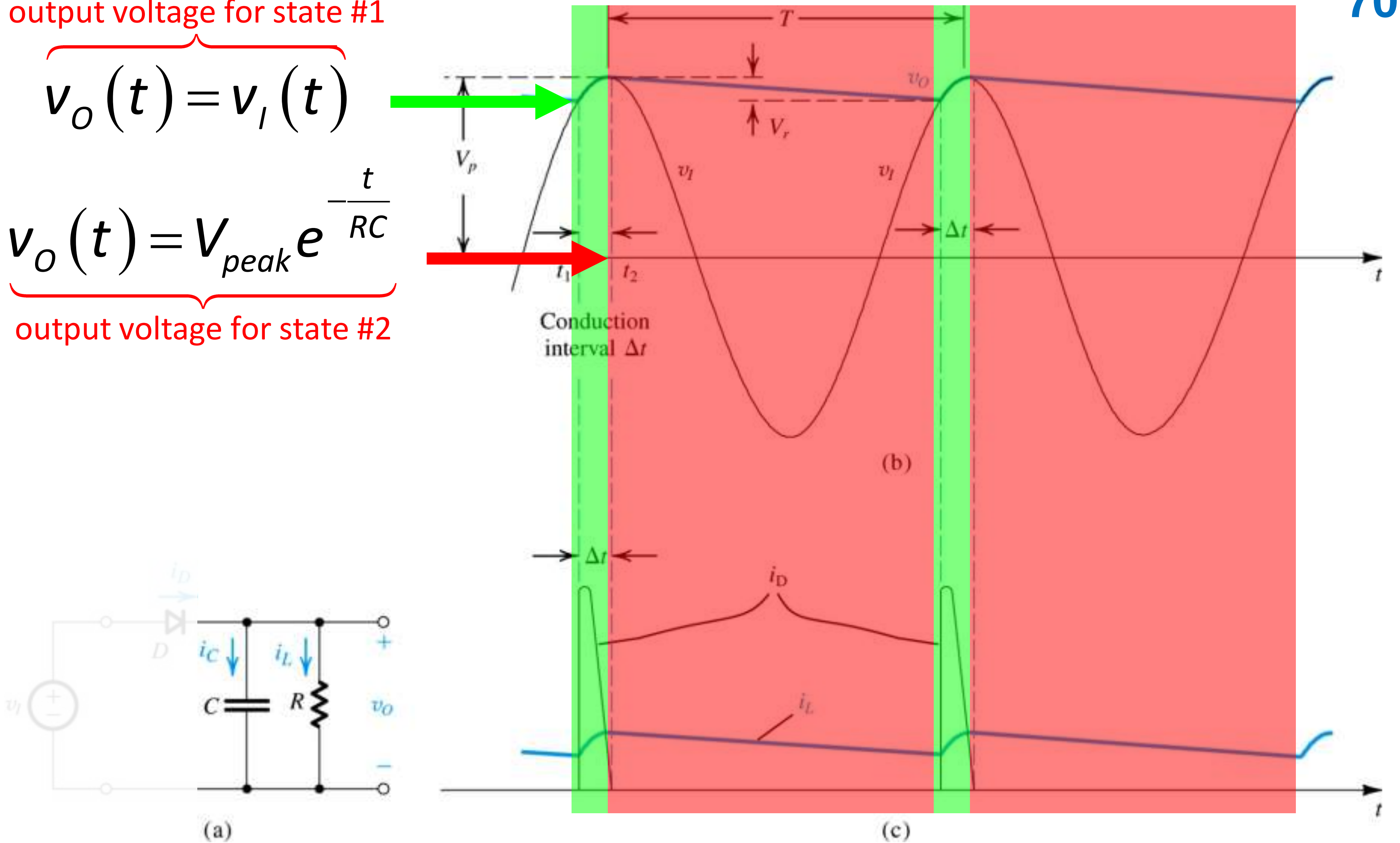


Figure 4.25: Voltage and Current Waveforms in the Peak Rectifier Circuit WITH *RC* >> *T*. The diode is assumed ideal.

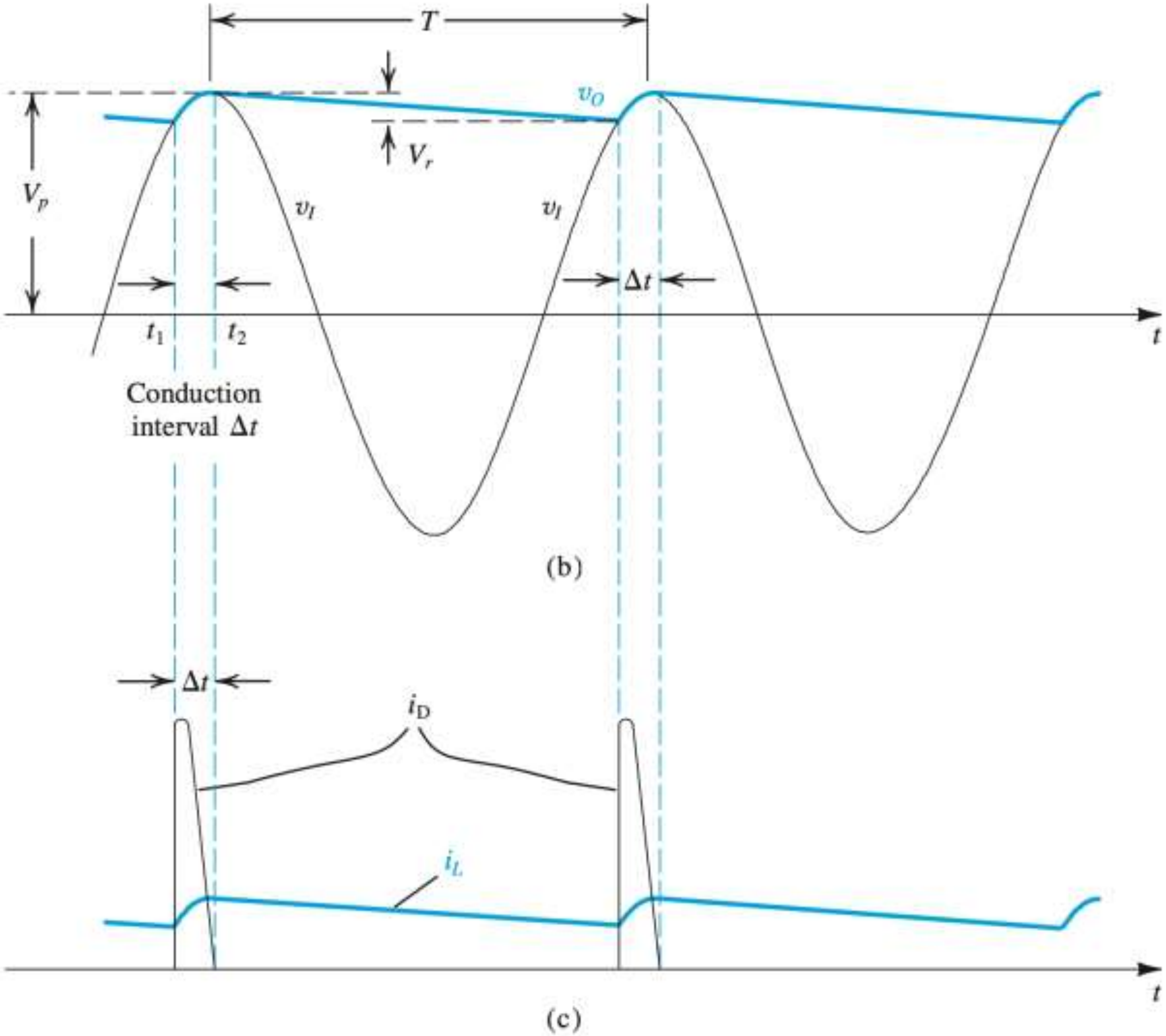


Figure 4.27 Voltage and current waveforms in the peak-rectifier circuit with $CR \gg T$. The diode is assumed ideal.

