上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Semiconductor physics and devices

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References

- **[1] Dona H. Neamen, Semiconductor physics and devices, McGraw-Hill Higher- Education**.
- [2] Howe and Sodini , Microelectronics: An Integrated Approach, Prentice hall.
- [3] Jan M. Rabaey, Digital Integrated circuits- a design perspective, Second Edition, Prentice hall.

Score

Attendance: 50%

Open-book examination: 50%

- Through microelectronic technologies, a quite large-scale electronic circuit or part and even an equipment or system can be designed and integrated on a small silicon chip or other semiconductor chip.

- “Semiconductor Physics & Devices” is important theoretical basis of modern integrated circuits design and fabrication.

Contents

- Semiconductor material physics
- Semiconductor device fundamental
- Semiconductor device application
- Modeling and simulation of semiconductor devices

- **Semiconductor material physics**
  - **quantum mechanics**
  - **the quantum theory of solids**
  - **semiconductor material physics**
  - **energy band theory**
  - **carrier distribution and transport phenomenon**
  - **current conduction property of semiconductor materials**

- **Semiconductor device fundamental**
  - **the device physics**
  - **operation and voltage-current characteristics of PN junction**
  - **operation and voltage-current characteristics of MOSFETs**

- **Semiconductor device application**
  - **operation and voltage-current characteristics of inverters**
  - **design of inverters**
  - **operation and voltage-current characteristics of amplifier**
  - **design of amplifier**

- **Modeling and simulation of semiconductor devices**
  - **equivalent circuit model**
  - **CAD software SPICE**

Course Structure

Title of Course 1: Introduction

Title of Course 2: VLSI Fabrication Technology（加工工艺）

- IC technologies
- IC fabrication steps(加工步骤)
- CMOS devices
- VLSI layout（版图）

**Title of Course 3: the Crystal Structure of Solids
（固体的晶体结构）**

- semiconductor materials
- types of solids
- space lattices（晶格）
- atomic bonding（原子键）
- imperfection and doping（掺杂）in solids .

Title of Course 4: Quantum Mechanics（量子物理）

- The principles of quantum mechanics
- Schrodinger（薛定谔） wave equation
- the electron behavior in an atom
- energy band theory（能带理论）
- statistical behavior（统计特性） of electrons in a crystal.

Title of Course 5: The Semiconductor in Equilibrium
（半导体均衡态）

•the concentration of electrons and holes （电子空穴浓度）
•the properties of an intrinsic semiconductor（本征半导体）
•the properties of an semiconductor with impurities (dopants)（掺杂）

Title of Course 6: Carrier Transport Phenomenon （载流子输运现象）

•the phenomenon of thermal motion（热运动）
• carrier drift（载流子漂移）
•and carrier diffusion（载流子扩散）

Title of Course 7: Non equilibrium Excess Carriers in Semiconductors（平衡态下的多余载流子）

•the excess carrier generation rate （多余载流子产生率）
•The excess carrier recombination rate （复合率）
•the ambipolar transport equation （双极输运方程）

Title of Course 8: PN junction (PN结)

- semiconductor electrostatics （静电）in thermal equilibrium
- electrostatics of pn junction in equilibrium
- pn junction under bias （偏置）
- I-V characteristics

Title of Course 9: Diodes （二极管）

- ideal diode
- terminal characteristics of junction diodes
- diode circuit models
- analysis of diode circuits

Title of Course 10: MOSFET

- MOS Electrostatics
- MOSFET_I-V characteristics
- MOSFET Equivalent Circuit Models.

Title of Course 11: CMOS inverter.

- I-V characteristics of CMOS inverter
- high-speed model of CMOS inverter
- time domain analysis of CMOS inverter

Title of Course 12: Transistor amplifier.

- amplifier fundamentals
- common source amplifier (共源放大器)
- common source amplifier with current source supply
- common drain amplifier (共漏放大器)
- common gate amplifier (共栅放大器)

Lecture 1

Introduction

1. What is microelectronics?

Integrated circuits contain millions of components in a small piece of silicon. For example, microprocessor is a microelectronic circuit.

2. **IC technologies.**

Digital technology --- CMOS

Analog technology ---CMOS, Biploar (双极), BICMOS

RF technology --- III-IV group technology

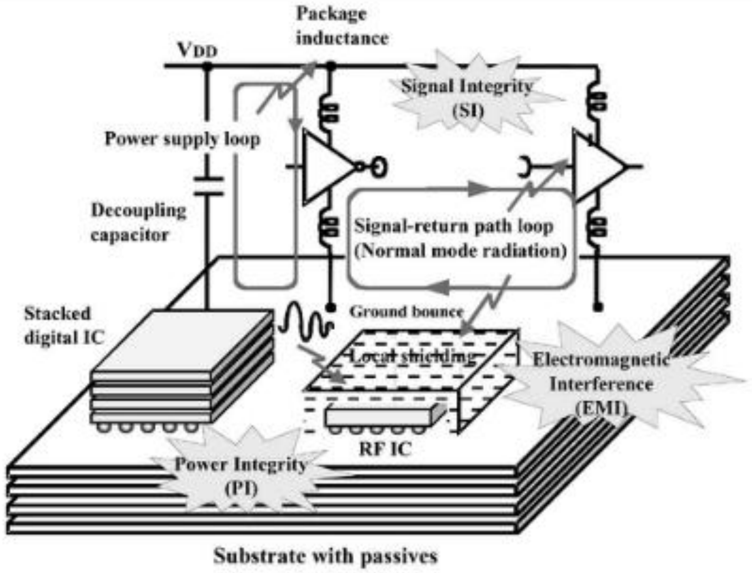
- **SOC---System on Chip**

is an integrated circuit (IC) that integrates all components of a computer or ther electronic system into a single chip. It may contain digital, analog, mixed-signal, and often radio-frequency functions—all on a single chip substrate. A typical application is in the area of embedded systems.

The AMD Geode is an x86compatible system on a chip

- **SOP---System on package**

  SIP --- System in package



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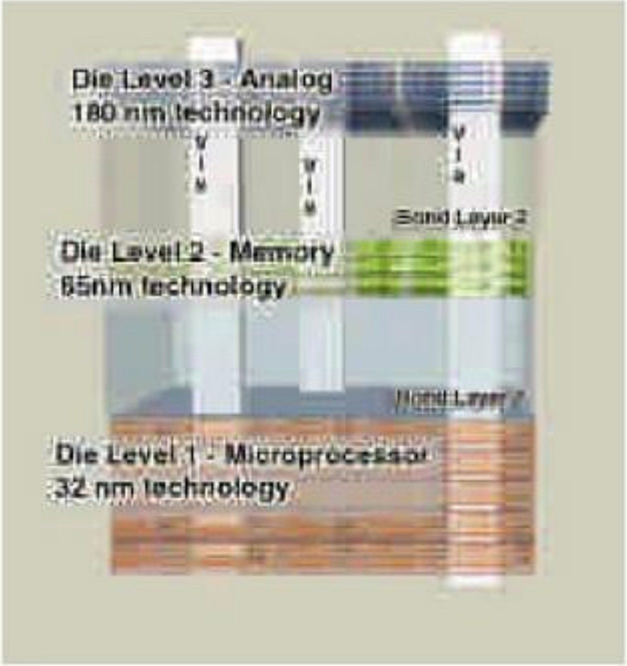
3D IC

chip mounted on chip interconnected by Through Sillcion Via (TSV)

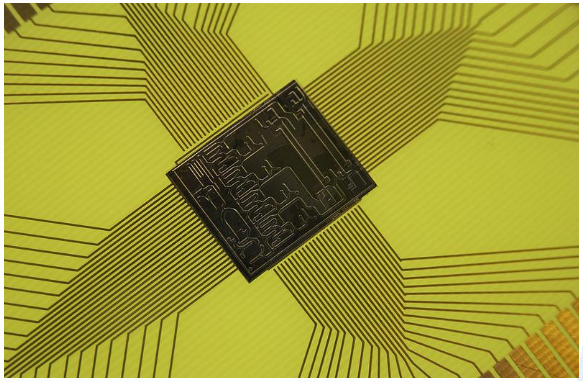
3D IC has four technologies：

- ✓ Monolithic
- ✓ Wafer-on-Wafer
- ✓ Die-on-Wafer
- ✓ Die-on-Die



- **MEMS---Microelectromechanical systems (MEMS)** (also written as *micro-electro-mechanical systems*)

  is the technology of very small devices; it merges at the nano-scale into nanoelectromechanical systems (NEMS) and nanotechnology. MEMS are also referred to as micromachines (in Japan), or *micro systems technology – MST* (in Europe).



