CHAPTER 01

Introduction

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Introduction

1. Light and opto-semiconductors

1 - 1 Light

Definition of light

Light, like radio waves, is a type of electromagnetic wave. The term "light" generally indicates visible light, ultraviolet light at wavelengths shorter than visible light, and infrared light at wavelengths longer than visible light.

Wavelength

Grouping electromagnetic waves into spectral bands by wavelength shows a spectrum starting from short wavelengths and including gamma rays, X-rays, ultraviolet (UV) light, visible light, near infrared light, middle infrared light, far infrared light, and radio waves [Figure 1-1].

Gamma rays and X-rays have particle properties and possess high energy. Radio waves are grouped into submillimeter waves, millimeter waves, and centimeter waves, as well as UHF, VHF, high frequency (HF), medium frequency (MF), low frequency (LF), and very low frequency (VLF) waves. The terahertz wave often mentioned in recent years is an electromagnetic wave at a frequency around 1 THz.

Electromagnetic waves have the characteristics of both waves and particles (photons). The energy (E) of one photon at a wavelength (λ) is expressed by equation (1).

$$E = h\nu = hc/\lambda \text{ [J]} \cdots\cdots\cdots (1)$$

h: Planck's constant (6.626×10^{-34} J·s)
ν: frequency of light [Hz]
c: speed of light in vacuum (2.998×10^{8} m/s)
λ: wavelength [m]

If the unit of photon energy (E) is in eV and the unit of wavelength (λ) is in µm, the energy of the photon is also expressed as shown in equation (2).

$$E = \frac{1.24}{\lambda} \text{ [eV]} \cdots\cdots\cdots (2)$$

Expressing the light range sensitive to human eyes as colors yields "wavelengths from violet at a 400 nm wavelength, indigo, blue, green, yellow, orange and red at a wavelength of 700 nm, and are the seven colors of the rainbow." Due to the structure of the eye, people sense visible light most vividly at 555 nm. The peak wavelength of most animals' vision is mostly the same as humans. The peak wavelength of light emitted for example by fireflies, noctilucae, and firefly squids is a yellow-greenish color around 500 nm on the luminescence spectrum.

Light level

The light level can be expressed by the number of photons per one second using equation (3).

$$W = NE = Nh\nu = Nhc/\lambda \cdots\cdots\cdots (3)$$

W: light level [W]
N: number of photons per second

The light level can also be expressed by the number of photons per unit of time and surface area [typical unit format: photons/(mm^2·s)].

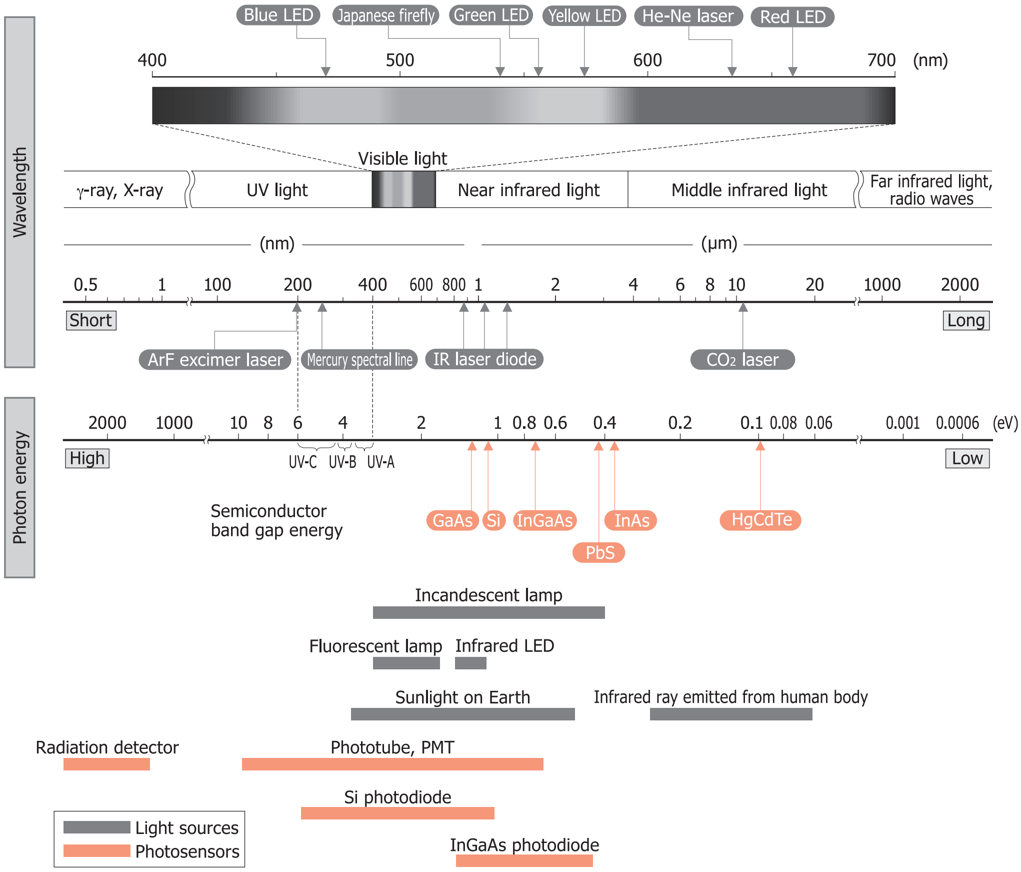
In addition, there are a variety of methods for expressing the light level. These methods can be broadly grouped into the radiant quantity and the photometric quantity. The radiant quantity expresses the light level as a purely physical quantity. The photometric quantity on the other hand expresses the light level capable of being captured by the human eye.

