光電子學導論

Introduction to Optoelectronics

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Optoelectronics (Optical Electronics)

- Optoelectronics is a study of interaction between optical wave and matter.
- An optoelectronic system usually consists of transmitter, optical media, and receiver.
- For most cases, a transmitter contains an optoelectronic emitter such as a light-emitting diode or a semiconductor laser. Optical elements such as lenses, apertures, and filters may also be used to affect light output characteristics.
- The emitted optical radiation then propagates through a medium, such as optical fiber or free space, to reach the receiver section.
- At the receiver the detector and its associated electronics convert the optical input into an electrical signal for further processing.

Maxwell's Equations

Maxwell's equations in *vacuum*:

$(i) \nabla \cdot \vec{E} = \frac{1}{\varepsilon_0} \rho$	(Gauss' s law)
$(ii) \nabla \cdot \vec{B} = 0$	(no name)
(<i>iii</i>) $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$	(Faraday' s law)
(<i>iv</i>) $\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$	(Ampere's law with Maxwell's correction)

Together with the *force law*: $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$, they summarize the entire theoretical content of classical electrodynamics.

 Maxwell's equations tell you how charges produce fields; the force law tells you how fields affect charges.
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Electromagnetic Waves in Vacuum

There is no charge or current in space: **Maxwell's equations:** (i) $\nabla \cdot \vec{E} = 0$ (iii) $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$ (ii) $\nabla \cdot \vec{B} = 0$ (iv) $\nabla \times \vec{B} = \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$ $\nabla \times (\nabla \times \vec{E}) = \nabla (\nabla \cdot \vec{E}) - \nabla^2 \vec{E} = \nabla \times \left(-\frac{\partial \vec{B}}{\partial t} \right) = -\frac{\partial}{\partial t} (\nabla \times \vec{B}) = -\mu_0 \varepsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2}$ $\nabla \times (\nabla \times \vec{B}) = \nabla (\nabla \cdot \vec{B}) - \nabla^2 \vec{B} = \nabla \times \left(\mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \right) = \mu_0 \varepsilon_0 \frac{\partial}{\partial t} (\nabla \times \vec{E}) = -\mu_0 \varepsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2}$

The wave equations for *E* and *B* :

$$\nabla^{2} \vec{E} = \mu_{0} \varepsilon_{0} \frac{\partial^{2} \vec{E}}{\partial t^{2}}, \nabla^{2} \vec{B} = \mu_{0} \varepsilon_{0} \frac{\partial^{2} \vec{B}}{\partial t^{2}} \quad c = \frac{1}{\sqrt{\mu_{0} \varepsilon_{0}}} = 3.00 \times 10^{8} \text{ m/s}$$

Maxwell's Equations in Matter

- In terms of *free charges* and *currents*, Maxwell's equations read
 - $(i) \nabla \cdot \vec{D} = \rho_{f} \quad (iii) \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \begin{array}{c} \text{Displacement} \\ \text{current} \\ \hline \\ (ii) \nabla \cdot \vec{B} = 0 \quad (iv) \nabla \times \vec{H} = \vec{J}_{f} + \frac{\partial \vec{D}}{\partial t} \end{array}$

For linear media:

D: Electric Displacement

$$\vec{P} = \varepsilon_0 \chi_e \vec{E} \quad \& \quad \vec{M} = \chi_m \vec{H} \implies \vec{D} = \varepsilon \vec{E} \quad \& \quad \vec{H} = \frac{1}{\mu} \vec{B}$$
$$\varepsilon = \varepsilon_0 (1 + \chi_e), \quad \mu = \mu_0 (1 + \chi_m)$$

Index of Refraction & Dilectric Constant

Electromagnetic waves propagate through a *linear* homogeneous medium at a speed:

$$v = \frac{1}{\sqrt{\varepsilon\mu}} = \frac{c}{n} \qquad n \equiv \sqrt{\frac{\varepsilon\mu}{\varepsilon_0\mu_0}}$$

- *n* is the *index of refraction* of the material.
- **For** *most* materials, μ is very close to μ_0 .
- \bullet ε_r is the dielectric constant.

 $n \cong \sqrt{\varepsilon_r} > 1 \Longrightarrow v < c \quad (\varepsilon_r = \varepsilon / \varepsilon_0)$

- All of our previous results carry over, with the simple transcription $\varepsilon_0 \rightarrow \varepsilon$, $\mu_0 \rightarrow \mu$, and hence $c \rightarrow v$.
- For monochromatic plane waves the angular frequency ω (=2πf) and wave number k (=2π/λ) are related by ω = kv, and the amplitude of B is 1/v times the amplitude of E.
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Dispersion Curves



Normal Dispersion: *n* gradually decreases with wavelength; or, equivalently, increases with frequency. $(f = c / \lambda)$

Figure 3.40 The wavelength dependence of the index of refraction for various materials.

EM Theory, Photons, and Light

- The work of J. Clerk Maxwell and subsequent developments since the late 1800s have made it evident that light is most certainly electromagnetic in nature.
- If the wavelength of light is small in comparison to the size of the apparatus (lenses, mirrors, etc.), one may use, as a first approximation, the technique of *Geometric Optics*.
- A somewhat more precise treatment, which is applicable as well when the dimensions of the apparatus are small, is that of *Physical Optics*. In physical optics the dominant property of light is its wave nature.
- The dual nature of light is evidenced by the fact that it propagates through space in a wavelike fashion and yet displays particlelike behavior during the processes of emission and absorption.
- **The photon has zero mass.**

Wavelength, Frequency, Period of EM Waves



Directions of E, B, and Wave Propagation



Figure 3.14 (a) Orthogonal harmonic \vec{E} - and \vec{B} -fields for a plane polarized wave. (b) The wave propagates in the direction of $\vec{E} \times \vec{B}$.

Spectrum of Electromagnetic Waves





Figure 3.4b The optical portion of the electromagnetic spectrum.

Specular Reflection & Diffuse Reflection



Figure 4.18 (a) Specular reflection. (b) Diffuse reflection. (Photos courtesy Donald Dunitz.)



A *ray* is a line drawn in space corresponding to the direction of flow of radiant energy.



Figure 4.17 (a) Select one ray to represent the beam of plane waves. Both the angle-of-incidence θ_i and the angle-of-reflection θ_r are measured from a perpendicular drawn to the reflecting surface. (b) The incident ray and the reflected ray define the plane-of-incidence, perpendicular to the reflecting surface.

Snell's Law and Total Internal Reflection (TIR)



Fundamental Laws of Geometrical Optics: (1) $\theta_i = \theta_r$ (2) $n_1 \sin(\theta_i) = n_2 \sin(\theta_t)$

Total Internal Reflection (TIR):If $n_1 > n_2$ and $\theta_i > \theta_c = \sin^{-1}(n_2/n_1)$, then reflection = 100%.2022/01/21光電子學導論 / 國立彰化師範大學物理學系 / 郭艶光14

Bending of Rays at an Interface



TE and TM Polarizations



S, TE Polarization (Perpendicular Polarization) E field is perpendicular to the plane of incidence



P, TM Polarization (Parallel Polarization) H field is perpendicular to the plane of incidence

Brewster's Angle for TM Mode

For TM Polarization, Reflection Coefficient R:

$$\mathbf{R} = \left(\frac{n_1 \cos(\theta_t) - n_2 \cos(\theta_i)}{n_1 \cos(\theta_t) + n_2 \cos(\theta_i)}\right)^2$$

R = **0** when θ_i = Brewster's Angle θ_B = tan⁻¹(n_2/n_1).

