Transparency Masters

Introduction to Electronic Devices

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TRANSPARENCY MASTERS TO ACCOMPANY

INTRODUCTION TO ELECTRONIC DEVICES

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Introduction to Electronic Devices

Goals

- Master Fundamentals of Electronic Devices
- Develop problem solving skills

- Understand the meaning of device parameters used in circuit simulation programs (SPICE)

Our Motivation and Economics

Adam Smith, "An Enquiry into Nature and Causes of the Wealth of Nations" (1776)
The wealth is created by a laissez-faire economy and free trade.

John Maynard Keynes, The General Theory of Employment, Interest, and Money (1936)
The wealth is created by careful government planning and government stimulation of economy.

Paul Romer (1990s)

The wealth is created by innovations and inventions, such as computer chips.

Example: 4 microprocessors

- PowerPC 620 (Apple, IBM, and Motorola)
- Available 1995
- 0.5 micron CMOS technology,133 MHz clock rate
- 7 million transistors
- 3.3 V power supply
- 30 W power dissipation

WHAT IS CMOS?

WHY SO MUCH?

- AMD K5
- 0.35 micron CMOS, 150 MHz clock expected in 1996

WHY SO SMALL?

- Ultrasparc 200 MHz

- TI T5 0.35 micron CMOS, 200 MHz
- > 6 million transistor
- Power consumption 20-30 W

History of Semiconductors

In 1821, the German physicist Tomas Seebeck first noticed unusual properties of semiconductor materials, such as lead sulfur (PbS).

In 1833, the English physicist, Michael Faraday, reported on the temperature dependence of the conductivity for a new class of materials - semiconductors.

In 1873, the British engineer W. Smith discovered that the resistivity of selenium - a semiconductor material - is very sensitive to light.

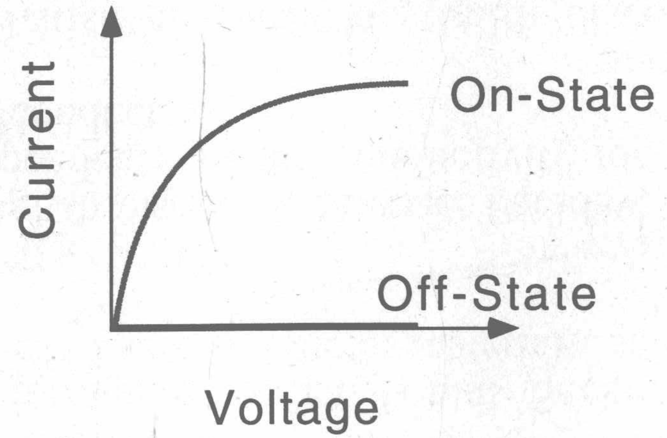
In 1875, Werner von Siemens invented a selenium photometer

In 1878 Graham Bell used this device for a wireless telephone communication system.

In 1948, Bardeen, Brattain, and Shockley discovered a Bipolar Junction Transistor and MODERN AGE BEGAN.

ON and OFF

Semiconductor devices can quickly change their conducting properties from those approximating insulators to those closer to good conductors. These "off" and "on" states correspond to zeros and ones of the Boolean logic. In a computer, semiconductor devices perform many millions or even billions of such operations per second.



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Basics of Quantum Mechanics Particle-Wave Duality

In 1901, Planck showed that the energy distribution of the black body radiation can only be explained by assuming that this radiation (i. e. electromagnetic waves) is emitted and absorbed as discrete energy quanta - **photons**.

$$E = \hbar\omega$$

where constant $\hbar = h/2\pi = 1.055\text{x}10^{-34}$ Js is called the **reduced Planck constant**, $h = 6.62\text{x}10^{-34}$ Js is the **Planck constant**, $\omega = 2\pi/T$ where T is the period.

Albert Einstein was the first to show that each photon has a **momentum**

- $p = E/c$

where c is the velocity of light. Hence, Planck and Einstein demonstrated that light has not only wave-like but also particle-like properties.

Example

The peak of the human eye sensitivity corresponds to green light with a wavelength of 0.555 μm , frequency

$$\omega = \frac{2\pi c}{\lambda} \approx \frac{2\pi \times 3.00 \times 10^{8} \frac{m}{s}}{0.555 \times 10^{-6} m} = 3.40 \times 10^{15} \frac{1}{s}$$

and a photon energy $E = \hbar\omega$ = 3.58×10^{-19} J.

Photon momentum 1.19×10^{-27} N-s

Such energies are usually measured in electron-volts. The unit of energy called **electron-volt** (eV) is the energy acquired by an electron accelerated by a 1 V potential difference. Since the electronic charge is equal to $-q$ where $q = 1.602 \times 10^{-19}$ C,

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ C} \times 1 \text{V} = 1.602 \times 10^{-19} \text{ Joule}$$

$$E \approx 2.23 \text{ eV}$$

Wave Function

In 1924, de Broglie suggested that this quantum mechanical duality applies also to particles, such as electrons. He introduced a wave associated with an electron (called the **de Broglie wave**). Later, Erwin Schrödinger and Max Born introduced the **wave function** $\Phi(x,y,z,t)$, such that the probability, dP, of finding a particle in an incremental volume $dxdydz$ is equal to $|\Phi(x,y,z,t)|^2 dxdydz$. The wave function, $\Phi(x, y, z, t)$, can be interpreted as the amplitude of the probability density of finding the particle in a given point of space at a given time.