microelectromechanical systems chip,
sometimes called "lab on a chip"

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Appendix

Signals

1. What are signals?

- Signals contain information
- There are various signals

  --- sound

  --- light

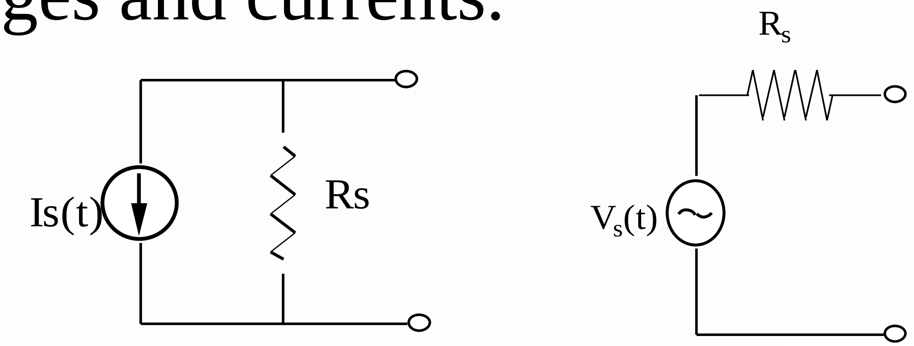
  --- pressure

  --- electromagnetic waves
- Signals can be transduced from one form to other form.

  Sound signal->Microphone->electric signal

2. What are electronic signals?

Voltages and currents.



(a) The Thevenin form　　(b) The Norton form

Fig two alternative representations of a signal source.

The description of time-varying signal source

--- mathematical functions

--- data

--- curve

Frequency spectrum of signals

1. How can we characterize signals?

- ✓ **Signal in time domain**

  --->Fourier series (periodical signal)

  --->Fourier transform (arbitrary signal)

- ✓ **Signal in frequency domain**

  --->As the sum of sine-wave signals of different frequencies and amplitudes.

2. What is the sine wave signal?

$$v_a(t) = V_a \sin \omega t$$

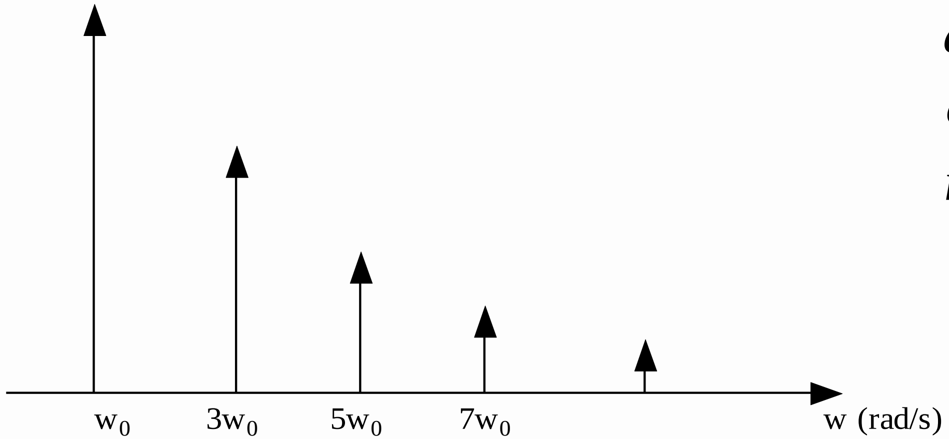
V_a : the peak value or amplitude in volts

$V_a / \sqrt{2}$: root-mean-square (rms) value

ω : the angular frequency in radians per seconds

f : frequency in hertz

$$\omega = 2\pi f \text{ rad/s}$$



ω_0 :the basic angular frequency

$\omega_0 = 2\pi / T$

$m\omega_0$:its harmonics

Fig The frequency spectrum of the periodic square wave.

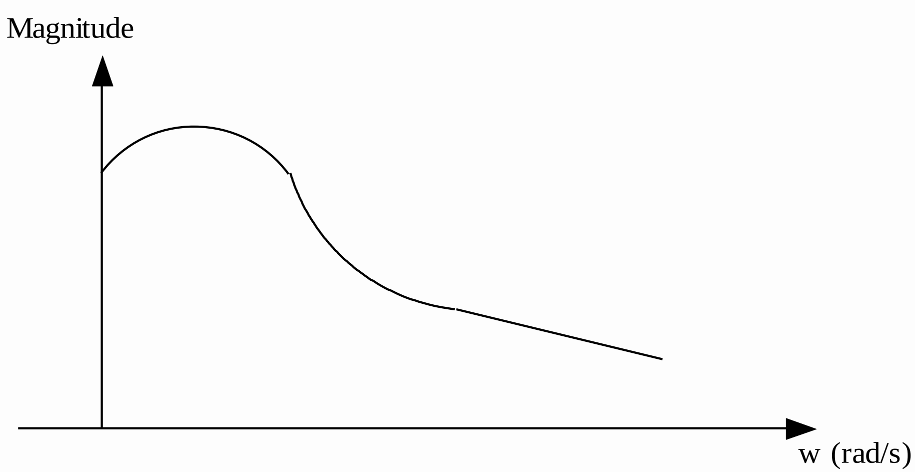


Fig The frequency spectrum of an arbitrary waveform.

Analog and digital signals

- **What are analog signals ?**

  --- The name is from that such a signal is analogous to the physical signal in the world.

  --- The amplitude of an analog signal is any value and exhibits a continuous variation.

- **What are analog circuits?**

  Electronic circuits that process analog signals.

- **What are digital signals?**

  A sequence of digital numbers, each number may be 0 or 1.

- **What are digital circuits?**

  Electronic circuits that process digital signals.

•How are signals converted from analog form to digital form?

1)Sampling process

Continuous signal is sampled at equal intervals along the time axis.

2)Discretization process

We use *N* binary digits to represent each sample of the analog signal, then the discretized (digitized) signal can be expressed as :

$$D = b_0 2^0 + b_1 2^1 + b_2 2^2 + \cdots + b_{N-1} 2^{N-1}$$

where b0, b1, …,b_{N-1} denote the N bits and have values of 1 or 0.

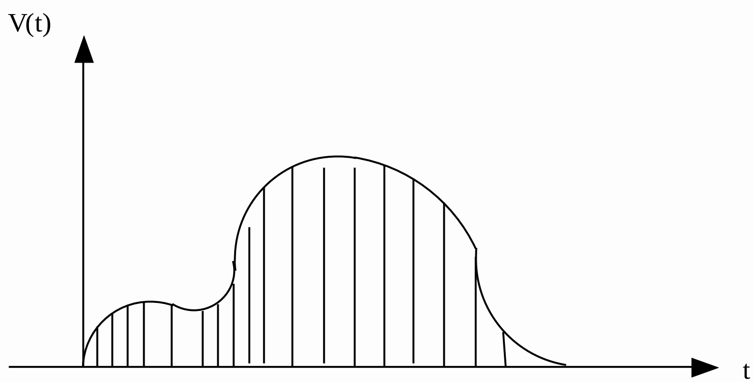


Fig Sampling the continuous-time analog signal

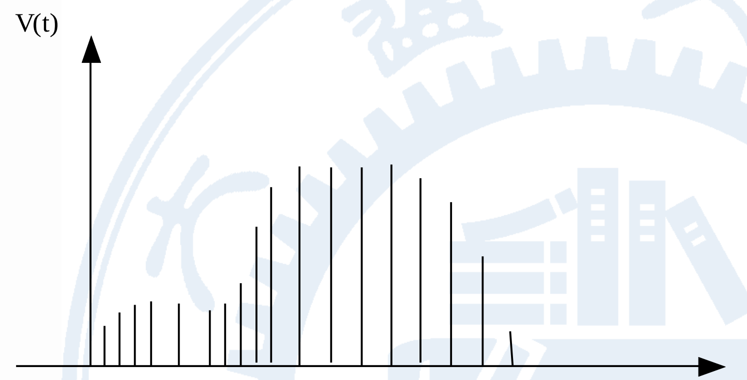


Fig Discretizng the signal

Analog-to-digital converter (ADC)