For TE Polarization, Reflection Coefficient R:

$$\mathbf{R} = \left(\frac{n_1 \cos(\theta_i) - n_2 \cos(\theta_t)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)}\right)^2$$

There is not any angle at which $\mathbf{R} = \mathbf{0}$.

Brewster's Angle, θ_B (Parallel Polarization TM Only)



A plot of the transmitted and reflected *amplitudes* as functions of θ_I for light incident on glass (n₂ = 1.5) from air (n₁ = 1).
 Reflection goes to zero at *Brewster's* angle, θ_B.
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Superposition of Two Harmonic Waves In-Phase and Out-of-Phase



 $E = E_1 + E_2$

$$E(x,t) = E_0 \sin[wt + \alpha(x,\varepsilon)]$$

where $\alpha(x,\varepsilon) = -(kx + \varepsilon)$
$$E_1 = E_{01} \sin(wt + \alpha_1)$$

$$E_2 = E_{02} \sin(wt + \alpha_2)$$

$$E = E_1 + E_2 = \cdots$$

$$E_0^2 = E_{01}^2 + E_{02}^2 + 2E_{10}E_{20}\cos(\alpha_2 - \alpha_1)$$

 $\tan \alpha = \frac{E_{01} \sin \alpha_1 + E_{02} \sin \alpha_2}{E_{01} \cos \alpha_1 + E_{02} \cos \alpha_2}$

Standing Waves



 $\Psi(x,t) = C_1 f(x - vt) + C_2 f(x + vt)$ $E_I = E_{0I} \sin(kx + wt + \varepsilon_I)$ $E_{R} = E_{0R} \sin(kx - wt + \varepsilon_{R})$ $E = E_I + E_P$ If $E_{0I} = E_{0R}$, and, E = 0 when x = 0 for all values of t: $E = E_{01} \left| \sin(kx + wt) + \sin(kx - wt) \right|$ $\Rightarrow \cdots \Rightarrow E(x,t) = 2E_{01} \sin kx \cos wt$

Figure 7.10 The creation of standing waves. Two waves of the same amplitude and wavelength traveling in opposite directions form a stationary disturbance that oscillates in place.

A Standing Wave at Various Time



Diffraction of Light

http://micro.magnet.fsu.edu/primer/java/diffraction/basicdiffraction/index.html



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What Is LASER?

LASER is the abbreviation of ^CLight Amplification by Stimulated Emission of Radiation

Taiwan ♀ 雷射(取其音)
China ♀ 激光(取其意)

Interaction Between Photon and Electron



Fundamentals of Laser Light

Laser light is electromagnetic wave in nature. It travels with a speed of 3×10⁸ m/sec in free space (vacuum).

- Laser light has very narrow spectral width, which is close to the characteristic of monochromatic light.
- Laser light has very high degree of coherence so that all the photons travel in the same direction with the same phase.

Fundamental Elements of a Laser System



Typical Performance Curve (Output-Input Relation)



4-Level and 3-Level Laser Systems



- The dynamics of most lasers, including the semiconductor lasers, can be described by the four energy levels shown above. These lasers are called "4-level lasers" that usually have good laser efficiency.
- For some lasers (e.g., ruby) the lower laser level is in fact the ground state. These lasers are called "3-level lasers" that usually have relatively poor laser efficiency.

Q-Switching

- In an optical resonator the quality factor Q is defined as the ratio of the energy stored in the laser cavity to the energy loss per cycle. Therefore, the quality factor of a laser resonator can be altered by varying the cavity loss.
- In the technique of Q-switching, energy is stored in the gain medium through optical pumping while the quality factor is lowered in a particular way, depending on the method used, to prevent from laser oscillation. After a high population inversion has been developed, the high cavity Q is then restored, or "switched", such that the stored energy can be released in very short time.
- The pulsewidth available in this manner is usually in the order of tens of nanoseconds and the peak power can be several orders higher than that of the ordinary long laser pulse.
- Q-switching of the solid-state lasers is important because it provides short duration optical pulses required for laser ranging, nonlinear studies, medicine and other important applications.



Pumping System





Pumping System



Mode-Locking

- Ultrashort pulses with pulse widths in the picosecond (10⁻¹² sec) or femtosecond (10⁻¹⁵ sec) regime may be obtained from solid-state lasers by mode-locking.
- Employing this technique, which phase-locks the longitudinal modes of the laser, the pulse width is inversely related to the bandwidth of the laser emission. Therefore, tunable solid-state lasers are perfect candidates for mode-locking, although other solid-state lasers (e.g., Nd:YAG, etc.) may also be mode-locked to obtain short laser pulses.
- The output from laser oscillators is subject to strong fluctuations which originate from the interference of longitudinal laser modes with random phase relations. These random fluctuations can be transformed into a powerful well-defined single pulse circulating in the laser resonator by the introduction of a suitable nonlinearity (i.e., passive mode-locking) or by an externally driven optical modulator (i.e., active mode-locking).

Characteristics of Mode-Locked Lasers

- Longitudinal modes: L = (λ/2) × n, n = 1, 2, 3, ...
 ⇒ L = (C/2ν) × n ⇒ ν = (C/2L) × n ⇒ Δν = C/2L (Hz)
 = longitudinal mode spacing in frequency (i.e., Free Spectral Range, FSR)
- $1/\Delta v = 2L/C = \Delta T$ (sec) = round-trip transit time
- For a mode-locked laser, pulse width = $\tau_p \cong 1/\Delta v_L$, Δv_L = gain bandwidth
- Assuming that we have N longitudinal modes, $\Delta v_L = N \times \Delta v = N/\Delta T \Rightarrow \tau_p \simeq 1/\Delta v_L = \Delta T/N$
- Peak Power = $P_{peak} = N \times P_{avg}$ (W), $P_{avg} = Average Power$
- Example: for a typical Nd:YAG laser, $\lambda = 1.064 \mu m$, L = 1.2 m, $\Delta T = 8 ns$, $\Delta v = 125 MHz$, N = 400 (modes), $\tau_p \cong 20 ps$.
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Longitudinal and Transverse Laser Modes

- Light emitted by most lasers contains several discrete optical frequencies, separated from each other by frequency differences that can be associated with different modes of the optical resonator.
- **Longitudinal modes differ from one another in their frequency.** The mode spacing Δv is equal to c/2nd, where c is the speed of light, n and d are refractive index and cavity length, respectively. (note: $\Delta \lambda = \lambda^2/2nd$)
- Transverse modes (also called "lateral modes", or "spatial modes") differ from one another in their field distribution in a plane perpendicular to the direction of propagation.
- The fundamental transverse mode is TEM₀₀ Gaussian mode. The spot size of the Gaussian beam (w) is defined as the radius at which the intensity of the TEM₀₀ mode is 1/e² of its peak value on the axis.

Stability Diagram for Laser Resonators



Gaussian Beams (TEM₀₀ Mode)



For lowest-order TEM₀₀ **mode (in cylindrical coordinates):**
Spreading of a TEM₀₀ Mode



The expansion angle (full angle) of the laser beam is: $\theta \cong \frac{2\lambda_0}{2\lambda_0}$

 $\pi n W_0$

Category of Laser Systems

- 1) Gas Lasers (氣態雷射) He-Ne Laser, Ar⁺ Laser, CO₂ Laser, N₂ Laser, ...
- 2) Liquid Lasers (液態雷射) Organic Dye Lasers, ...
- 3) Solid-State Lasers (固態雷射) Ruby Laser, Nd:YAG Laser, Nd:Glass Laser, ...
- 4) Semiconductor Lasers (半導體雷射) AIGaAs, InGaAsP, AIGaInP, InGaN, InGaAsN, ...
- 5) Other Lasers (其他雷射) Chemical Laser, Free-Electron Laser, ...