Particle <-> Wave

Wave Function for a Free Particle

For a particle with a given momentum p in free space, the wave function, $\Phi(x,y,z,t)$, is proportional to $\exp[i(k_x x + k_y y + k_z z)] \exp(-i\omega t)$ where ω is frequency and k_x, k_y, and k_z are components of the **wave vector**, **k** (which is related to the wave length by $|\mathbf{k}| = 2\pi/\lambda$):

- $$\Phi(x,y,z,t) = A\exp[i(k_x x + k_y y + k_z z)]\exp(-i\omega t)$$

Here A is a constant, and

- $$\lambda = h/p = 2\pi\hbar/p$$

is called the **de Broglie wavelength**.

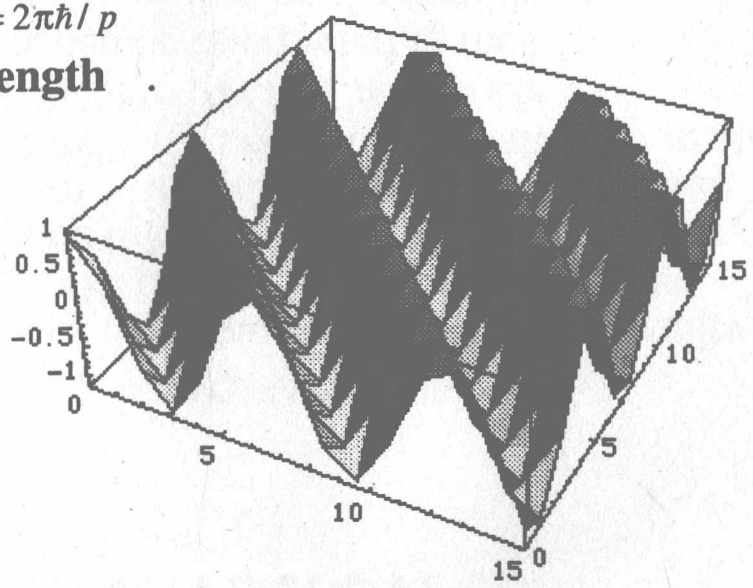
Since $\lambda = 2\pi/k$, we obtain

$$p = \hbar k$$

Example:

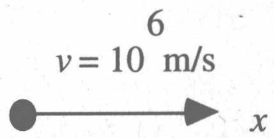
k = 1

ω = -1



Example

Consider an electron propagating in free space with velocity $v = 10^6$ m/s in direction x. The free electron mass is 9.11×10^{-31} kg. Calculate the electron momentum, wave vector, de Broglie wavelength, and energy.



Solution

The electron momentum and wave vector are directed along the x-axis. Hence $p_x = mv = 9.11 \times 10^{-31} \times 10^{6} = 9.11 \times 10^{-25}$ kgm/s, $p_y = p_z = 0$.

$k_x = p_x/\hbar = mv/\hbar = 9.11 \times 10^{-25}/1.054 \times 10^{-34} = 8.64 \times 10^{9}$ 1/m

$k_y = k_z = 0$

The de Broglie wavelength:

$\lambda = 2\pi/k = 7.27 \times 10^{-10}$ m $= 7.27$ Å

(1 meter (1 m) is equal to 10^{10} Angstroms (10^{10} Å))

The electron energy is kinetic energy:

$$E = \frac{mv^2}{2} = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m} = \frac{9.11 \times 10^{-31} \times \left(10^6\right)^2}{2}$$

$$= 4.55 \times 10^{-19}(J) = \frac{4.55 \times 10^{-19}}{1.602 \times 10^{-19}} = 2.84(eV)$$

Uncertainty Principle

In 1927, Werner Heisenberg stated the famous **Uncertainty Principle** :

The product of uncertainties, Δp_x and Δx, of a particle's momentum and its coordinate must be larger than $\hbar/2$

$$\Delta p_x \Delta x > \hbar/2$$

According to statistical physics, the average energy of an electron in a gas of free electrons at thermal equilibrium is $3 k_B T/2$ where T is temperature and $k_B = 1.38\text{x}10^{-23}$ Js is the Boltzmann constant.

The velocity of random electronic thermal motion, v_T, can be found by equating the kinetic energy of this motion, $m_e v_T^2/2$, to $3 k_B T/2$.

The free electron mass is $m_e = 9.11\text{x}10^{-31}$ kg, so that $v_T = (3k_B T/m_e)^{1/2} \approx 1.2\text{x}10^5$ m/s, $p = m_e v_T \approx 1.1\text{x}10^{-25}$ kgm/s, $k = p/\hbar \approx 10^9$ m^{-1}, and $\lambda = 2\pi/k \approx 6.3\text{x}10^{-9}$ m = 63 Å.

Hence, λ is comparable to the dimensions of very small semiconductor devices (which may have certain dimensions as small as 50 Å), and quantum effects may play a very important role in such devices.

Example

Consider an electron propagating with velocity $v = 10^6$ m/s in direction x in a 100 Å wide gap. The free electron mass is 9.11×10^{-31} kg. Calculate the electron momentum and energy.