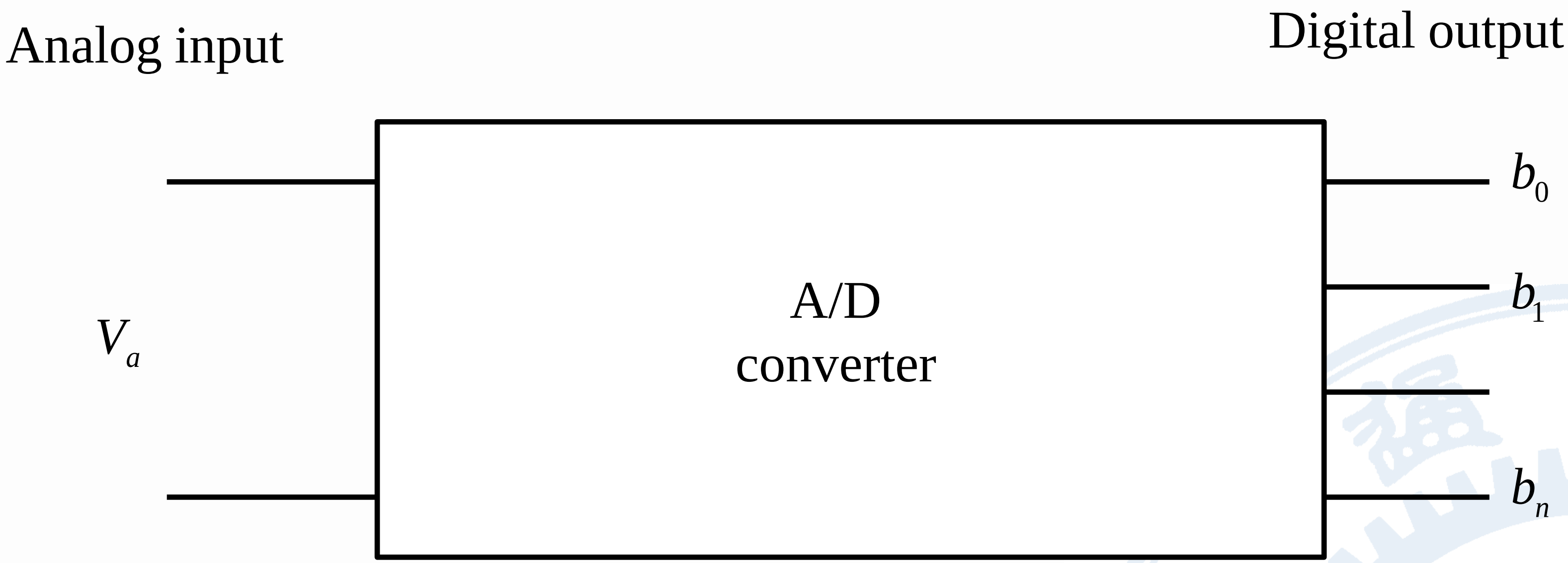


Fig Block-diagram representation of ADC.

Analog circuits: Amplifiers

1. What is signal amplification?

--- amplify the weak signal to strong signal for reliable processing.

--- the simplest signal-processing task.

$$v_o(t) = Av_i(t)$$

A :The magnitude of amplification - amplifier gain.

2. What is the requirement for amplifier?

- Linearity :Information amplified without distortion.
- Nonlinear distortion should be avoided for signal integrity.

Amplifier circuit symbol

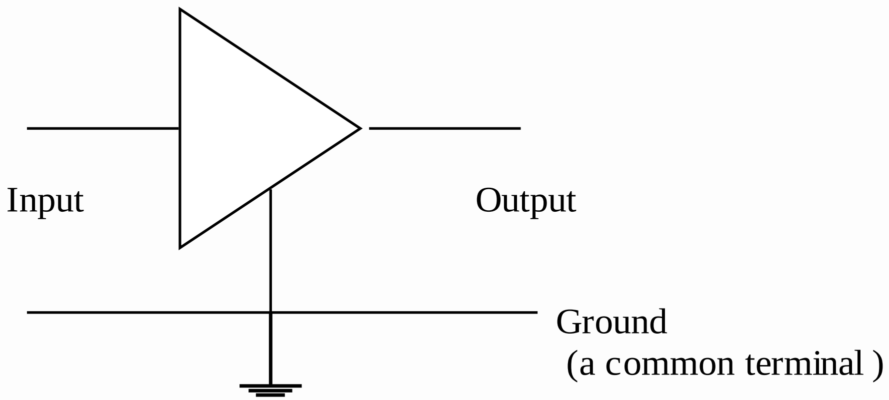


Fig Circuit symbol for amplifier.

Voltage gain: $A_v = \frac{v_o}{v_i}$

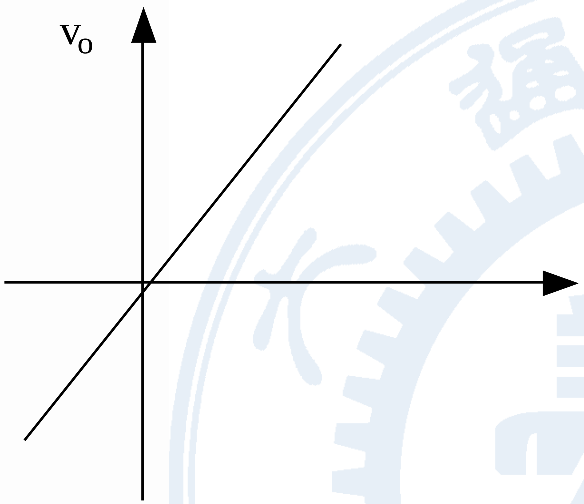


Fig Transfer characteristic of a linear amplifier.

Power gain: $A_p = \frac{v_o i_o}{v_I I_I}$

Comparison between amplifier and a transformer:

- An amplifier not only amplify the voltage but also the power
- A transformer may amplify voltage but not power.

Current gain: $A_i = \frac{i_o}{i_I}$

Relationship: $A_P = A_v A_i$

Expressing gain in decibels:

Gain in decibels= $20\log|A|$

The amplifier power supplies

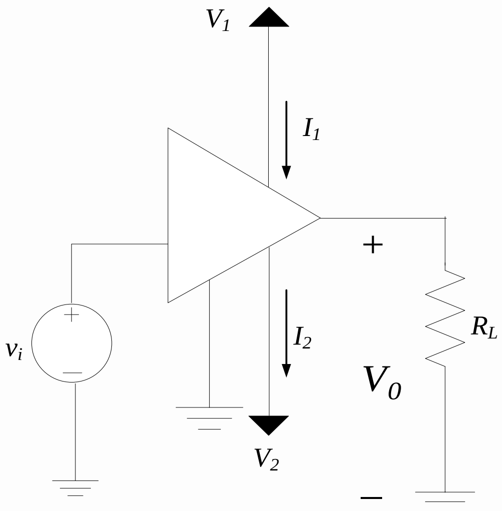


Fig Amplifier circuit with two power supplies.

The power drawn from the dc source:

$$P_{dc} = V_1 I_1 + V_2 I_2$$

The power balance equation:

$$P_{dc} + P_I = P_L + P_{dissipated}$$

P_I : input power
P_L: output power
$P_{dissipated}$: power dissipated in the amplifier (converted to heat)

The **amplifier efficiency** is defined as:

$$\eta = \frac{P_L}{P_{dc}}$$

Noting the input power is very small and neglected.

Amplifier saturation

Because the amplifier remains linearity over only a limited range of input and output voltages, so there is the restriction for the input voltage.

$$\frac{L_-}{A_v} \le v_i \le \frac{L_+}{A_v}$$

L_- : the minimum output voltage (usually the negative supply).
L_+ : the maximum output voltage (usually the positive supply).