Typical Gas Laser Configuration



He-Ne Laser

- The first CW laser, as well as the first gas laser, was one in which a transition between the 2S and the 2P levels in atomic Ne resulted in the emission of 1.15 µm radiation.
- Transitions in Ne were used subsequently to obtain laser oscillation at $\lambda_0 = 0.6328 \ \mu m$ and at $\lambda_0 = 3.39 \ \mu m$.
- The operation of this laser can be explained as follows: a dc (or rf) discharge is established in the gas mixture containing, typically, 1.0 mm Hg of He and 0.1 mm Hg of Ne. The energetic electrons in the discharge excite helium atoms into a variety of excited states. In the normal cascade of these excited atoms down to the ground state, many collect in metastable levels 2³S and 2¹S. Since the metastable levels nearly coincide in energy with the 2S and 3S levels of Ne, they can excite Ne atoms into these two excited states.

Energy Levels of He-Ne Laser



Figure 7-15 He-Ne energy levels. The dominant excitation paths for the red and infrared laser-maser transitions are shown. (After Reference [11].)

Absorption and Fluorescence of Rhodamine 6G

Figure 10.8 Energy-level diagram typical of a dyc. (Data from Bass et al.⁹)

Figure 10.9 Singlet-state absorption and fluorescence spectra of rhodamine 6G obtained from measurements with a 10^{-4} M ethanol solution of the dye. (Data from Snavely.⁸)

Configuration of Continuous-Wave (CW) Dye Laser

Figure 10.10 Typical configuration for a CW dye laser. (Standing - wave configuration)

Continuously Tunable Ring-Laser Cavity

Ruby Laser – the first laser in this planet

- The Cr:Al₂O₃ (ruby) laser was the first working laser that was introduced by Theodore H. Maiman in 1960.
- Although neodymium doped YAG (Nd:YAG) laser has replaced ruby laser as general-purpose pulsed solid-state laser, ruby laser is still playing an important role in various applications.
- Ruby laser is capable of generating high-energy, visible red pulses (at 694.3 nm) which are powerful tools for removal of tattoos and disfiguring pigmented lesions from the skin.
- Ruby laser can also generate high-energy pulses from a compact package which makes the ruby laser a valuable tool for holographic nondestructive testing, double-pulse holography, and plasma diagnostics.
- The host of ruby laser is Al₂O₃ (sapphire), which is a unique host material since it is hard, durable, and chemically stable. The sapphire is transparent from 0.15 μm to 6.5 μm. When doped with chromium ions (Cr³⁺), which substitute the Al³⁺, the crystal becomes pink or red depending upon the doping concentration.

Characteristics of Ruby Laser

Chemical formula Color **Type of crystal** Main absorption peaks Laser wavelength at 25 °C Peak emission cross-section Fluorescence lifetime at 25 °C **Density Refractive index at 694 nm** dn/dT **Melting point** Thermal conductivity at 25 °C

Cr:Al₂O₃ (Cr-doped sapphire) Red or Pink Hexagonal, uniaxial 400 nm and 550 nm 694.3 nm (R₁ line) $2.5 \times 10^{-20} \text{ cm}^2$ **3.0 ms (4.3 ms at 77 K)** 3.98 g/cm³ $n_0 = 1.763, n_e = 1.755$ $12.6 \times 10^{-6} / {}^{\circ}C$ 2027 °℃ $42 \text{ W/m}^{\circ}\text{C}$

Characteristics of Nd:YAG Laser

Chemical formula

Color Type of crystal Atomic % Nd Laser wavelength at 25 °C Peak emission cross-section Fluorescence lifetime at 25 °C Density Refractive index at 1064 nm Melting point

Nd:Y₃Al₅O₁₂ (Nd-doped yttrium aluminum garnet) **Light purple-blue Cubic**, isotropic 1.0 1.064 µm (1064 nm) $2.8 \times 10^{-19} \text{ cm}^2$ 230 µs 4.56 g/cm³ 1.82 **1970 °C**

Nd:YAG has absorption near 810 nm
 AlGaAs semiconductor laser can be used as a pump source

• Wavelength of Nd:Glass laser \cong 1054 nm (depending on the host used)

Characteristics of Nd:Glass Lasers

Glass Type Spectroscopic Properties	Q – 246 Silicate (Kigre)	Q – 88 Phosphate (Kigre)	LHG – 5 Phosphate (Hoya)	LHG – 8 Phosphate (Hoya)	LG – 670 Silicate (Schott)	LG - 760 Phosphate (Schott)
Peak Wavelength [nm]	1062	1054	1054	1054	1061	1054
Cross Section $[\times 10^{20} \text{ cm}]$	2.9	4.0	4.1	4.2	2.7	4.3
Fluorescent Lifetime [µs]	340	330	290	315	330	330
Linewidth FWHM [nm]	27.7	21.9	18.6	20.1	27.8	19.5
Density [gm/cc]	2.55	2.71	2.68	2.83	2.54	2.60
Index of Refraction [Nd]	1.568	1.545	1.539	1.528	1.561	1.503
Nonlinear Index n_2 [10 ⁻¹³ esu]	1.4	1.1	1.28	1.13	1.41	1.04
dn/dt (20°–40°C [10 ⁻⁶ /°C]	2.9	-0.5	8.6	-5.3	2.9	-6.8
Thermal Coefficient of Optical						
Path (20°–40°C)[10 ⁻⁶ /°C]	+8.0	+2.7	+4.6	+0.6	8.0	_
Transformation Point [°C]	518	367	455	485	468	_
Thermal Expansion coeff.						
$(20^{\circ}-40^{\circ} [10^{-7}/^{\circ}C]$	90	104	86	127	92.6	138
Thermal Conductivity						
[w/m]	1.30	0.84	1.19	_	1.35	0.67
Specific Heat [J/g · K]	0.93	0.81	0.71	0.75	0.92	0.57
Knoop Hardness	600	418	497	321	497	_
Young's Modulus [kg/mm ²]	8570	7123	6910	5109	6249	_
Poisson's Ratio	0.24	0.24	0.237	0.258	0.24	0.27

Ti:sapphire Laser – tunable between 670 and 1070 nm

- Since laser action was first reported by P. F. Moulton in 1982, the Ti:sapphire (Ti:Al₂O₃) laser, which has a broad tuning range of about 400 nm, has been the most widely used tunable solid-state laser.
- Crystal of Ti:sapphire exhibits a broad absorption band, located in the blue-green region of the visible spectrum with a peak around 490 nm. The Ti:sapphire laser is tunable from 670 nm to 1070 nm, with a peak of the gain curve around 800 nm.
- Commercial Ti:sapphire lasers are usually pumped by argon lasers to obtain continuous wave (cw) output, and by frequency-doubled Nd:YAG, Nd:YLF, or Nd:YVO₄ lasers for pulsed operation.
- Tuning ranges from about 700 nm to 1050 nm require several (usually three) sets of cavity mirrors. For pulsed solid-state lasers as pump source, output energies range from a few mJ at repetition rates of around 1 kHz, to 100 mJ per pulse at 20 pps.
- A very important application of Ti:sapphire lasers is the generation and amplification of femtosecond (10⁻¹⁵ sec) mode-locked pulses. A pulse width of a few tens of femtoseconds may be obtained easily from the Ti:sapphire lasers.