电容放电时：

$$v_O = V_p e^{-t/CR}$$

假设 $CR \gg T$，指数衰减变直线

$$V_r \simeq V_p \frac{T}{CR}$$

电容充电时间

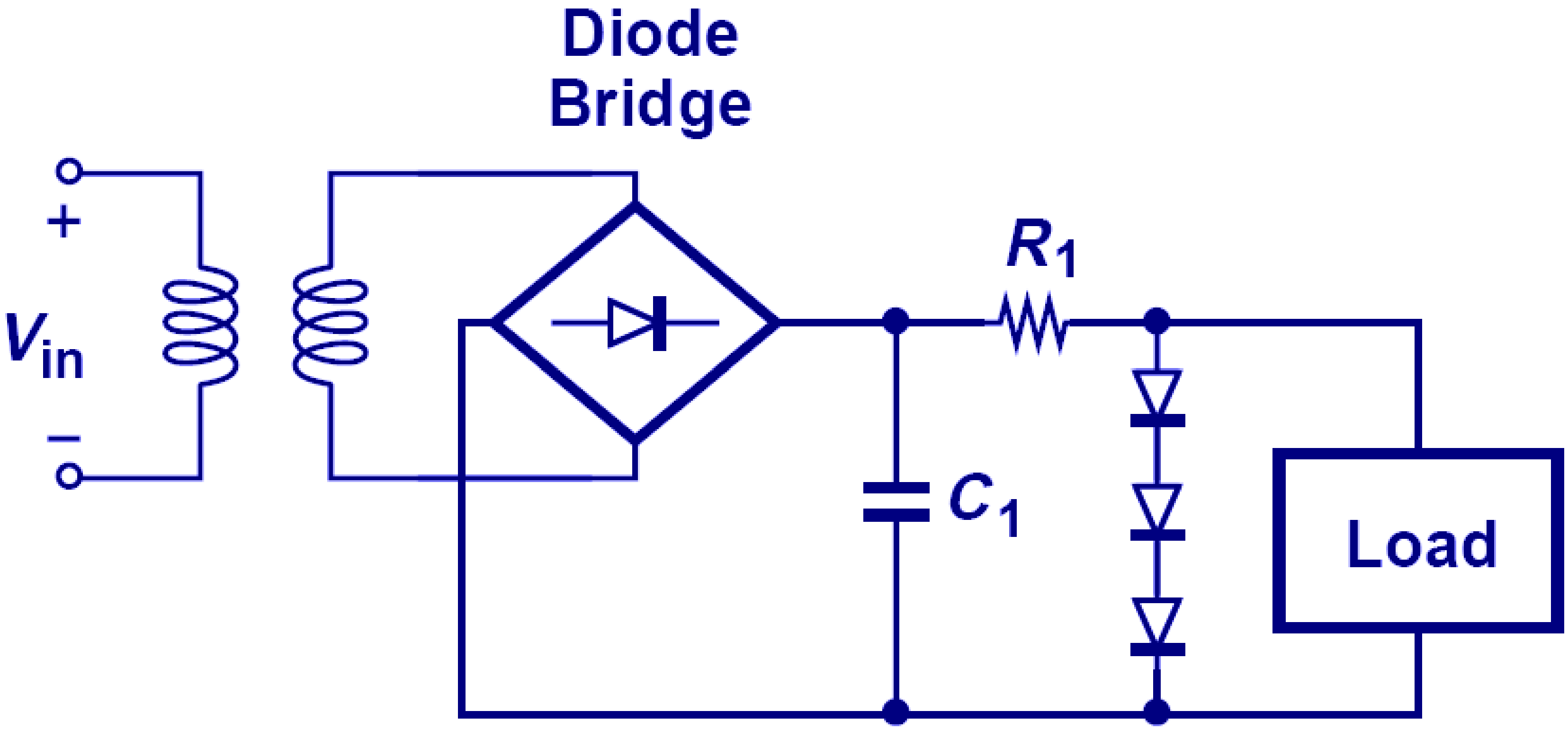
$$V_p \cos(\omega \Delta t) = V_p - V_r$$

近似 $\cos(\omega \Delta t) \simeq 1 - \frac{1}{2}(\omega \Delta t)^2$

$$\Rightarrow \quad \omega \Delta t \simeq \sqrt{2V_r/V_p}$$

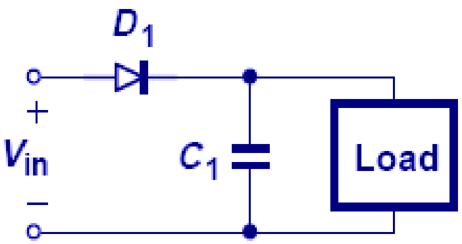
这一电路也可以用来检测波形的峰值，可用作**峰值检波电路**

滤波之后加稳压电路

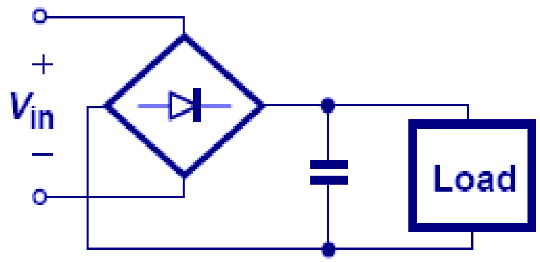


- The ripple created by the rectifier can be unacceptable to sensitive load; therefore, a regulator is required to obtain a very stable output.
- Three diodes operate as a primitive regulator.

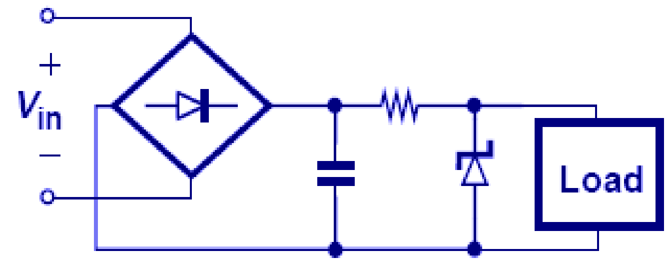
Evolution of AC-DC Converter



半波整流 + 滤波

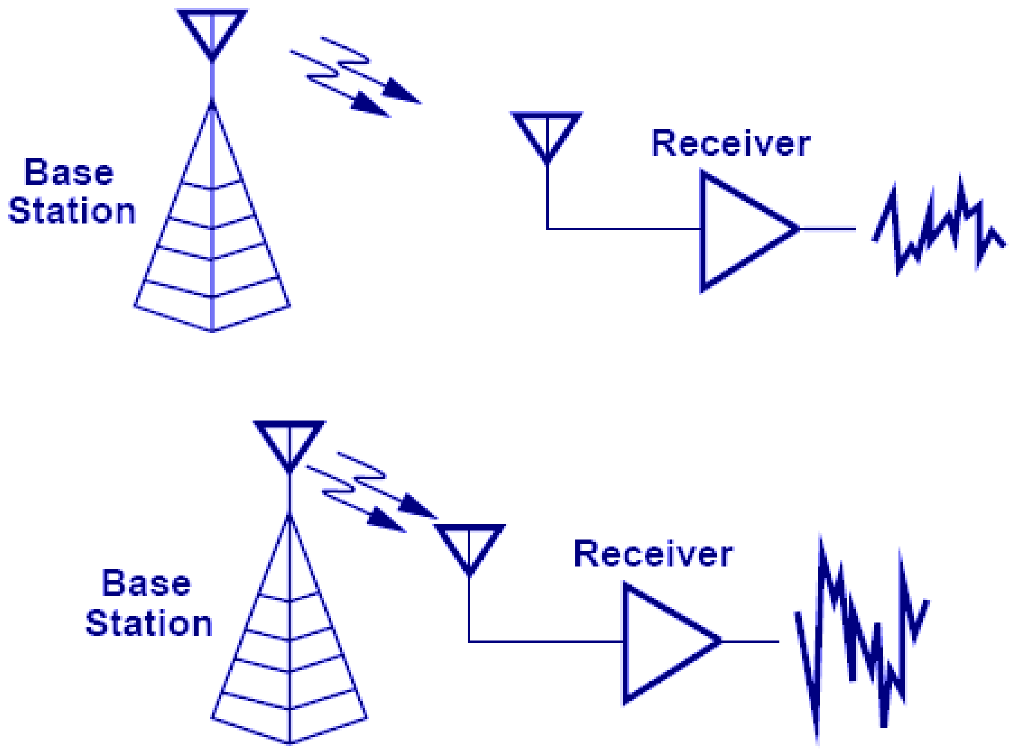


全波整流 + 滤波



全波整流 + 滤波 + 稳压

Limiting Circuits （限幅电路）



- 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.