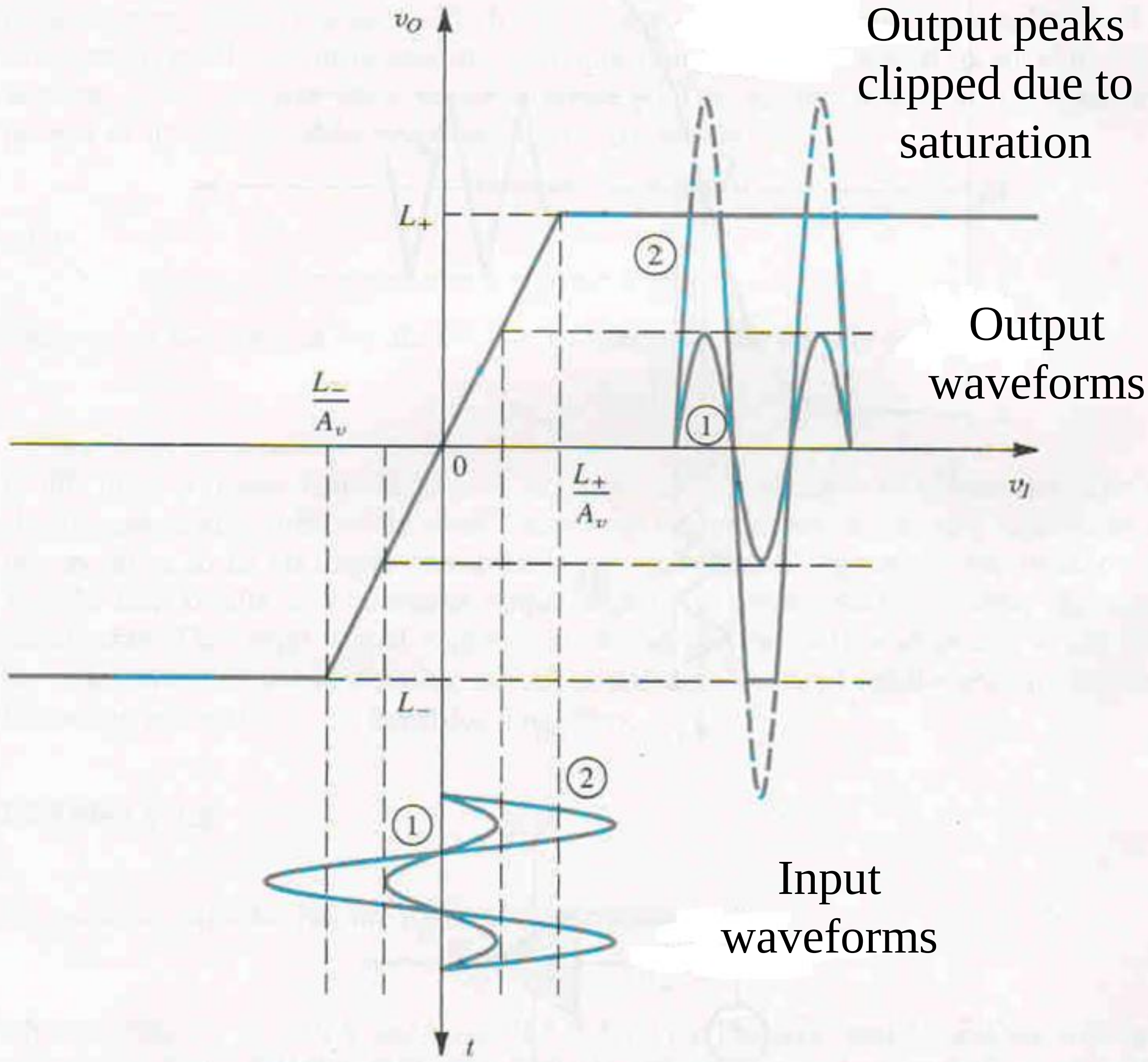
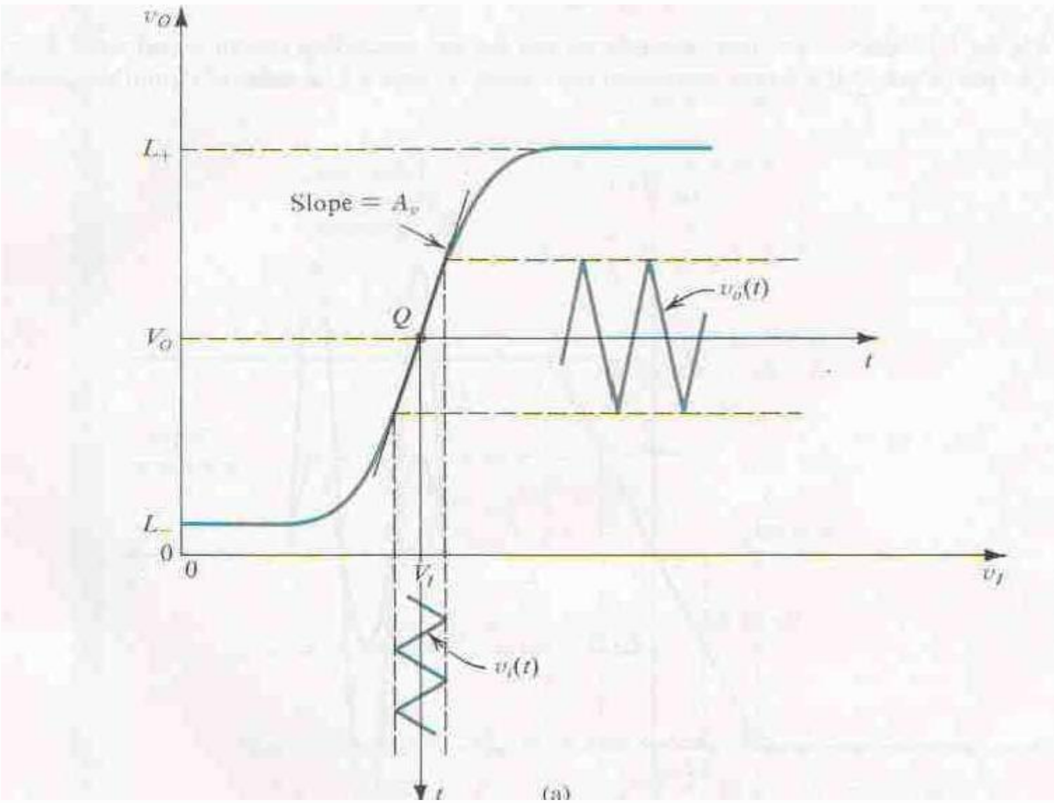


Fig An amplifier transfer characteristic with output saturation.

Nonlinear transfer characteristics and biasing



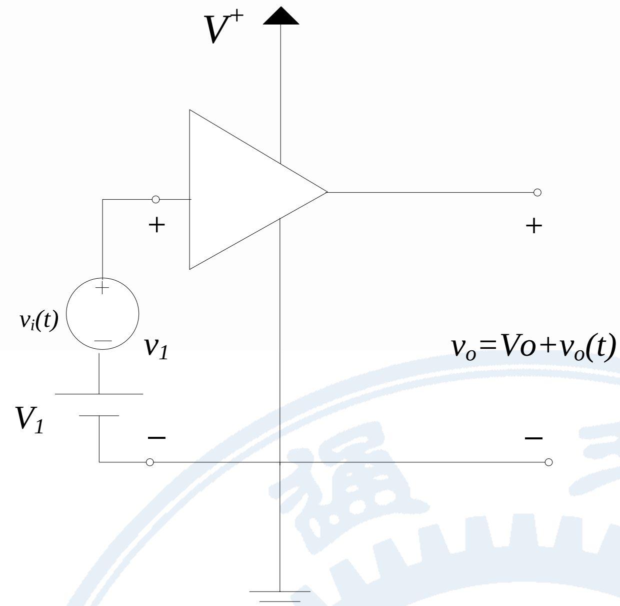


Fig Amplifier circuit with only one power supply.

(a) an amplifier transfer characteristic that shows considerable nonlinearity
(b) to obtain linear operation the amplifier is biased and the signal amplitude is kept small.

Circuit models for amplifiers

The voltage amplifier model consists of

1) A voltage-controlled voltage source having a gain factor A_{vo}
2) An input resistance R_i that accounts for the fact that the amplifier draws an input current from the signal source
3) An output resistance R_0 that accounts for the change in output voltage.