Characteristics of Ti:Sapphire Laser

Index of refraction Fluorescent lifetime Fluorescent linewidth (FWHM) Peak emission wavelength Peak stimulated emission cross section parallel to c axis perpendicular to c axis Stimulated emission cross section at 0.795 μ m (|| c axis) Quantum efficiency of converting a 0.53 μ m pump photon into an inverted site Saturation fluence at 0.795 μ m

- n = 1.76 $\tau = 3.2 \,\mu s$ $\Delta \lambda \sim 180 \,\mathrm{nm}$ $\lambda_{\mathrm{p}} \sim 790 \,\mathrm{nm}$
- $\sigma_{\mathrm{p}\parallel} \sim 4.1 \times 10^{-19} \,\mathrm{cm}^2$ $\sigma_{\mathrm{p}\perp} \sim 2.0 \times 10^{-19} \,\mathrm{cm}^2$

$$\sigma_{\parallel} = 2.8 \times 10^{-19} \,\mathrm{cm}^2$$

 $\eta_Q \approx 1$ $E_{\rm sat} = 0.9 \,{\rm J/cm}^2$

Ring Configuration for a CW Ti:Sapphire Laser Cavity

Crystal Property

- In studying solid state electronic devices we are interested primarily in the electrical behavior of solids. The transport of charge through a metal or a semiconductor depends not only on the properties of the electron but also on the arrangement of atoms in the solid.
- Semiconductors are a group of materials having electrical conductivities intermediate between metals and insulators. The conductivity of these materials can be varied over orders of magnitude by changes in temperature, optical excitation, and impurity content.
- Semiconductor materials are found in column IV and neighboring columns of the periodic table. The column IV semiconductors (Si and Ge) are called *elementary semiconductors* because they are composed of single species of atoms.
- In addition to the elementary materials, compounds of column III and column V atoms, as well as certain combinations from II and VI, and from IV, make up the *compound semiconductors*.
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A Portion of Periodic Table

Ι	ΙΙ	IIb	III	IV	V	VI
³ Li	⁴ Be		⁵ B	6 C	7 N	⁸ O
¹¹ Na	¹² Mg		13	¹⁴ Si	15 P	16 <mark>S</mark>
¹⁹ K	²⁰ Ca	³⁰ Zn	³¹ Ga	³² Ge	³³ As	³⁴ Se
³⁷ Rb	³⁸ Sr	48 Cd	49 In	⁵⁰ Sn	⁵¹ Sb	⁵² Te
⁵⁵ Cs	⁵⁶ Ba	⁸⁰ Hg	⁸¹ Tl	⁸² Pb	⁸³ Bi	⁸⁴ Po

IV: Photo-detector III-V & II-VI: LED/LD & Photo-detector

Elementary, Binary, Ternary, Quaternary Compounds

- The *elementary* semiconductor Ge was widely used in semiconductor development for transistors and diodes. Silicon is now used for the majority of rectifiers, transistors, and integrated circuits (IC).
- The compounds are widely used in high-speed devices and devices requiring the emission or absorption of light.
- The two-element (*binary*) III-V compounds such as GaN, GaP:N, and GaAs are common in light-emitting diodes (LED). The three-element (*ternary*) compounds such as AlGaAs and GaAsP, and four-element (*quaternary*) compounds such as InGaAsP, AlGaInP, and AlGaInN can be grown to provide added flexibility in choosing material properties.
- Light detectors are commonly made with InSb, CdSe, PbTe, and HgCdTe. Si, Ge, GaAs, and InGaAs are also widely used as visible light, infrared, and nuclear radiation detectors.
- Semiconductor lasers are made using GaAs, AlGaAs, InGaAsP, AlGaInP, InGaN, InGaAs, InGaAsN, and other ternary and quaternary compounds.

Crystal Lattices

- A crystalline solid is distinguished by the fact that the atoms making up the crystal are arranged in a periodic fashion.
- Not all solids are crystals; some have no periodic structure at all (*amorphous solids*), and others are composed of many small regions of single-crystal material (*polycrystalline solids*).
- The periodic arrangement of atoms in a crystal is called the *lattice*. The lattice contains a volume, called a *unit cell*, which is representative of the entire lattice and is regularly repeated throughout the crystal.
- The simplest three-dimensional lattice is one in which the unit cell is a cubic volume. The simple cubic structure (sc) has an atom located at each corner of the unit cell. The body-centered cubic (bcc) lattice has an additional atom at the center of the cubic, and the face-centered cubic (fcc) unit cell has atoms at the eight corners and centered on the six faces.

Crystalline, Amorphous, and Polycrystalline Solids

(a) Crystalline

(b) Amorphous

(c) Polycrystalline

Three types of solids, classified according to atomic arrangement: (a) crystalline and (b) amorphous materials are illustrated by microscopic view of the atoms, whereas (c) polycrystalline structure is illustrated by a more macroscopic view of adjacent single-crystalline regions, such as (a).

Unit Cells for Cubic Lattice Structures

Simple cubic

Body-centered cubic

Face-centered cubic

Three types of cubic lattice structures: simple cubic (sc), body-centered cubic (bcc), and face-centered cubic (fcc).

The dimension a for a cubic unit cell is called the *lattice constant*.

Diamond Lattice

- The basic lattice structure for many important semiconductors is the *diamond lattice*, which is characteristic of Si and Ge.
- In many compound semiconductors, atoms are arranged in a basic diamond structure but are different on alternating sites. This is called a *zincblende lattice* and is typical of the III-V compounds.
- The diamond lattice can be thought of as an *fcc* structure with an extra atom placed at a/4 + b/4 + c/4 from each of the fcc atoms.
- If the atoms are all similar, we call this structure a diamond lattice; if the atoms differ on alternating sites, it is a zincblende structure. For example, if one fcc sublattice is composed of Ga atoms and the interpenetrating sublattice is As, the zincblende structure of GaAs results.
- Most of the compound semiconductors have this type of lattice (zincblende lattice), although some of the compounds are arranged in a slightly different structure called the wurtzite lattice.
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Diamond Lattice Structure

Diamond lattice structure: (a) a unit cell of the diamond lattice constructed by placing atoms ¼, ¼, ¼ from each atom in an fcc; (b) top view (along any <100> direction) of an extended diamond lattice.

Diamond / Zincblende Lattice Unit Cells

Each atom in the diamond and zincblende structures is surrounded by four nearest neighbors.

Bonding Force in Solids

- NaCl is typified by *ionic bonding*. In NaCl lattice, each Na atom is surrounded by six nearest neighbor Cl atoms, and vice versa.
- In the *metal* the outer electrons of the atoms are contributed to the crystal as a whole, so that the solid is made up of ions with closed shells immersed in a sea of free electrons. The forces holding the lattice together arise from an interaction between the positive ion cores and the surrounding free electrons. This is one type of *metallic bonding*.
- A third type of bonding is exhibited by the diamond lattice semiconductors. Each atom in the Ge, Si, or C diamond lattice is surrounded by four nearest neighbors, each with four electrons in the outer orbit. In these crystals each atom shares its valence electrons with its four neighbors. The bonding forces arise from a quantum mechanical interaction between the shared electrons. This is known as *covalent bonding*; each electron pair constitutes a covalent bond.

Covalent Bonding in the Si Crystal

- The bonding forces arise from interaction between the shared electrons. Each electron pair constitutes a covalent bond. In the sharing process it is no longer relevant to ask which electron belongs to a particular atom – both belong to the bond.
- **The two electrons are indistinguishable, except that they must have opposite spin to satisfy the** *Pauli exclusive principle*.