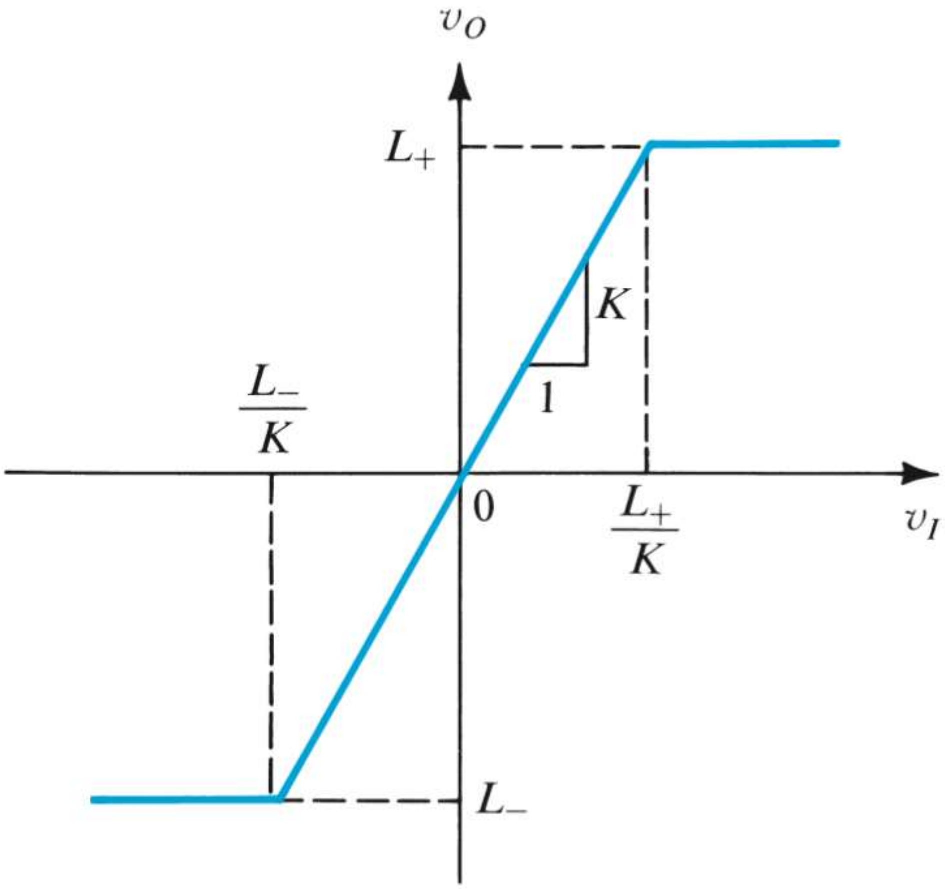
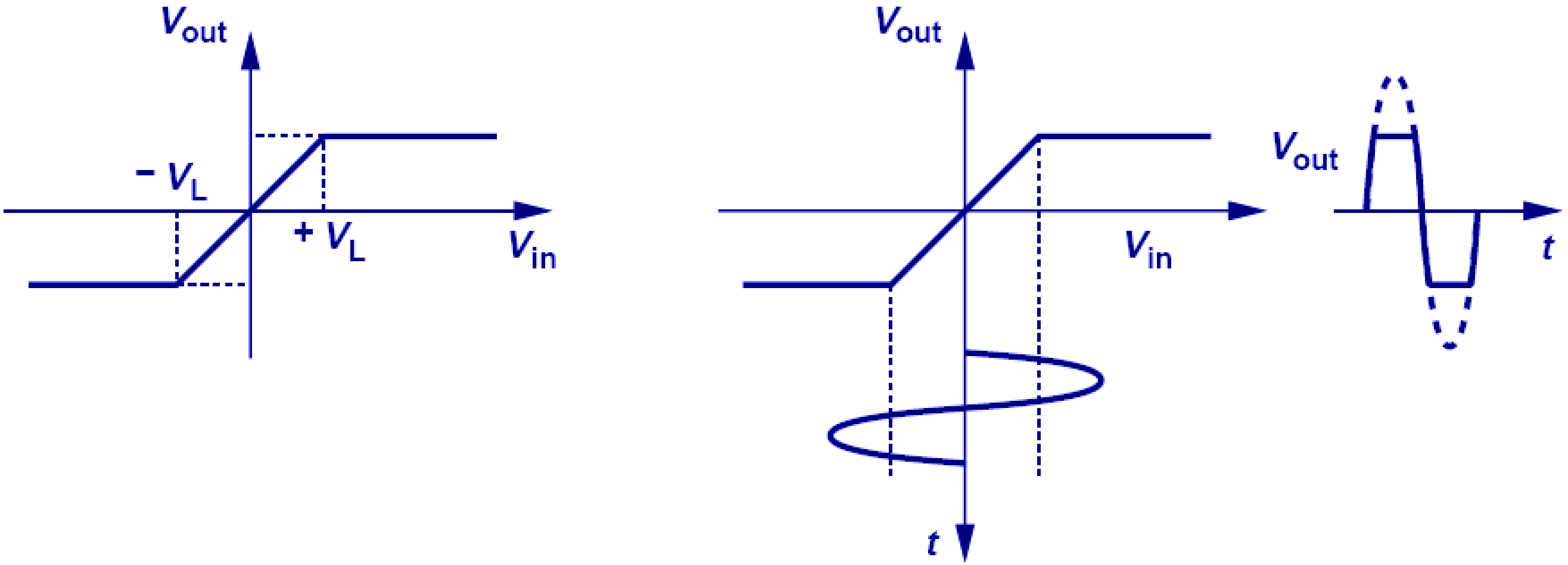


Figure 4.30 General transfer characteristic for a limiter circuit.

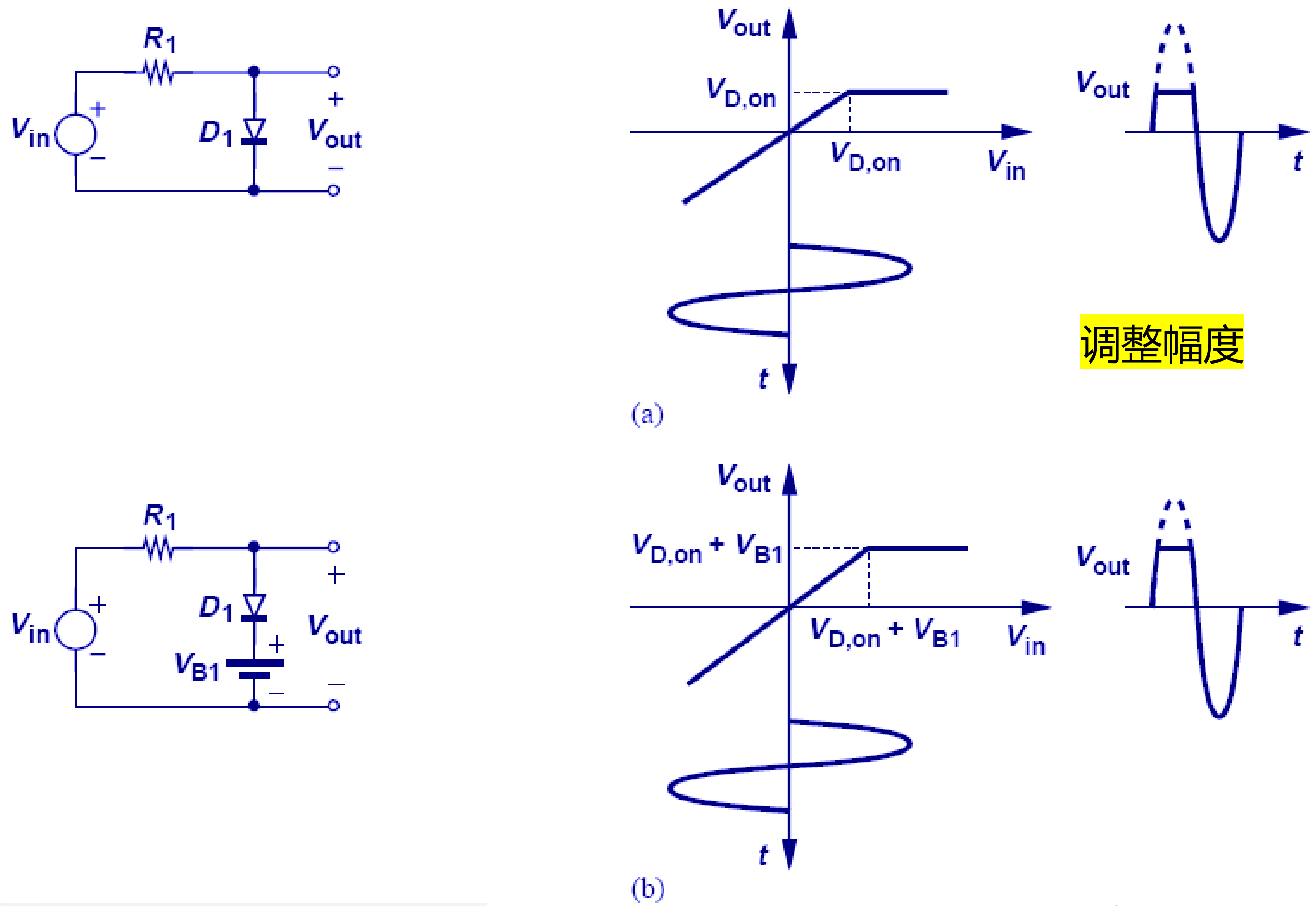
Input/Output Characteristics



(a) (b)

- Note the clipping of the output voltage.