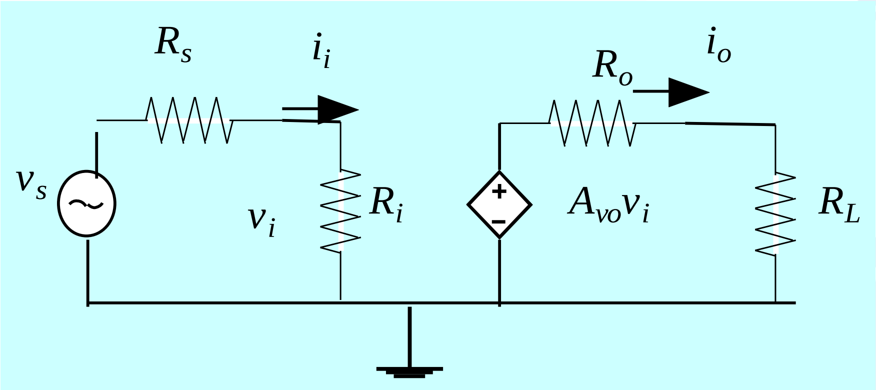


Fig The voltage amplifier with input signal source v_s with the resistance *Rs* and load resistance $R_{L.}$

The first voltage divider

The voltage gain: $A_v = \frac{v_o}{v_i} = A_{v0} \frac{R_L}{R_L + R_o}$

If $R_0 = 0$, we can get the maximum voltage gain A_{vo};
If $R_L = \infty$, we can also get the maximum voltage gain A_{vo}.
So A_{V0} is the voltage gain of the unloaded amplifier, or the open-circuit voltage gain.

The second voltage divider

$$v_i = v_s \frac{R_i}{R_i + R_s}$$

The input resistance R_i introduces another voltage-divider action at the input.

In order not to lose a significant portion of the input signal in coupling the signal source to the amplifier input, the amplifier must be designed to have $R_i >> R_s$

The overall voltage gain:

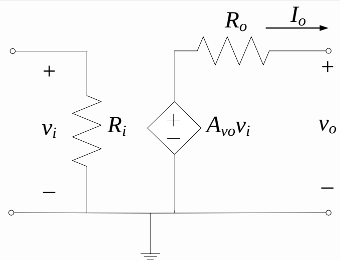
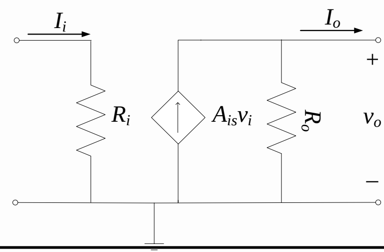
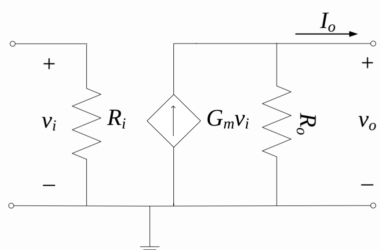
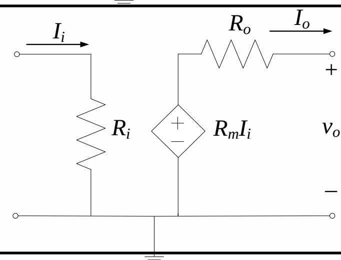
$$\frac{v_o}{v_s} = A_{vo}\frac{R_i}{R_i + R_s}\frac{R_L}{R_L + R_o}$$

An ideal voltage amplifier is one with

$$R_i = \infty \qquad R_o = 0$$

Other amplifier types

- ✓ current amplifier
- ✓ transconductance amplifier
- ✓ transresistance amplifier

Type	Circuit Model	Gain Parameter	Ideal Characteristics
Voltage Amplifier		Open-Circuit Voltage Gain $A_{v_0} \equiv \left.\frac{v_0}{v_i}\right\vert_{i_0=0} \quad (V/V)$ Voltage-controlled voltage	$R_i = \infty$ $R_o = 0$
Current Amplifier		Short-Circuit Current Gain $A_{i_s} \equiv \left.\frac{I_0}{I_i}\right\vert_{v_0=0} \quad (A/A)$ Current-controlled current	$R_i = 0$ $R_o = \infty$
Transconductance Amplifier		Short-Circuit Transconductance $G_m \equiv \left.\frac{I_0}{v_i}\right\vert_{v_0=0} \quad (A/V)$ Voltage-controlled current	$R_i = \infty$ $R_o = \infty$
Transresistance Amplifier		Open-Circuit Transresistance $R_m \equiv \left.\frac{v_0}{I_i}\right\vert_{i_0=0} \quad (V/A)$ Current-controlled voltage	$R_i = 0$ $R_o = 0$

Relationships of various amplifier models

Voltage amplifier- The open-circuit output voltage $v_o = A_{vo} v_i$

Current amplifier- The open-circuit output voltage $v_o = A_{is} I_i R_o$

Equating these two values and noting that $v_i = R_i I_i$

$$A_{vo} = A_{is} \frac{R_o}{R_i}$$

Similarly, we can get

$$A_{vo} = G_m R_o \qquad A_{vo} = \frac{R_m}{R_i}$$

Ideal amplifier is unilateral (单向的)

--- signal flow is from input to output.

Real amplifier shows some reverse transmission

--- undesirable but need to be modeled.

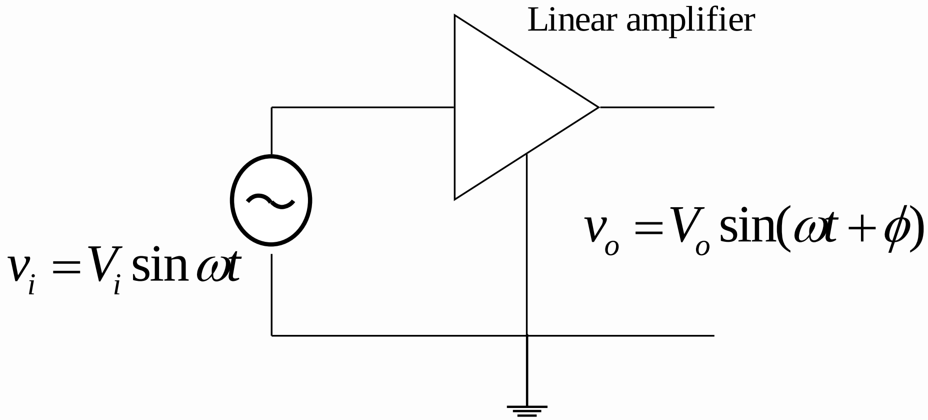
Frequency response of amplifier

- **Superposition rule**

  --- An amplifier is a linear system

  --- The input signal to an amplifier can always be expressed as the sum of sinusoidal signals, we can characterize an amplifier in terms of its response to input sinusoids of different frequencies.

- **Measuring the amplifier frequency response**



At the test frequency, the amplifier is characterized by its magnitude v_o / v_i and phase ϕ

The general transfer function of an amplifier in complex frequency domain is

$$T(s)=\frac{V_o(s)}{V_i(s)}$$

Magnitude response: $|T(\omega)|=\frac{V_o}{V_i}$

Phase response: $\angle T(\omega)=\phi$

We can measure the transfer function at different frequency to obtain the complete frequency response of the amplifier.

Amplifier bandwidth

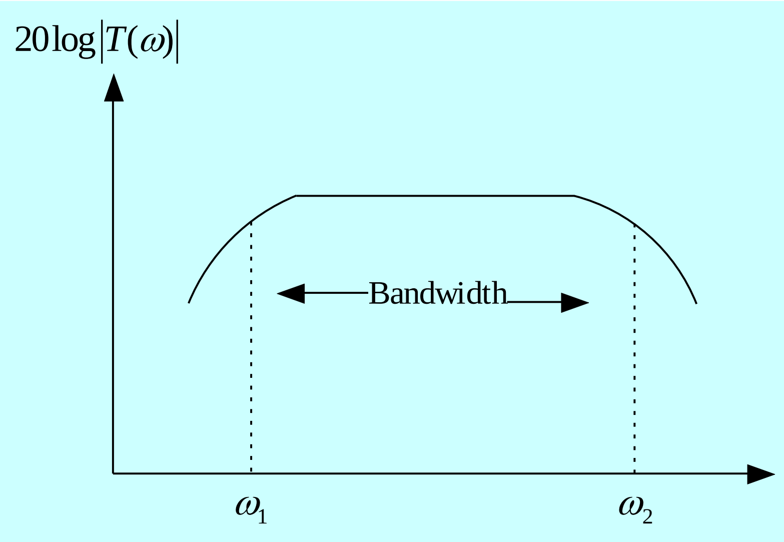


Fig Typical magnitude response of an amplifier.

•What is the bandwidth?
The gain is almost constant over a wide frequency range, roughly between ω_1 and ω_2 .