More About Covalent Bonding

- In addition to semiconductors, covalent bonding is also found in certain molecules, such as H₂.
- As in the case of the ionic crystals, no free electrons are available to the lattice in the covalent diamond structure. By this reasoning Ge and Si should also be insulators. However, we have pictured an idealized lattice at 0 K in this figure.
- An electron can be thermally or optically excited out of covalent bond and thereby become free to participate in conduction. This is an important feature of semiconductors.
- Compound semiconductors such as GaAs have mixed bonding in which both ionic and covalent bonding forces participate. Some ionic bonding is to be expected in a crystal such as GaAs because of the difference in placement of the Ga and As atoms in the periodic table.
- The ionic character of the bonding becomes more important as the atoms of the compound become further separated in the periodic table, as in the II-VI compounds.

Typical Band Structures at 0 K

Direct and Indirect Semiconductors

Band Structure of Semiconductor Under Stress

Fig. 9.23 Band structure of a direct band-gap semiconductor under stress. The left and right diagrams show the cases of compressive and tensile strain respectively. The heavy-hole (HH) and light-hole (LH) bands coincide at the center in the absence of strain. Emitted light is TE or TM polarized depending on whether the electron combines with the heavy or light hole.

Electron-Hole Pair in a Semiconductor

The few electrons and holes in the conduction and valence bands are free to move about via the many available empty states.

Conductivity, Mobility, and Effective Mass

- The charge carriers in a solid are in constant motion. The thermal motion of an electron may be visualized as random scattering from lattice vibrations, impurities, other electrons, and defects. Since the scattering is random, there is no net motion of the group of *n* electrons/cm³ over any period of time.
- If an electric field *E* is applied in the *x*-direction, electrons and/or holes experience a net force from the field, which causes drift motion of the electrons and holes. A current density *J* is hence resulted: $J = \sigma E$, where σ is the conductivity of the material.
- The mobility μ is defined as the average particle drift velocity ν per unit electric field, i.e., $\nu = \mu E$.
- The electrons in a crystal are not completely free, but interact with the periodic potential of the lattice. As a result, their "wave-particle" motion cannot be expected to be the same as for electrons in free space. Thus, in applying the usual equations of electrodynamics to charge carriers in a solid, we must use altered values of particle mass (i.e., the effective mass, *m**).

$$E = \frac{1}{2}mv^2 = \frac{1}{2}\frac{p^2}{m} = \frac{\hbar^2}{2m}k^2 \Longrightarrow E = \frac{\hbar^2}{2m}k^2 \Longrightarrow m^* = \frac{\hbar^2}{d^2E/dk^2}$$

Properties of Common Semiconductor Materials

Material	Band Gap	ε _r	μ_{e}	$\mu_{\rm h}$	${ m m_e}^*/{ m m_0}$	Lattice
	(eV)		cm²/'	V-sec		Å
C(i)	5.27	5.7	1800	1200	0.2	3.56
GaP(i)	2.26	11.1	1600	100	0.82	5.45
AlAs(i)	2.16	10.9	180	-	-	5.66
GaAs(d)	1.43	13.2	8500	400	0.067	5.65
InP(d)	1.35	12.4	4600	150	0.077	5.86
Si(i)	1.12	11.9	1500	450	1.1	5.43
GaSb(d)	0.72	15.7	5000	850	0.042	6.09
InAs(d)	0.36	14.6	33,000	460	0.023	6.05
InSb(d)	0.17	17.7	80,000	1250	0.0145	6.47

(d) → Direct bandgap material, (i) → Indirect bandgap material (After Verdeyen)
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Intrinsic Material and Extrinsic Material

- A perfect semiconductor crystal with no impurities or lattice defects is called an *intrinsic semiconductor*. In such material there are no charge carriers at 0 K, since the valence band is filled with electrons and the conduction band is empty. At higher temperatures electron-hole pairs are generated as valence band electrons are excited thermally across the band gap to the conduction band: n (electrons per cm³) = p (holes per cm³) = n_i ($\approx 1.5 \times 10^{10}$ cm⁻³ for Si at 300 K).
- In addition to the intrinsic carriers generated thermally, it is possible to create carriers in semiconductors by purposely introducing *impurities* into the crystal. This process, called *doping*, is the most common technique for varying the conductivity of semiconductors.
- By doping, a crystal can be altered so that it has a predominance of either electrons or holes. Thus there are two types of doped semiconductors, *n-type* (mostly electrons) and *p-type* (mostly holes).
- When a crystal is doped such that the equilibrium carrier concentration n_0 and p_0 are different from the intrinsic carrier concentration n_i , the material is said to be *extrinsic*.
- The product of n_0 and p_0 at equilibrium is a constant for a particular material and temperature, even if the doping is varied: $n_0 p_0 = n_i^2$.

n-Type Semiconductor: Donation of Electrons From Donor Level to Conduction Band

- The impurity level is filled with electrons at 0 K.
- Very little thermal energy is required to excite these electrons to the conduction band. At about 50–100 K, virtually all of the electrons in the impurity level are "donated" to the conduction band.
- Such an impurity level is called a *donor level*, and the column V impurities in Si or Ge are called *donor impurities*.

p-Type Semiconductor: Acceptance of valence Band Electrons by an Acceptor Level and the Resulting Creation of Holes

- **The impurity level is empty of electrons at 0 K.**
- At about 50–100 K, enough thermal energy is available to excite electrons from the valence band into the impurity level, leaving behind holes in the valence band.
- Since this type of impurity level "accepts" electrons from the valence band, it is called an *acceptor level*, and the column III impurities in Si or Ge are called *acceptor impurities*.
Pure, n-Type, and p-Type Silicons



Valence band

÷ 4

Valence band

Figure 10.1 Silicon lattice structure for (a) pure, (b) n-type, and (c) p-type silicon. The energy band diagram is given below each type.

Optical Absorption Without Pumping



Figure 11.6 Optical absorption experiment: (a) indicates a wave propagating through a slab of semiconductor, (b) shows the band diagram of a "normal" semiconductor, and (c) indicates the data.

An Optically Pumped Amplifier At T = 0K and T > 0K



Light Sources for Daily Life



Light-emitting diode, organic light-emiting diode, and semiconductor laser (laser diode) play an important role!

Comparison Among Various Light Sources



Light-Emitting Diode (LED)



Electrons and holes are injected from n and p contacts respectively. **Electrons and** holes recombine to generate photons.

After Prof. Man-Fang Huang (Institute of Photonics, NCUE)

Typical LED Structure

Energy bandgap of window layer must be wide enough to avoid absorption of/ emitted light

p, n - cladding layers are for confinement of carriers (electrons and holes)



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Reflective Mirror and Rough Surface



Fig. 1. Total internal reflection and substrate absorption limit the photon extraction efficiency of conventional LEDs grown on absorbing substrates.



Fig. 2. In substrate-less LEDs a highly reflective metal mirror reflects all the downward-travelling light. The thin active layer minimizes internal absorption.

Effect of Temperature

Intensity Vs. Current

Wavelength Vs. Current



Intensity of LED light outputWaveleymay saturate at high currentmay incdue to temperature effectto tempAfter Prof. Man-Fang Huang

Wavelength of LED light output may increase with current due to temperature effect Huang

Applications of LEDs



Ledtronics include DécorLED lamps with Edison screw bases.



Fig. 3. This white lamp produced 1200 lm, about the same as an incandescent bulb, but with twice the efficiency.