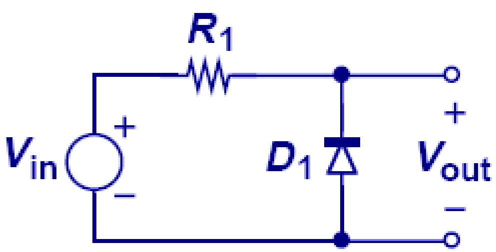
Limiting Circuit Using a Diode: Positive Cycle Clipping

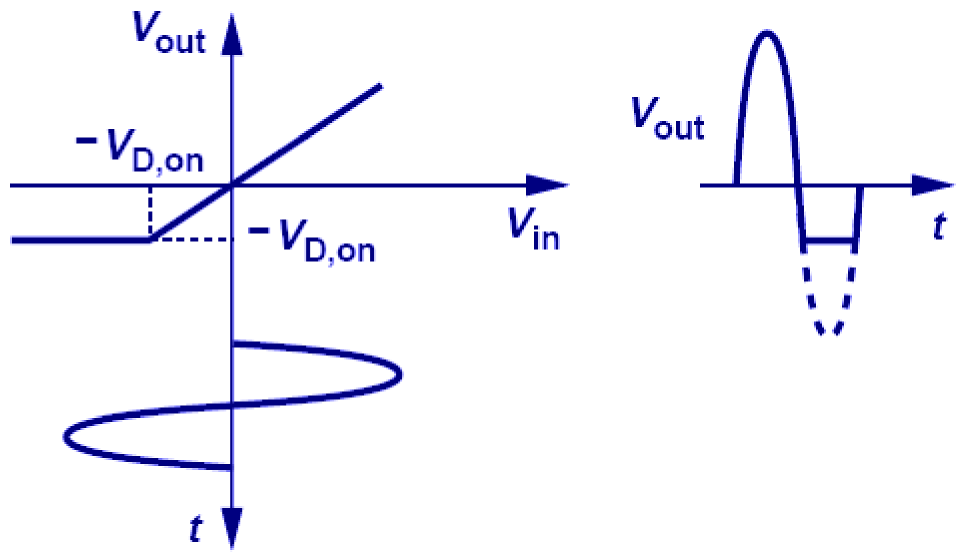


调整幅度

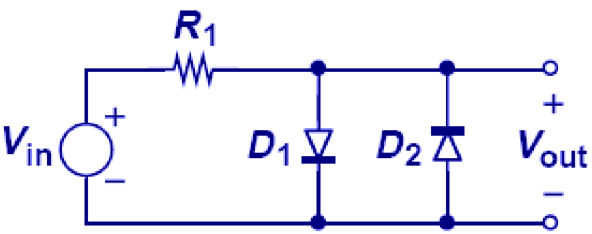
- As was studied in the past, the combination of resistor-diode creates limiting effect.

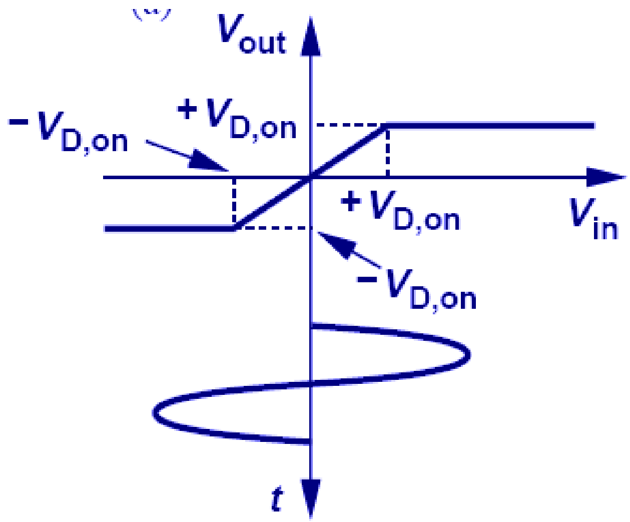
Limiting Circuit Using a Diode: Negative Cycle Clipping

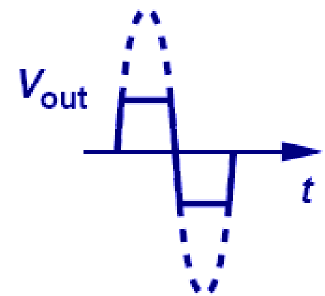




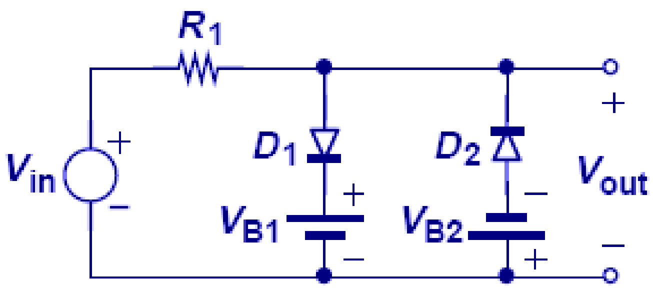
Limiting Circuit Using a Diode: Positive and Negative Cycle Clipping