• Signals whose frequencies are below or above bandwidth will experience lower gain.
• The band frequencies over which the gain of the amplifier is almost constant, to within a certain number of decibels (usually 3 dB) is called **amplifier bandwidth**.

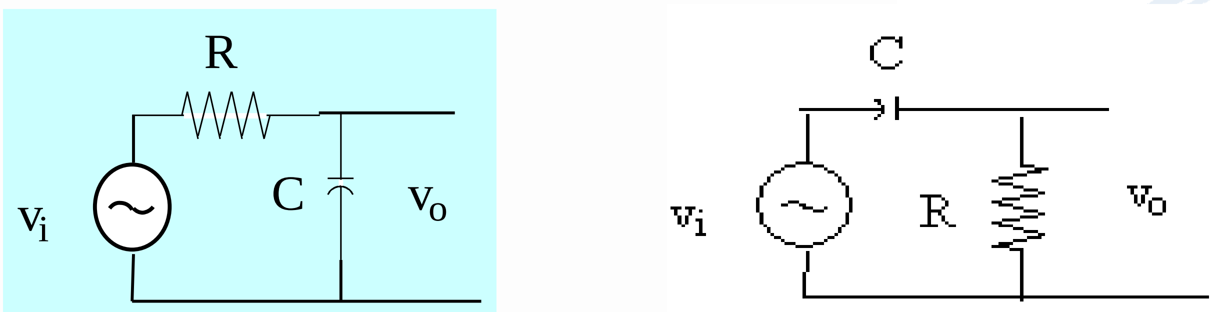
◆ How should we design amplifier?

Its bandwidth should coincide with the spectrum of the signals to be amplified, or else the amplifier would distort the frequency spectrum of the input signal with different components of the input signals being amplified by different amounts. —**no distortion**

Single-time-constant (STC) networks

An STC network is RC or LR network, with single time constant $\tau = RC$ or $\tau = L / R$

Most STC networks can be classified into two categories: Low pass (LP) and high Pass (HP).



(a) Low pass network (b) High pass network

Fig STC networks.

	Low-Pass(LP)	High-Pass(HP)
Transfer Function *T(s)*	$\frac{K}{1+(s/\omega_0)}$	$\frac{Ks}{s+\omega_0}$
Transfer Function (for physical frequencies) *T(jω)*	$\frac{K}{1+j(\omega/\omega_0)}$	$\frac{K}{1-j(\omega_0/\omega)}$
Magnitude Response $\angle\lvert T(j\omega)\rvert$	$\frac{\lvert K\rvert}{\sqrt{1+(\omega/\omega_0)^2}}$	$\frac{\lvert K\rvert}{\sqrt{1+(\omega_0/\omega)^2}}$
Phase Response *T(jω)*	$-\tan^{-1}(\omega/\omega_0)$	$\tan^{-1}(\omega_0/\omega)$
Transmission at ω=0 (dc)	K	0
Transmission at ω=∝	0	K
3-dB Frequency	$\omega_0 = 1/\tau; \tau \equiv$ time constant	$\tau = RC$ or $\tau = L/R$

Fig Table Frequency response of STC networks.

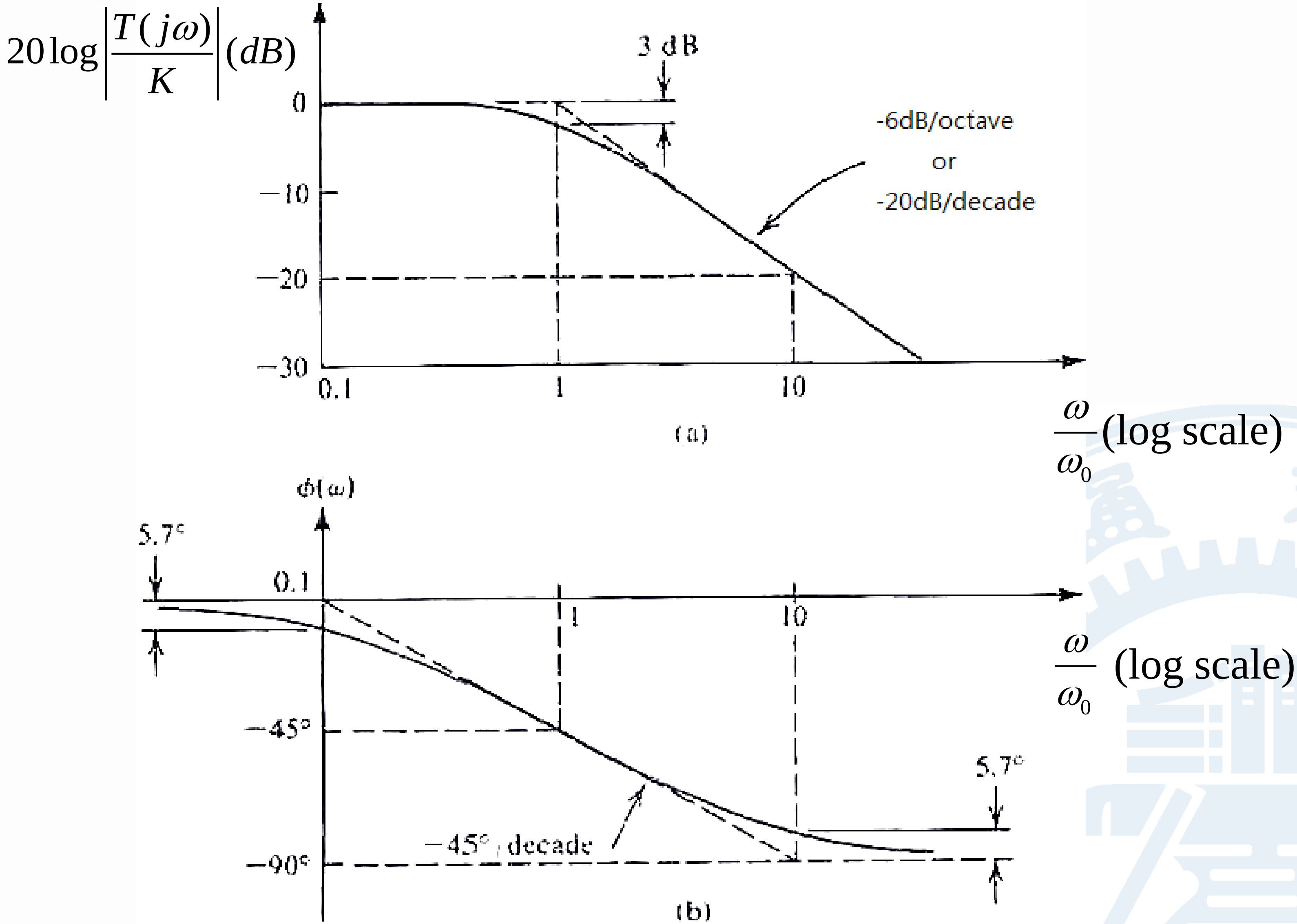


Fig Magnitude and phase response of low-pass filter.