After Prof. Man-Fang Huang (Institute of Photonics, NCUE)

Applications of LEDs

Signal mirrors, Center high-mounted stop lamps (CHMSL) approach lighting, & cargo bed lighting and exterior security lighting Backup lighting and stop lamps Running board & footwell lighting License plate Illuminators Turnsignals

Interior Applications

- Map lamps
- Passenger reading lights
- PRNDL/gear selector lighting
- · Dome lights
- Interior door lights
- Instrument panel lights
- & displays
- Ambience lighting
- Trunk lights

資料來源:東貝光電·2005/6

Applications of White LEDs



Fig. 1. Applications of white LEDs. Left: a Ford concept car uses Luxeon LEDs from Lumileds as part of an adaptive lighting system that can produce <u>different beam patterns</u> to suit different situations such as highway, in-town or curve driving. Right: white LEDs can replace conventional <u>discharge lamps</u> as the flash for mobile phone cameras. The RGB

multichip version can produce a variety of color temperatures.

Distributed Bragg Reflector (DBR)



Reflectivity as a Function of the Number of DBR Pairs





Fig. 10.4 Calculated reflectivity of an AlAs-Al_{0.1}Ga_{0.9}As multilayer semiconductor Bragg reflector as a function of the number of pairs.

Reflectivity Spectrum of a 20-Pair AlAs/GaAs DBR



FIGURE 5.4. Calculated reflectivity spectrum for a plane wave ($\lambda = 0.98 \ \mu$ m) entering from semi-infinite GaAs material onto a 20-pair AlAs/GaAs DBR and exiting into air.

Resonant-Cavity LED (RC-LED)



LED Versus RC-LED



Fig. 1. In a conventional LED (left) the light emission is isotropic. Only a small percentage of the emitted light can be extracted. In an RCLED (right) the active layer and mirrors can be designed such that the light is emitted mostly inside the extraction cone.

Vertical-Cavity Surface-Emitting Laser (VCSEL)

- The major difference between a vertical-cavity surface-emitting laser (VCSEL) and an edge-emitting laser (EEL) lies in the fact that a VCSEL emits light in the direction along the axis of crystal growth.
- The VCSELs have symmetrical laser beams that have small divergent angles. Hence, when compared to the EEL, the light emitted by a VCSEL may be coupled into an optical fiber more effectively.
- VCSELs are of advantage in the application of 2D arrays for communication.
- There is no need for the VCSEL wafers to be cleaved and coated for device performance testing, which saves a lot of time in device characterization.
- Light-emitting diode (LED) have been used in some short-distance optical fiber communication systems. If the LED light source were replaced by a VCSEL, the operating distance and data transmission rate would be greatly enhanced. Since the packaging for both LED and VCSEL are almost identical, the substitution of a LED by a VCSEL in an optical fiber communication system is very cost effective.

Vertical-Cavity Surface-Emitting Laser (VCSEL)



LED, RC-LED, and VCSEL

Property	LED	RC-LED	VCSEL	
Line-width	Broad	Medium	Narrow	
Modulation Speed	Low	Medium	Very High	
Extraction Efficiency	Low	Medium	High	
Brightness	Low or Medium	Medium	High	
Price	Low	Low or Medium	Medium or High	

Sensitivity of Human Eye to Visible Spectrum



Human eyes are sensitive to green light (~555 nm), and hence the
development of green (or yellowish green) LED is desirable.2022/01/21光電子學導論 / 國立彰化師範大學物理學系 / 郭艶光93

Semiconductors Applicable in Visible Region



Optoelectronic Semiconductor Materials

- The elementary and compound semiconductor materials are useful in electric and optical applications. We will discuss the fundamental characteristics of a few semiconductor materials that are important in optical applications.
- Firstly, we will start with the AlGaAs because it possesses unique material properties. The AlAs and the GaAs have almost identical lattice constants, which indicates that the ternary Al_xGa_{1-x}As compounds can be grown on the GaAs substrate with very little strain and hence a very small density of traps (caused by defects) at the interface can be expected.
- In addition to the AlGaAs, there are several semiconductor materials that have important application in the light emitting diodes (LED) and laser diodes (LD). We will focus on the In_xGa_{1-x}As_yP_{1-y}/InP that is important in optical fiber communication, the (Al_xGa_{1-x})_{0.5}In_{0.5}P/GaAs that has important application in 570~670 nm (yellowish green to red) LED and LD, and In_xGa_{1-x}N/Al₂O₃ that has important application in ultraviolet (UV) and visible LED and LD.

Al_xGa_{1-x}As Semiconductor Materials



InGaAsP Semiconductor Materials

- The InGaAsP semiconductor material is capable of emitting light in a spectral range from 1.1 to 1.6 µm when grown on the InP substrate. Note that, this material system is also capable of emitting light of a wavelength smaller than 1 µm when grown on the GaAs substrate.
- Since the SiO₂ optical fiber is least dispersive at 1.31 µm, and is least absorptive at 1.55 µm, the InGaAsP semiconductor material is important in the application of long-haul optical fiber communication.

Bandgap and Lattice Constant for InGaAsP Lasers



indirect-band-gap regions (shown hatched). Dotted lines show the wavelength range (top scale) for a semiconductor laser whose quaternary active layer is lattice-matched to the binary compound. (After Ref. 24)

AlGaInP for Red to Yellowish Green LEDs

- When the indium composition in AlGaInP is 50% (0.5), the lattice of AlGaInP layers has a good match to that of the GaAs substrate.
 - \rightarrow (Al_xGa_{1-x})_{0.5}In_{0.5}P
- AlGaInP is a direct bandgap semiconductor when the emission wavelength is larger than 555 nm and becomes an indirect bandgap semiconductor when the emission wavelength is below 555 nm.
- AlGaInP LED is an efficient emitter for red to yellowish green light.

(Al_xGa_{1-x})_{0.5}In_{0.5}P Semiconductor Materials



FIG. 2. Room temperature (300 K) bandgap energies and corresponding emission wavelengths of the Γ and X bands for the unordered (Al_xGa_{1-x})_{0.5}In_{0.5}P alloy as a function of alloy composition x adopted from low-temperature (2 K) pressure measurements (Prins *et al.*, 1995a). At room-temperature the direct-indirect crossover occurs for an alloy composition of x = 0.53, corresponding to an emission wavelength of 555 nm.

AlGaInP is efficient between 570 nm (yellowish green) and 670 nm (red). 2022/01/21 光電子學導論/國立彰化師範大學物理學系/郭艶光 100

InGaN for Yellowish Green to UV LEDs

- InGaN LED has no lattice-matched substrate and is usually grown on sapphire (Al₂O₃) substrate, which is an insulator.
- SiC semiconductor is a good substrate for InGaN LED but it is relatively expensive.
- InGaN LED is capable of emitting light in the infrared (IR), visible, and ultraviolet (UV) spectra.
- AlGaN plays an important role in ultraviolet LEDs (UV LEDs).

In_xGa_{1-x}N Emission Spectrum

Color	UV	Purple	Blue	Green	Yellow	Red	Infrared
λ	363 nm	405 nm	450 nm	520 nm	590 nm	650 nm	1610 nm
Eg	3.42 eV	3.06 eV	2.76 eV	2.38 eV	2.10 eV	1.91 eV	0.77 eV
х	0	0.09	0.173	0.282	0.372	0.438	1

$E_{g} \approx x \cdot E_{g,InN} + (1-x) \cdot E_{g,GaN} - b \cdot x \cdot (1-x)$ b = Bowing Parameter

E_{g,InN} = 0.77 eV, E_{g,GaN} = 3.42 eV, b = 1.43 eV (Reference: Wu *et al.*, Appl. Phys. Lett. 80, 4741, 2002) III-N is very efficient between 250 nm and 570 nm. 2022/01/21 光電子學導論/國立彰化師範大學物理學系/郭艶光 102

InGaN LED Structure



Polarizer for Liquid Crystal Display (LCD)

Polarizer: An optical device whose input is natural light and whose output is some form of polarized light.