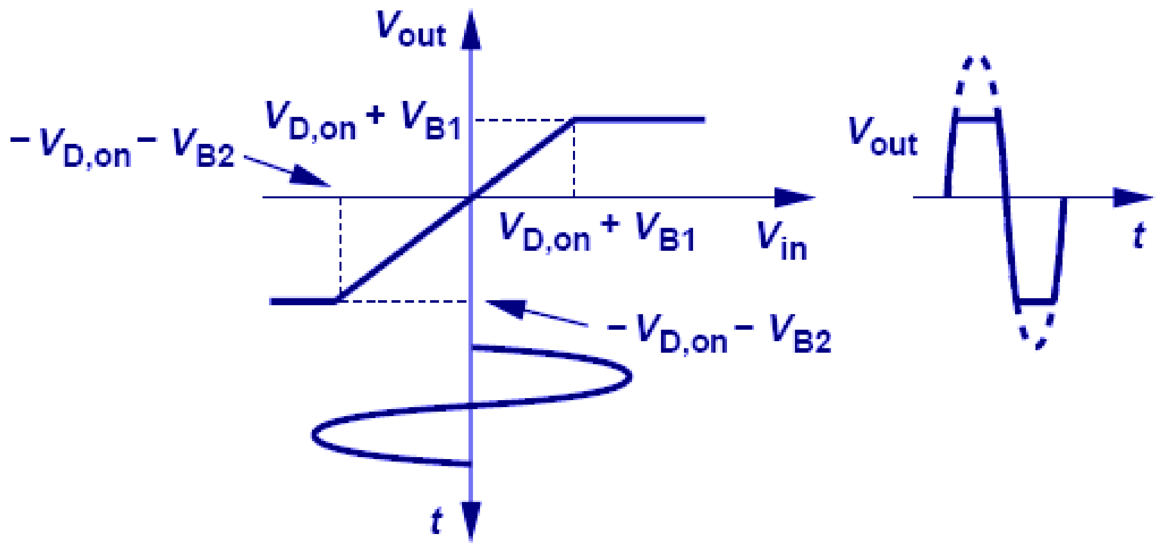






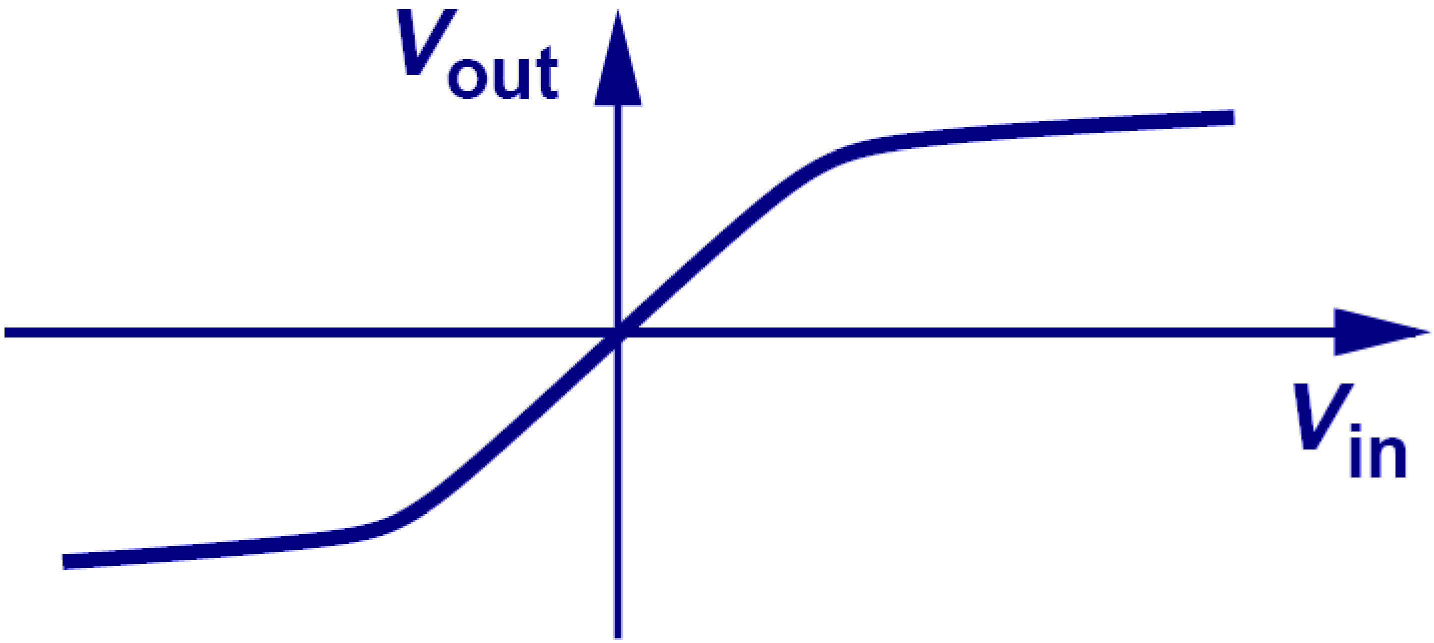
General Voltage Limiting Circuit





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

Non-idealities in Limiting Circuits

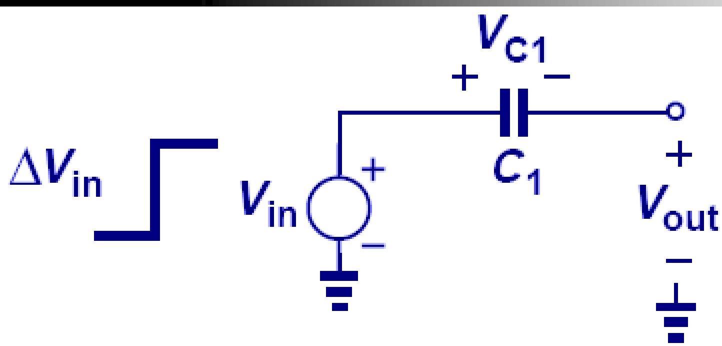


- The clipping region is not exactly flat since as Vin increases, the currents through diodes change, and so does the voltage drop.

Capacitive Divider

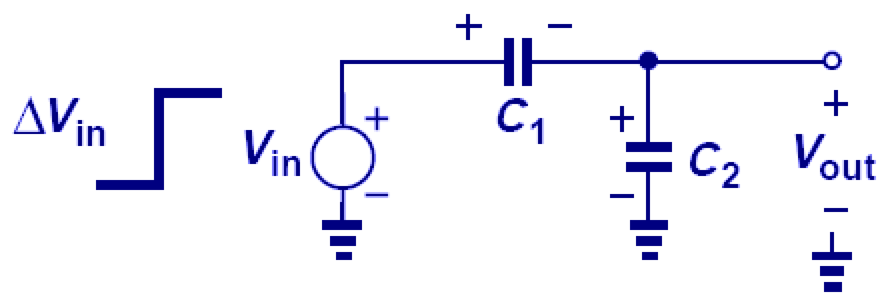
理解1:电荷变化相等
理解2:复阻抗分压

电容有Vin和Vout，当Vin突变的时候，Vout也是德塔Vin，
果电容两端电压不变。又因为所有电容电路都有充放电过
，且因为此电路输出开路，所以电容电荷Q无法导走



电压无法突变，
且无法导走Q

(a)



(b)

输出开路，电容电荷Q无法导走（电容无法充放电），即电容两端Q不变，所以V也不变

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

$$\Delta Q_2 = C_2 \cdot \Delta V_{out} = \Delta Q_1$$

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

$$\Downarrow$$

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

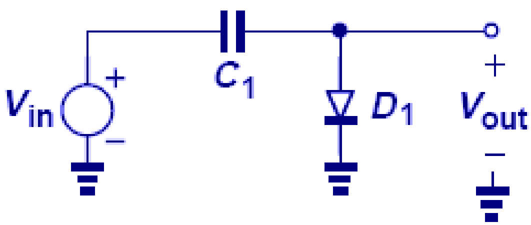
当成阻抗，即为阻抗分压

钳位电路

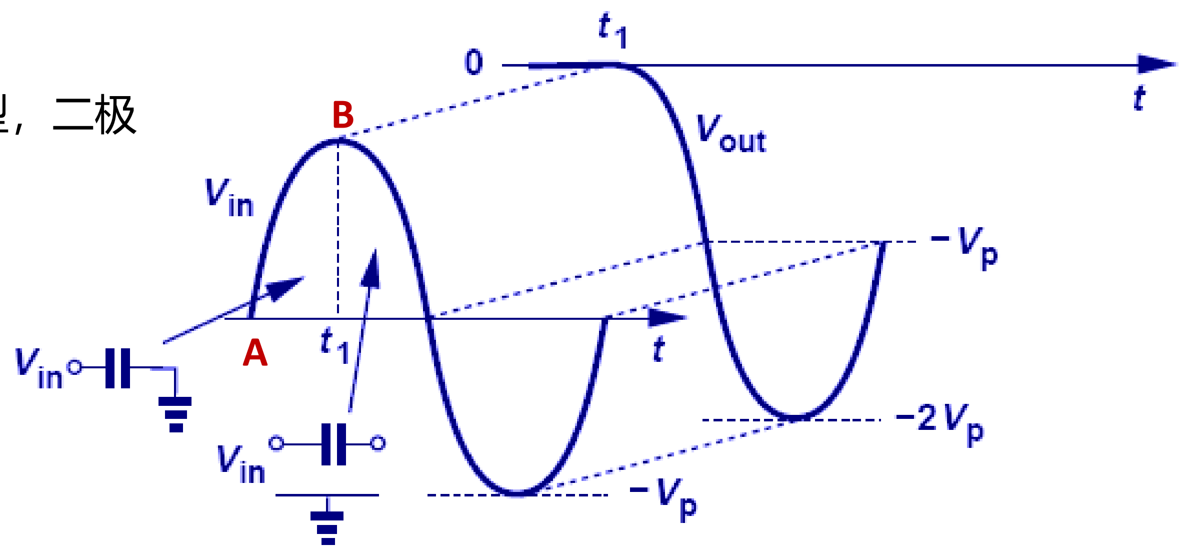
钳位电路（clamping circuit）把输入电压变成峰值钳制在某一预定的电平上的输出电压，而不改变信号

即平移

关注电容电压。此处考虑理想模型，二极管一有电压就导通



(a)