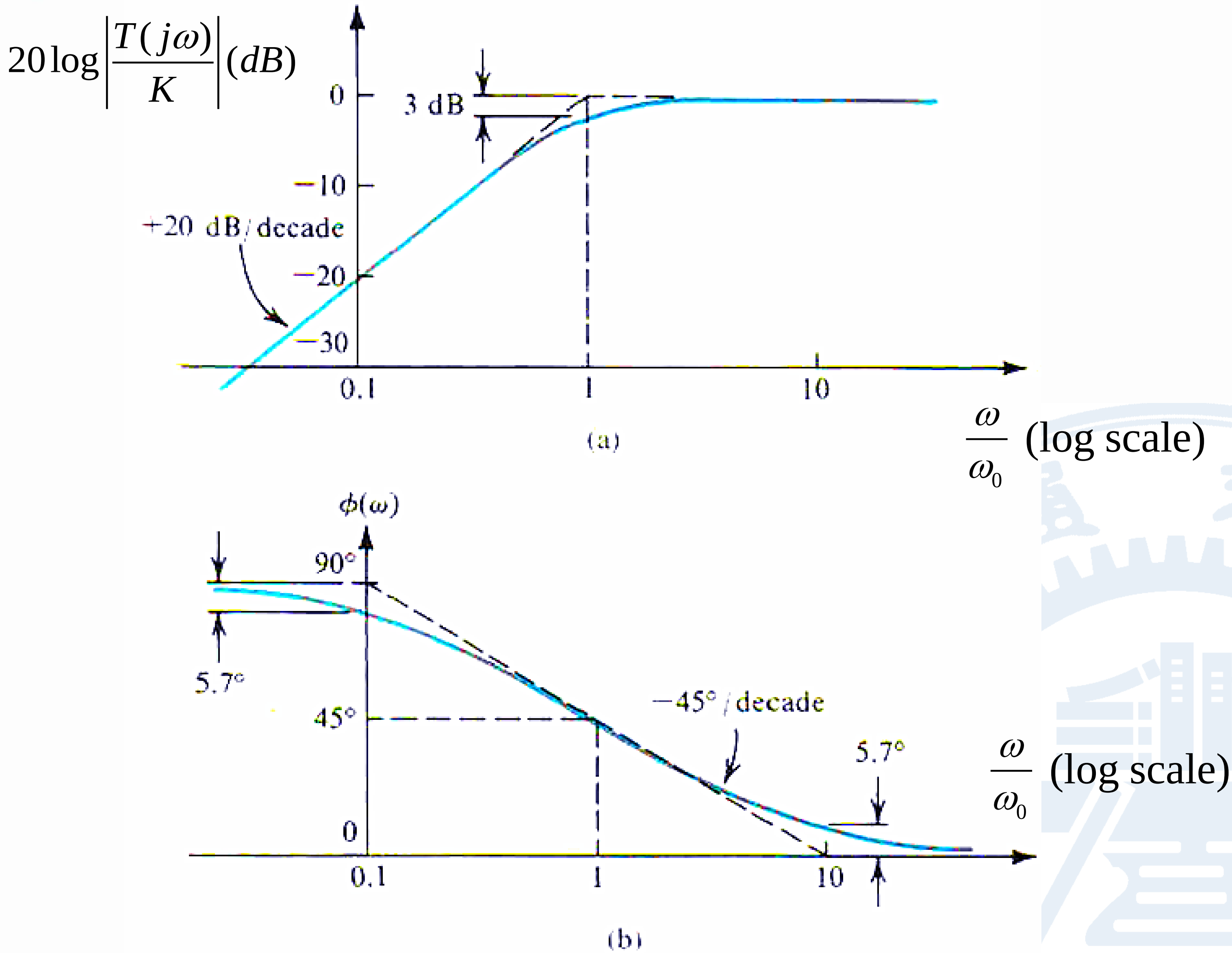
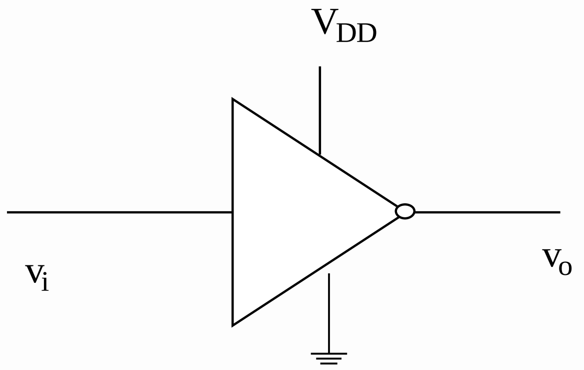
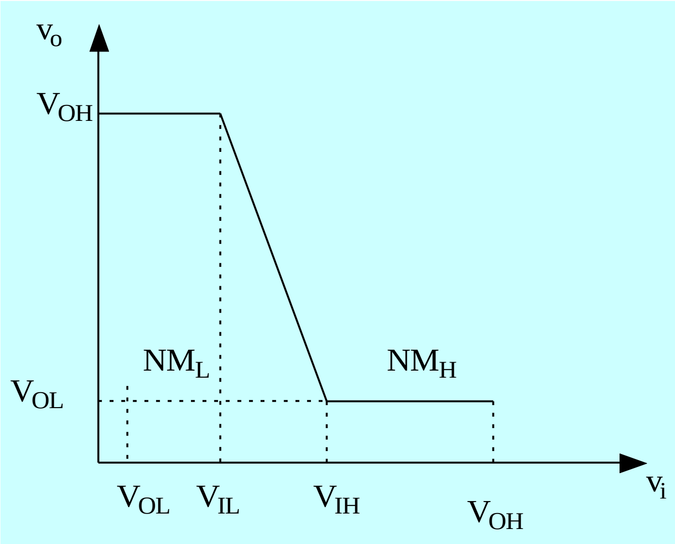


Fig Magnitude and phase response of high-pass filter.

The digital circuits Inverter





Function of the inverter

--- inverts the logic value of the input signal.

The voltage transfer characteristic (VTC), approximated by three straight-line segments.

Comparison between the amplifier and inverter:

--- Amplifier should be biased at the middle of VTC and the signal is kept sufficiently small so as to restrict operation in a linear region.

--- Digital applications (inverter) make use of the gross nonlinearity exhibited by the VTC.

Noise margin

- The advantage of the digital circuits over analog circuits: insensitivity of the inverter output to the exactly value of V_i within allowed regions－called as noise margins.
- The changes of the input within the noise margins will not change the output.
- Noise margin for high input: $NM_H = V_{OH} - V_{IH}$
- Noise margin for low input: $NM_L = V_{IL} - V_{OL}$

The ideal VTC

- **The ideal VTC is one that has:**

--- the maximized noise margins

--- equal distribution between the low and high regions.