Figure 8.10 Natural light incident on a linear polarizer tilted at an angle θ with respect to the vertical.

Optical Activity

Optical activity: the plane of vibration of a beam of linear light undergoes a continuous rotation as it propagates along the optic axis of a crystal, e.g., quartz (SiO₂), plate.



$$\beta = \frac{\pi d}{\lambda_0} (n_L - n_R)$$

Specific rotatory power:

$$\beta / d = \frac{\pi}{\lambda_0} (n_L - n_R)$$

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Quartz

Dextro

Optic axis

Liquid Crystals (LC)



Figure 8.58 The long cigar-shaped molecules of a nematic liquid crystal align themselves in a random but parallel formation.

Liquid crystal possesses physical properties between those of ordinary liquids and solids. Liquid crystals have long cigarshaped molecules that can move about, and consequently, like ordinary liquids, they lack positional order. Nevertheless, like crystals, their molecules strongly interact to sustain a large-scale orientational order.

Effect of Electric Field on LC Molecules



Figure 8.60 (a) A twisted nematic cell. The LC molecules are aligned horizontally on the left window and vertically on the right window, and they gradually twist (plane upon plane) from one to the other. (b) When a voltage is applied across the cell, the molecules align with the electric field.

液態晶體顯示器 (Liquid Crystal Display, LCD)

Operation Principle of LCD



Figure 8.61 (a) A twisted nematic cell between crossed linear polarizers. Light polarized vertically emerges from the device. (b) When a voltage is applied across the cell it no longer rotates the plane of polarization; light polarized horizontally enters and leaves the LC cell. That light is subsequently absorbed by the second polarizer and no light emerges from the device.
Seven-Bar Electrode Array



A B C D E F G

Figure 8.62 A seven-bar electrode array used to display numerals. For example, to form the number 9, a voltage is applied between all of the following segments and the large back electrode, *D*, *E*, *F*, *G*, *A*, and *B*.

The Issue of Global Warming



Structure of Solar Cell



Photovoltaic Effect (光伏效應)



Efficiency of Solar Cells



Organic Light-Emitting Diode (OLED)

- An organic light-emitting diode (OLED) is a lightemitting diode in which the emissive electroluminescent layer is a film of organic compound that emits light in response to an electric current.
- This organic layer is situated between two electrodes; typically, at least one of these electrodes is transparent.
- OLEDs are used to create digital displays in devices such as television screens, computer monitors, and portable systems such as smartphones and handheld game consoles.
- A major area of research is the development of white OLED devices for use in solid-state lighting applications.

Applications of OLED

: 59 59









Advantages of OLED Devices

- Light weight
 High flexibility (可撓曲性)
- Wide range of viewing angle
- High color saturation
- **Fast response time**
- High contrast
- Self-emissive characteristics
- Transparent screens

OLED Vs. LCD Display



OLED is self-emissive

LCD needs backlight sources

Small-Molecule OLED



Small molecules are thermally evaporated in vacuum





OLED Structure



OLED Operation Mechanism



Electroluminescence in Doped Organic Film



Electroluminescence of Alq₃ and Doped Alq₃



Semiconductor Lasers

- The material is "semiconductor"
 - At very low temperature, their conductivity is low
 - At high temperature, they act like conductors
 (temperature ↑ ⇒ conductivity ↑)
 (For metals: temperature ↑ ⇒ conductivity ↓)
- They are (the most widely used) "lasers"
 - Active medium ⇒ p-n junction (active layer)
 - Pumping scheme ⇒ Current injection (usually)
 - Laser mirrors \Rightarrow Cleaved end surfaces (usually)

Laser Diode & Light-Emitting Diode

- Small Size, Light Weight
- Long Operation Lifetime (>> 1000 hours)
- High Efficiency, Low Power Consumption
- High Power Density, High Brightness
- Very Low Price (A laser pointer costs only a hundred NT!)
- Wide Bandwidth (Ranging from ultraviolet, visible, to infrared spectrum)
- Perfect for Optical Fiber Communication

Edge-Emitting Laser (EEL)



Cleaved Facet

Pumping Level Required for Laser Action



Size of a Laser Diode $\approx 300 \ \mu m \ (L) \times 200 \ \mu m \ (W) \times 100 \ \mu m \ (H)$ Laser Threshold: $R_1R_2e^{2gL} = 1$ $g = (1/2L) \ln(1/R_1R_2)$ If $R_1 = R_2 = [(n-1)/(n+1)]^2 = [(3.5-1)/(3.5+1)]^2 = 0.3$, Then $g = [1/(2 \times 300 \times 10^{-6})] \ln[1/(0.3 \times 0.3)] \approx 4000 \ m^{-1} = 40 \ cm^{-1}$ 2022/01/21 光電子學導論 / 國立彰化師範大學物理學系 / 郭艷光 126

Homojunction Semiconductor Lasers

同質材科 → Pfn have same materials (e.g., GaAs)







Figure 11.10 The homojunction laser: (a) shows a cross section of the junction with the bowed area being due to current spreading; (b) and (c) show the band diagram in equilibrium and with injected current; (d) illustrates the electromagnetic mode experiencing gain and loss.

Notes. 1) Direction of laser light is out of (or, into) paper. (2) Tail of optical (lateral) modes experiences losses.

Double-Heterojunction (DH) Structure



AlGaAs Double-Heterostructure Semiconductor Lasers



Distance across a heterojunction -----

Figure 11.13 The band diagram for a forward-biased heterostructure in (a), the refractive index in (b), and a sketch of the light intensity in the vicinity of the active region in (c).

Quantum-Well Semiconductor Lasers

- A double-heterostructure laser consists of an active layer sandwiched between two higher-gap cladding layers. The active layer thickness is typically in the range of 0.1 to 0.3 μm.
- If the double-heterostructure laser with an active-layer thickness of ~10 nm is fabricated, the carrier (electron or hole) motion normal to the active layer is restricted. As a result, the kinetic energy of the carriers moving in that direction is quantized into discrete energy levels similar to the quantummechanical problem of the one-dimensional potential well.
- Quantum-well lasers have many advantages: (1) laser wavelength can be varied by changing the width of quantum well, (2) lower threshold current, (3) higher quantum efficiency, and (4) narrower linewidth.
- If there is only one quantum well in the active layer, we call it a Single Quantum Well (SQW) structure; if there are a few quantum wells in the active layer, we call it a Multiple Quantum Well (MQW) structure.

Eigenfunction and Eigenenergy in a Quantum-Well Structure



FIGURE 1.1. The eigenfunctions and eigenenergies for the first two conduction-band electron quantum states in an Al_xGa_{1-x}As-GaAs quantum-well heterostructure. By convention the lowest energy quantum state is the n = 1 or n_1 state. Also shown are the first two light-hole and heavy-hole valence-band eigenenergies.

(*i*) · E_n increases when the width of quantum well, L_z, decreases.
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愈拿,能紧急

Some Important Semiconductor Lasers

- Fiber Communication: InGaAsP (λ: 1.31 / 1.55 μm) Dispersion is minimum at 1.31 μm (less signal distortion); Loss is minimum at 1.55 μm (longer distance between repeaters).
- CD Player/CD ROM: AlGaAs (λ: 780 nm) Storage capacity ≈ 0.67 GB.
- **DVD:** AlGaInP (λ : 650 nm)

Storage capacity ≈ 4.7 **GB**.

High-Density DVD: InGaN (λ: 405 nm) Storage capacity > 18 GB.