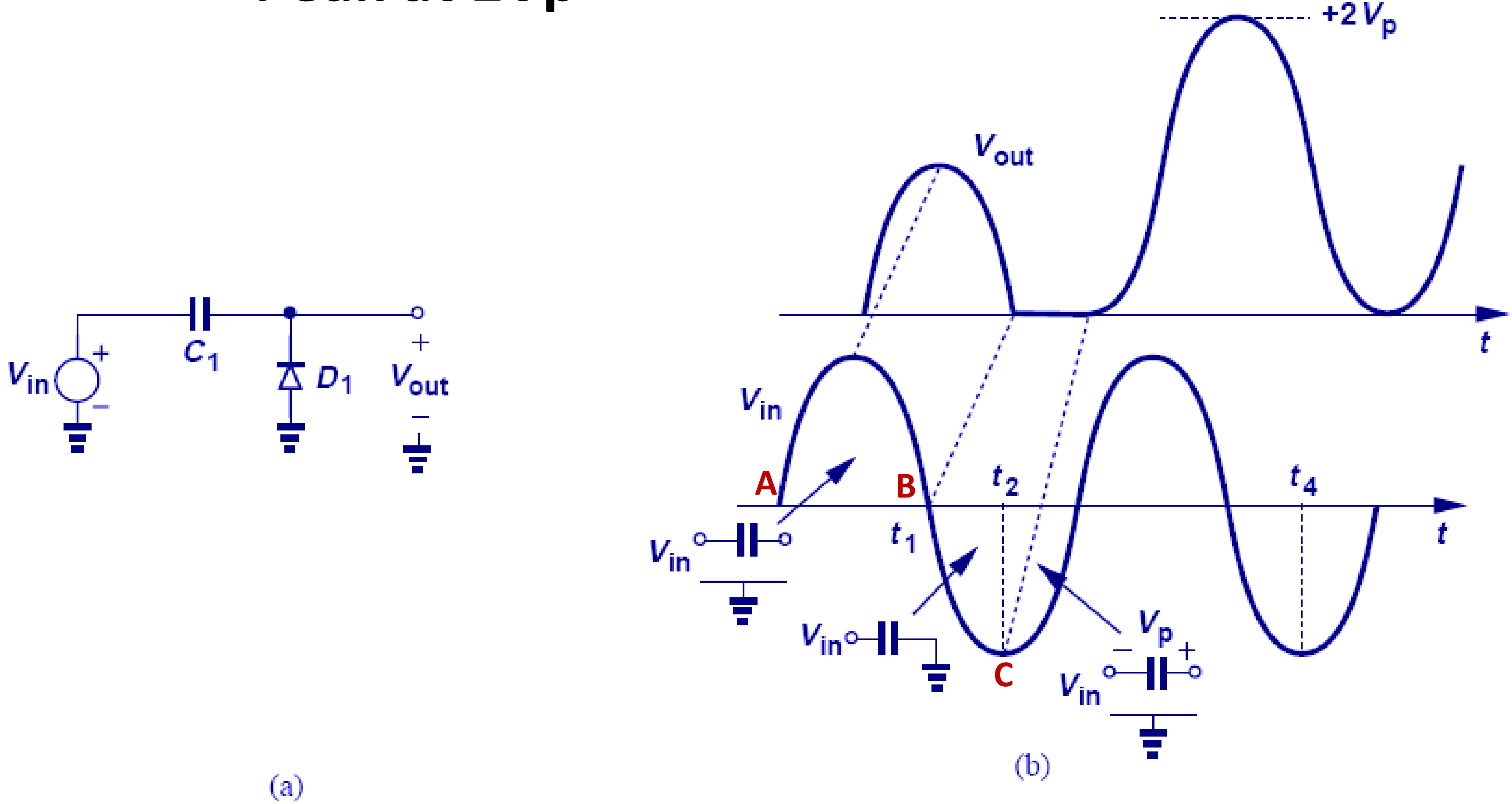


(b)

初始状态A点，$V_{in} = 0$，$V_{C1} = 0$； B点，$V_{C1} = V_p$；后续 $V_{C1} = V_p$

- As V_{in} increases, D_1 turns on and V_{out} is zero. 电容充电
- As V_{in} decreases, D_1 turns off, and V_{out} drops with V_{in} from zero. The lowest V_{out} can go is $-2V_p$, doubling the voltage. 【当过了B点时，V_{in}下降，电容电压不能突变，V_{out}有跟随下降的趋势，一旦下降，就导致D_1 turn off。关注电容两端的电压值】

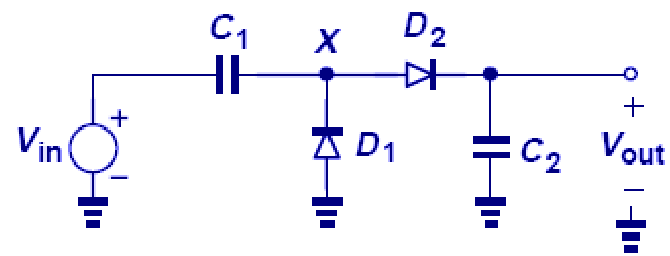
Waveform Shifter: Peak at 2Vp

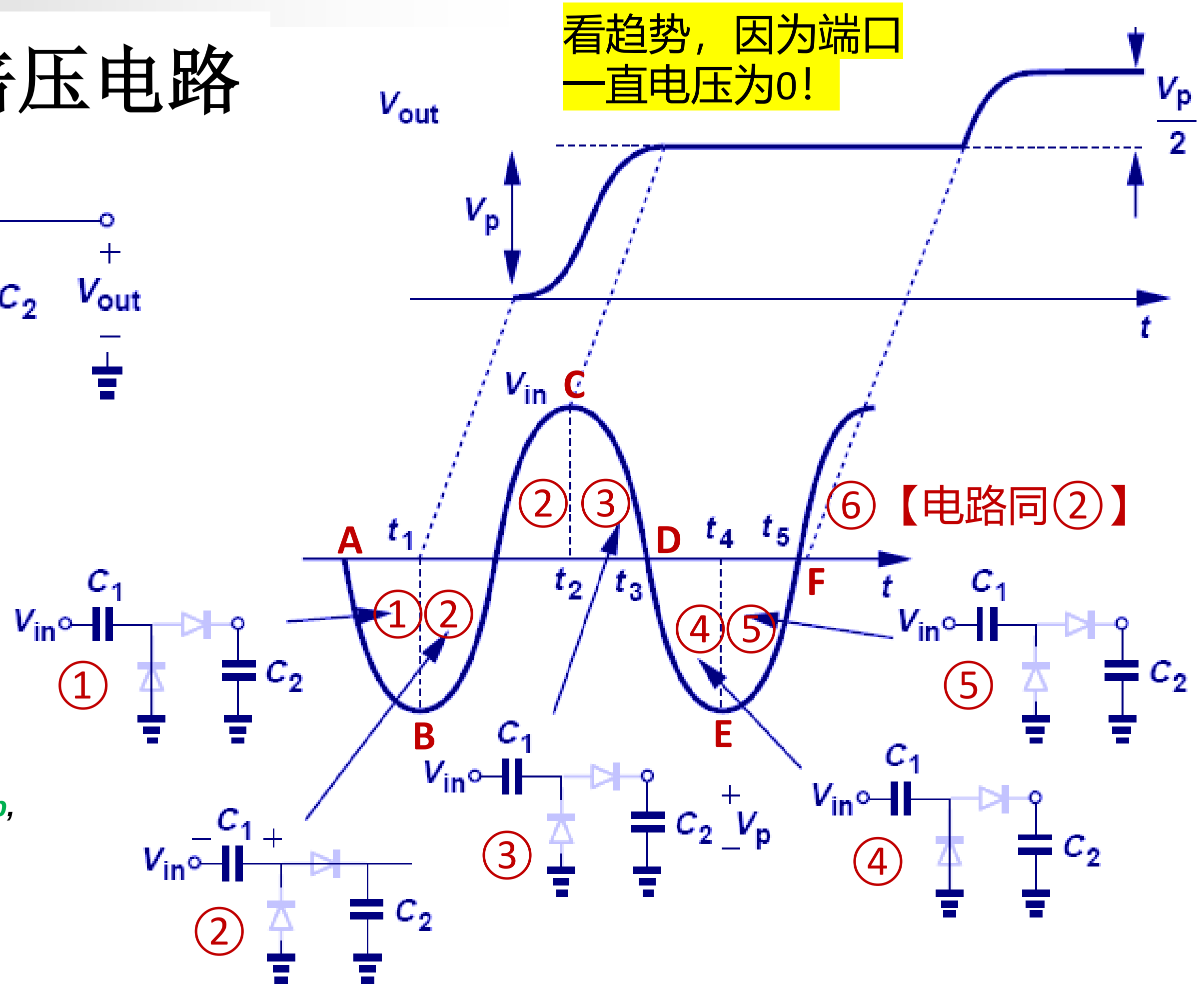


- Similarly, when the terminals of the diode are switched, a voltage doubler with peak value at $2V_p$ can be conceived.

A点，$V_{C1} = 0$； B点开始电容充电；C点 $V_{C1} = V_p$； 后续 $V_{C1} = V_p$

Voltage Doubler 倍压电路





$C_1 = C_2$

A点， $V_{C1} = 0$ $V_{C2} = 0$

①C1开始充电

B点， $V_{C1} = V_p$ $V_{C2} = 0$

②电容分压，输出变化是输入变化的一半 V_{out}增加V_p,

C点， $V_{C1} = 0$ $V_{C2} = V_p$

③D2 off，假设D2 on，则电流从负端到正端

D点， D1 on

④C1开始充电

E点， $V_{C1} = V_p$ $V_{C2} = V_p$

⑤D1 off

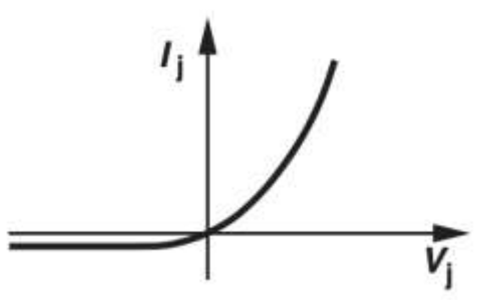
F点， X点电压 = V_p

⑥D2 on，电容分压，输出变化是输入变化的一半 V_{out}增加$V_p/2$

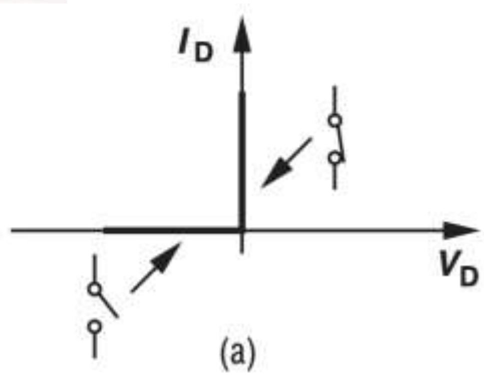
- **The output increases by V_p, $V_{p/2}$, $V_{p/4}$, etc in each input cycle, eventually settling to $2\ V_p$.**