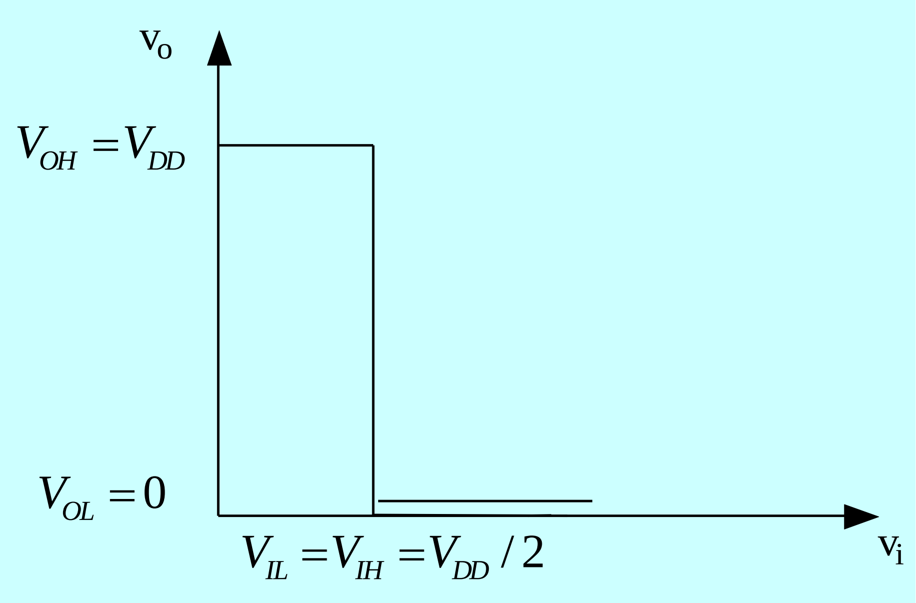


Fig ideal VTC

$$NM_H = NM_L = V_{DD}/2$$

Inverter implementation

- The first type: transistor switches

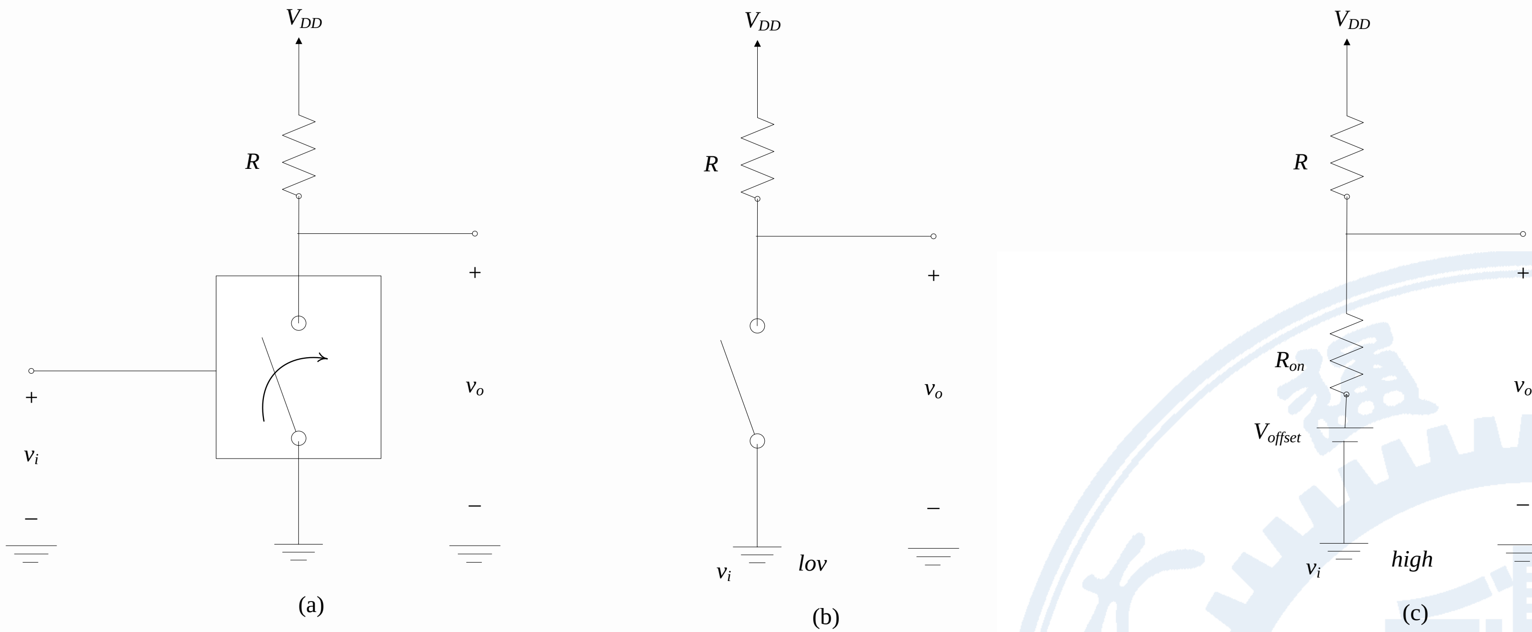


Fig (a) the transistor switch

and it equivalent circuit at the low input (b) and high input (c).

Shortcoming: a) The low output is not very low because of finite “on” resistance and the offset voltage V_{offset}.

b) The power consumption is large.

➢The second type: CMOS inverter
– complementary switches

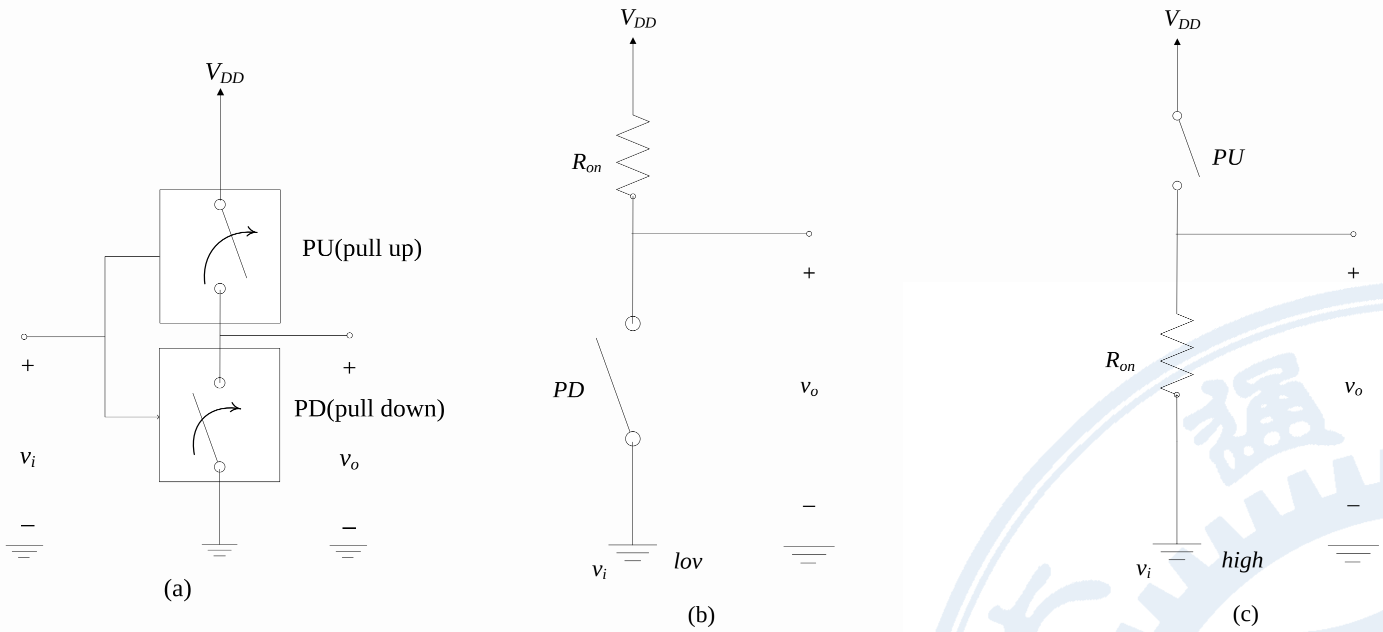


Fig (a) the CMOS inverter
and it equivalent circuit at the low input (b) and high input (c).

Advantages: a) no offset voltage
b) nearly zero static power consumption

➢The third type: **Double-throw switches**

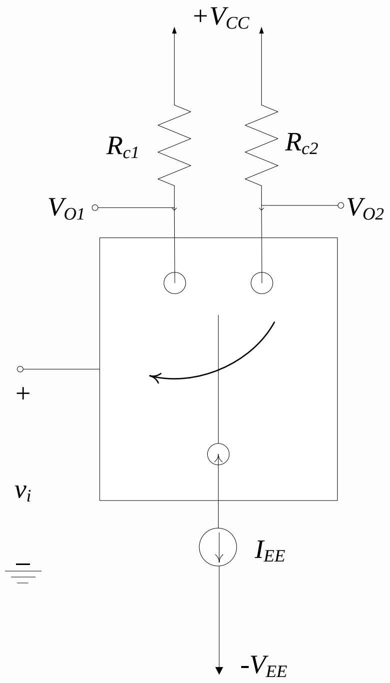


Fig Double-throw switch to steer the constant current I_{EE} to *Rc1* (when V_i is high) or *Rc2* (when V_i is low).

Summary

1. Signal source model:

— Thevenin form (a voltage source in series with a source impedance)

— Norton form (a current source in parallel with a source impedance)

2. Sine-wave signal is characterized by

— **peak value** (or **rms** (root- mean-square) value)

— **frequency** (f)

— **phase** with respect to an arbitrary reference time

3. Signal representations:

— time domain: its waveform versus time

— frequency domain (frequency spectrum): the sum of sinusoids

4. Analog signal : Its magnitude can be any value

Analogy circuits: Electronic circuits that process analog signals.

5. Digital signal:

—has one or two values: low and high (0 and 1) based on the binary system.

—resulted by sampling the magnitude of an analog signal at discrete instants of time and representing each signal sample by an number.

Digital circuits: process digital signals.

6. Analog-to digital converter (ADC)

— converts analog signals into digital signals.

7. Characteristic of the ideal amplifier: Linearity

— The transfer characteristic (v_o versus v_i) is a straight line with a slope equal to the **voltage gain.**

8. Four basic amplifier types:

— voltage, current, transconductance, transresistance amplifier

— depending on the signal to be amplified and the desired output signal.

9. Amplifier analysis: the transfer function in frequency domain:

— magnitude response

— phase response.

10. Amplifier bandwidth:

— the magnitude is nearly constant in 3db frequency region

— coincide with the signal spectrum to insure linearity.

11. Single-time-constant (STC) networks: only one time constant.

— Low-pass (LP): pass dc and low frequencies and attenuate high frequency

— High-pass (HP): opposite to LP

— 3db loss of LP STC circuit is at a frequency $\omega_0 = 1/\tau$.

12. Digital logic inverter: basic digital circuits.

– Voltage transfer characteristic (VTC) determine static operation and noise margins.

13. Simple inverter model: voltage controlled switches.

14. Power consumption of inverter:

– Static power consumption: operated in 0 or 1 state.

– Dynamic power consumption: during switching.