Optical Fiber Communication

- The transmission of optical signals from source to detector can be greatly enhanced if an *optical fiber* is placed between the light source and the detector.
- One type of optical fiber has an outer layer of very pure fused silica (SiO₂), with a core of germanium doped glass having a higher index of refraction. Such a *step-index fiber* maintains the light beam primarily in the central core with little loss at the surface. The light is transmitted along the length of the fiber by internal reflection at the step in the refractive index.
- In a step-index fiber, different modes propagate with different path lengths, which causes an extra dispersion in addition to the chromatic dispersion that caused by the fact that the refractive index is a function of wavelength. This type of dispersion can be reduced by grading the refractive index of the core such that various modes are continually refocused, reducing the differences in path lengths.

Distortion Caused by Dispersion



Figure 5.74 Rectangular pulses of light smeared out by increasing amounts of dispersion. Note how the closely spaced pulses degrade more quickly.

Step-Index and Graded-Index Fibers







Figure 8-12 Two examples of multimode fibers: (a) step-index, having a core with slightly larger refractive index n; (b) graded-index having in this case a parabolic grading of **n** in the core. The figure illustrates the cross section (left) of the fiber, its index of refraction profile (center), and typical mode patterns (right).

Application of Total Internal Reflection



Figure 4.13 Internal reflection using two different glass media.

Acceptance Angle Measured by Numerical Aperture



Figure 4.14 Core-cladding structure of optical fiber.

Rayleigh Scattering and Infrared Absorption in Silica Fiber

- The attenuation of a laser light in the silica (SiO₂) fiber is not the same for all wavelengths. The absorption spectrum of the silica fiber shows that dips in attenuation curve near 1.31 µm and 1.55 µm provide "windows" in the attenuation.
- The overall decrease in attenuation with increasing wavelength is due to the reduced scattering from small random inhomogeneity which results in fluctuations of the refractive index on a scale comparable to the wavelength. This type of attenuation, called *Rayleigh scattering*, decreases with the fourth power of wavelength.
- Obviously, Rayleigh scattering encourages operation at long wavelengths in fiber optic systems. However, a competing process of *infrared absorption* dominates for wavelengths longer than about 1.7 µm, due to vibrational excitation of the atoms making up the glass. Therefore, a useful minimum in absorption for silica fibers occurs at about 1.55 µm, where epitaxial layers in the InGaAsP system can be grown lattice-mated to the InP substrate.

Rayleigh Scattering of Light



For a transparent solid, the scattering loss in decibels (dB) per kilometer is given by (分見)

2

Semiconductor Lasers for Fiber Communications



Optical fiber (SiO₂) has low-loss windows at 1.3 μm and 1.55 μm.

Loss ≅ 0.2 dB/km at 1.55 µm (Loss ≅ 3 dB after 15 km; i.e., the signal will attenuate to one half of its original amplitude in 15 km).

Note: $dB \equiv 10 \log (P_1/P_2) = 20 \log (E_1/E_2)$

Dispersion is minimum near 1.3 μm. (Distortion of signals is minimized near 1.3 μm.) Best candidate for long-range fiber communication: In_xGa_{1-x}As_yP_{1-y} / InP

Materials for Short-Range Optical Fiber Communication



PMMA (Polymethylmethacrylate) related optical fibers have low-loss windows near 570 nm, 650 nm, 780 nm, and 850 nm.

Plastic fibers and short-wavelength (edge-emitting and verticalcavity surface-emitting) semiconductor lasers are better options for short-range optical fiber communication if cost is a major concern.

Application of AlGaInP & InGaN LED and Laser Diode

- Application of AlGaInP & InGaN LED: Full-color LED display, Outdoor panel display, Traffic lights, LED light bulb (including white light source), Full-color scanner, Automobile lighting, etc.
- Application of AlGaInP & InGaN LD: DVD, High-density DVD, Laser pointer, Local communication, Laser printer, Bar code reader, Medicine, Sold-state laser pumping, Material processing, Entertainment, Instrumentation, etc.

Growth of AlGaInP and InGaN LEDs

- Metal-Organic Chemical Vapor Deposition (MOCVD, also called Metal-Organic Vapor Phase Epitaxy, MOVPE) is commonly used to grow AlGaInP and InGaN LEDs due to the relatively high speed in crystal growth.
- Molecular Beam Epitaxy (MBE) may have excellent crystalline quality in growing AlGaInP and InGaN LEDs but is relatively slow in crystal growth.

Liquid-Phase Epitaxy, LPE

- The liquid-phase epitaxy (LPE) technique was first demonstrated in 1963. Since then, it has been successfully utilized to fabricate various types of III-V compound semiconductor devices.
- In LPE a supersaturated solution of the material to be grown is brought into contact with the substrate for a desired period of time.
- If the substrate is a single crystal and the material to be grown has nearly the same lattice constant as the substrate, some of the material precipitates on the substrate while maintaining the crystal quality. The precipitated material forms a lattice-matched epitaxial layer on the surface of the substrate.
Vertical LPE & Multibin-boat LPE Apparatus



Schematic Illustration of a VPE Reactor





Metal-Organic Chemical Vapor Deposition , **MOCVD**

- Metal-organic chemical vapor deposition (MOCVD), also known as metal-organic vapor-phase epitaxy (MOVPE), is a variant of the VPE technique that uses metal alkyls (烷基) as sources from which the epitaxial layers form.
- For growth of InGaAsP, group III alkyls [(Ga(C₂H₅)₃ and In(C₂H₅)₃] and group V hydrides (氢化物) [AsH₃ and PH₃] are introduced into a quartz reaction chamber that contains a substrate placed on a radio-frequency (RF) heated (~ 500 °C) carbon reactor.
- Gas molecules diffuse to the hot surface of the substrate. At the hot surface the metal alkyls and the hydrides decompose, producing elemental In, Ga, P and As. The elemental species deposit on the substrate, forming an epitaxial layer. Zn(C₂H₅)₃ and H₂S are used as sources for p-type and n-type doping respectively.

Schematic Illustration of a Low-Pressure MOCVD System



Pressure = 0.1 - 0.5 atm.

Molecular Beam Epitaxy, MBE

- The lattice-matched growth of AlGaAs on GaAs substrates by molecular-beam epitaxy (MBE) was first reported in 1971.
- In the MBE technique, epitaxial layers are grown by impinging (撞擊) atomic or molecular beams on a heated substrate kept in an ultrahigh vacuum (note: the vacuum chamber is usually kept at a pressure of about 10⁻¹⁰ torr).
- The constituents of the beam "stick" to the substrate, resulting in a lattice-matched layer. The beam intensities can be separately controlled to take into consideration the difference in sticking coefficients of the various constituents of the epitaxial layers.

A MBE System for Epitaxial Growth of AlGaAs



Fig. 4.12 Schematic illustration of a molecular-beam-epitaxy (MBE) system for epitaxial growth of AlGaAs. (After Ref. 59)

Difficulty of Growing InGaN LEDs and LDs

- There is no lattice-matched substrate for InGaN semiconductor materials. InGaN LEDs and laser diodes are usually grown on latticemismatched sapphire substrate. Hence, a large amount of crystal defects may be expected.
- InGaN grown on sapphire can not be cleaved to form laser mirrors. Reactive-Ion Etching (RIE) is usually used to fabricate the laser mirrors. It is more expensive to fabricate laser mirrors with RIE. Moreover, the quality of the mirrors is poor when compared to that of cleaved ones.

Clusterlab 600 Research MBE System



國 立 彰 化 師 範 大 學 奈 米 科 技 中 心 於 2005年6 月 購 入 乙 台 MBE