小结

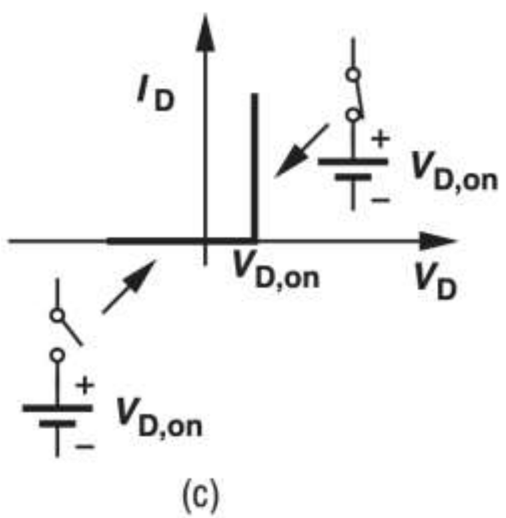
- 二极管模型



指数模型



理想模型



恒压降模型

- 直流 + 小信号分析方法 p43

小信号模型：电阻 $r_d = \dfrac{V_T}{I_D}$

小结

- 二极管电路的分析方法： 假设——分析——验证
- 会画二极管电路的 ①I/V；②输入输出；③时域图
- 熟悉 AC-DC 各部分功能电路

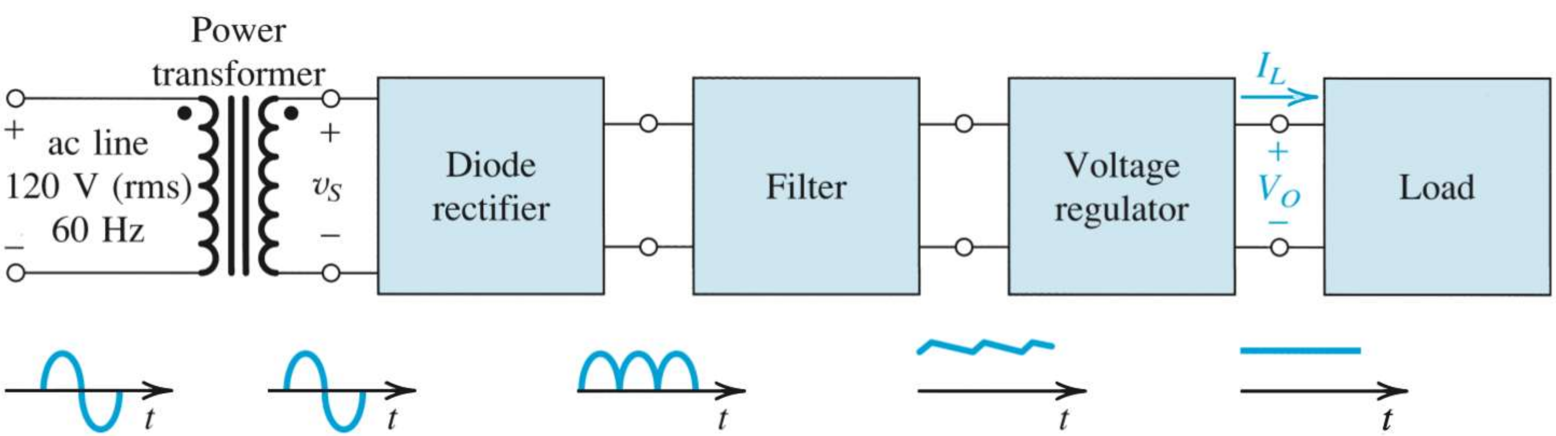


Figure 4.22 Block diagram of a dc power supply.

作业

***3.9.** Plot the input/output characteristics of the circuits depicted in Fig. 3.69 using an ideal model for the diodes. Assume $V_B = 2$ V.

***3.10.** Repeat Problem 3.9 with a constant-voltage diode model. $V_{D,on} = 0.8V$

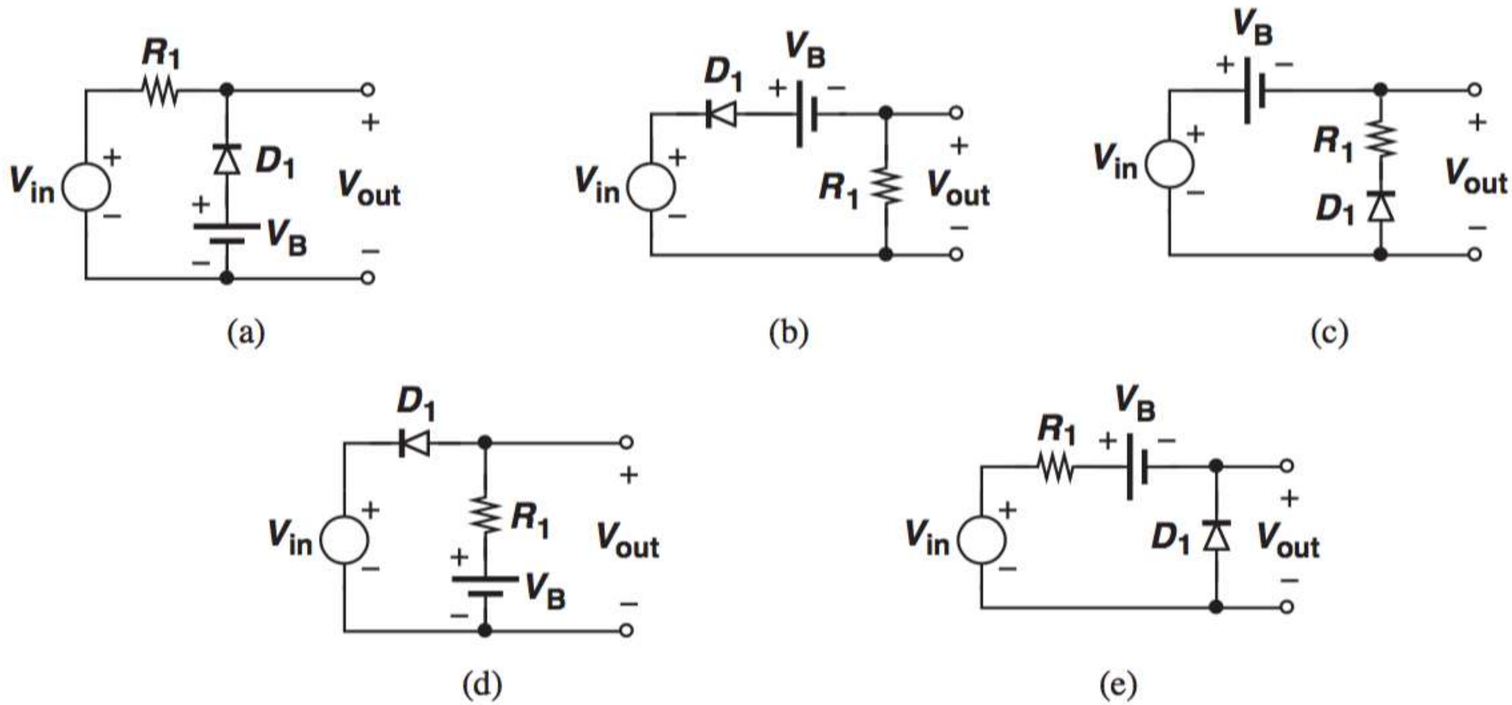
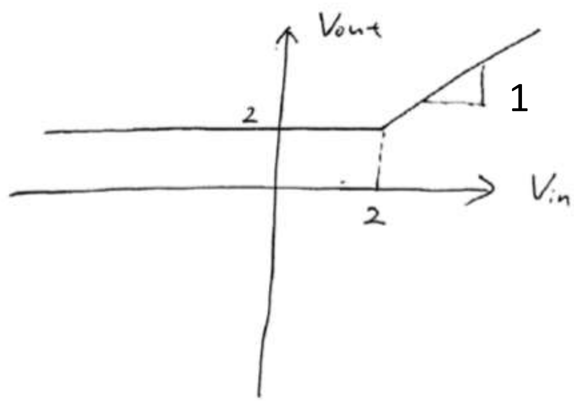


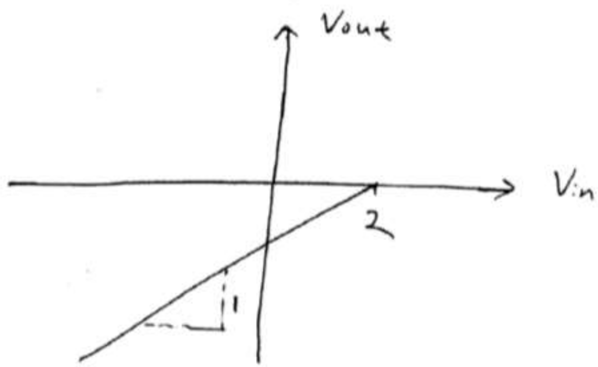
Figure 3.69

(9)

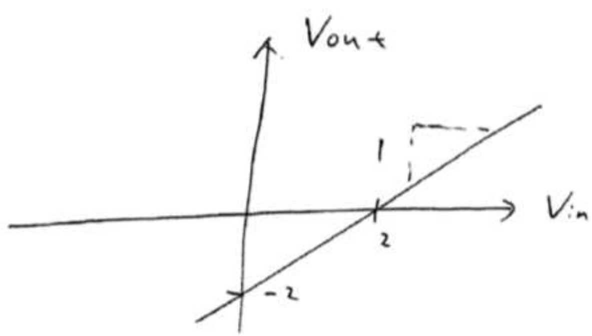
a)



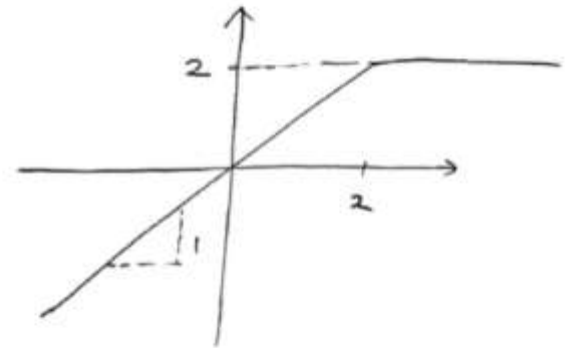
b)



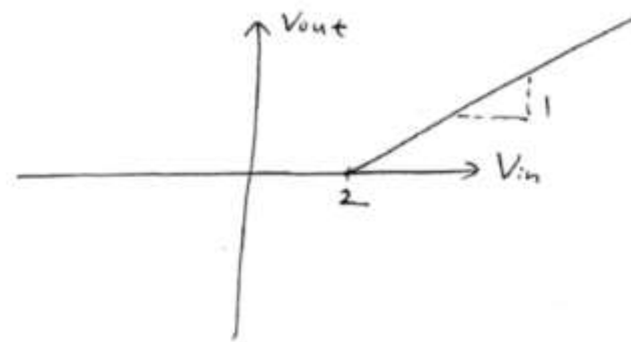
c)



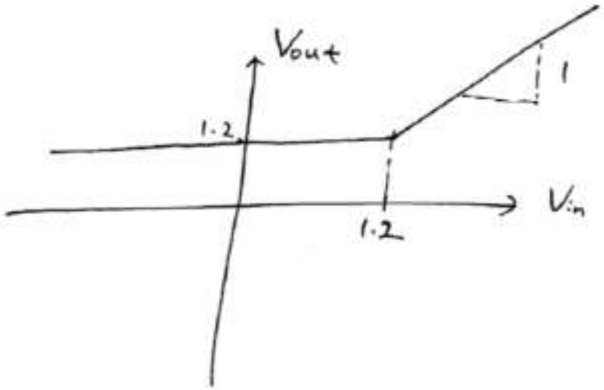
d)



e)

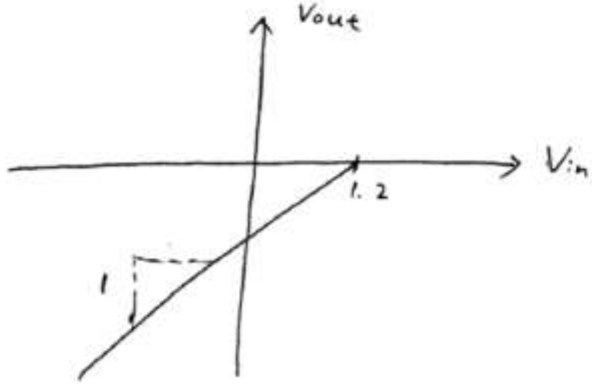


(10) a)



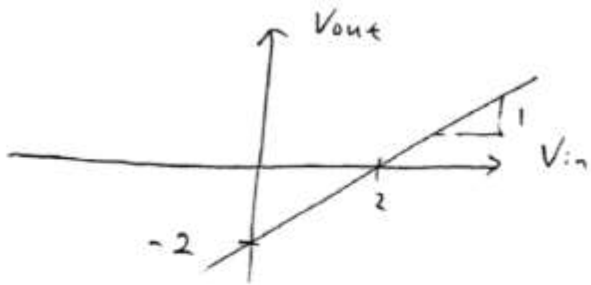
Vout
1.2
1
1.2
Vin

b)



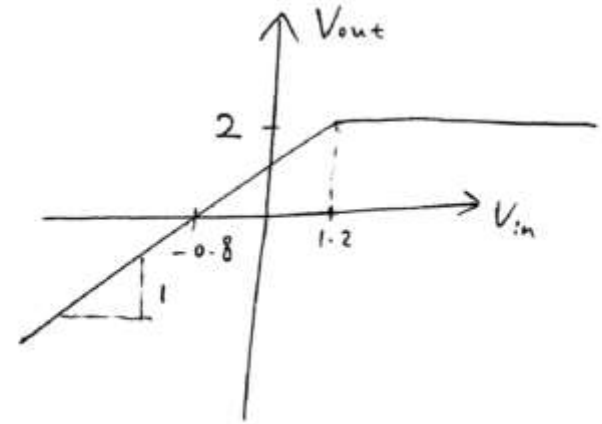
Vout
Vin
1.2
1

c)



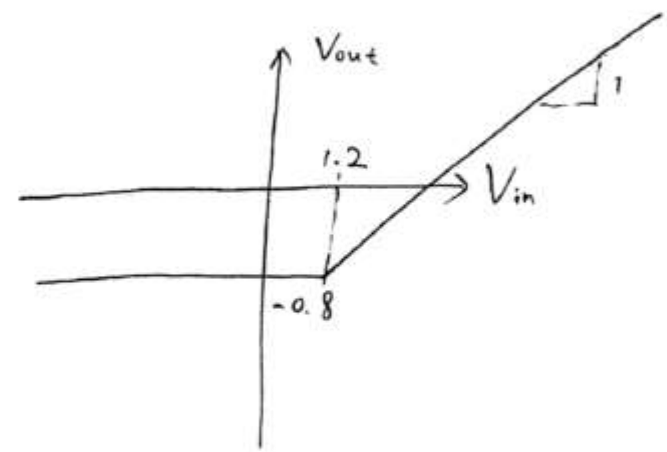
Vout
1
Vin
2
-2

d)



Vout
2
Vin
-0.8
1.2
1

e)



Vout
1
1.2
Vin
-0.8

D4.13 Design the circuit in Fig. E4.13 to provide an output voltage of 2.4 V. Assume that the diodes available have 0.7-V drop at 1 mA.

Ans. $R = 139\ \Omega$

V_T取 25mV

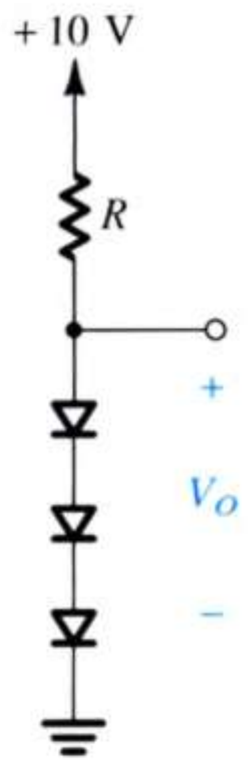


Figure E4.13

D4.19 Design the circuit of Fig. E4.19 so that $V_O = 3$ V when $I_L = 0$, and V_O changes by 20 mV per 1 mA of load current.

(a) Use the small-signal model of the diode to find the value of R.

$\boxed{V_T \text{ 取 } 25\text{mV}}$

(b) Specify the value of I_S of each of the diodes.

(c) For this design, use the diode exponential model to determine the actual change in V_O when a current $I_L = 1$ mA is drawn from the regulator.

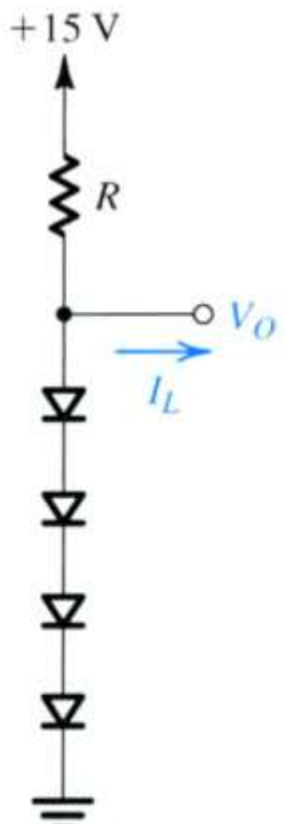


Figure E4.19

Ans. (a) $R = 2.4\ \text{k}\Omega$; (b) $I_S = 4.7 \times 10^{-16}$ A; (c) -23 mV.