There are different types of radiant quantities and photometric quantities according to the various conditions [Table 1-1].

Figure 1-2 shows photosensor examples that match different light levels. The brightness around us in our daily lives is typically several lux to several thousand lux. Normal room brightness is usually up to several hundred lux, and a brightness of 500 lux is sufficient for studying or cooking. The normal dynamic range of the human eye is about three to four orders of magnitude.

Semiconductor photosensors (Si photodiodes, etc.) and photomultiplier tubes have a wider dynamic range than the normal human eye. PMT and cooled Si APD (avalanche photodiode) are ideal for detecting weak light. Si photodiodes on the other hand are usually used to detect light levels higher

[Figure 1-1] Wavelength range covered by photosensors and light sources



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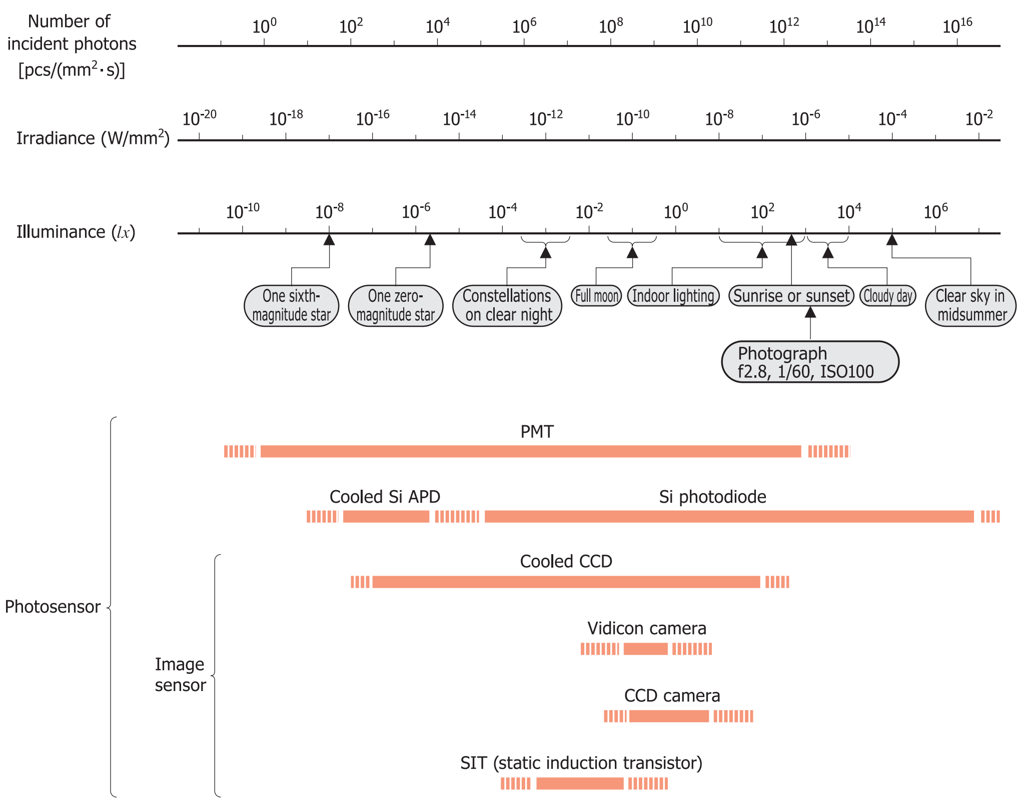
[Figure 1-2] Light level and photosensors



Note: Correlation between the number of incident photons, irradiance and illuminance is shown for light at λ=555 nm.

KOTHC0011EA

than those detected by PMT and cooled Si APD.

Among image sensors, cooled CCDs are better suited for low-light-level imaging. These cooled CCDs are, for example, ideal for capturing images of the moon or star constellations on a clear night. CCD cameras or vidicon (camera tube) cameras are well suited for capturing images at room brightness.

Properties of light

Light behaves like a wave and yet also behaves like particles called photons.

Light reflecting from the data storage surface of a CD or DVD may sometimes appear as rainbow colors. This effect is due to interference caused by diffracted light from irregularities on the disk surface because the light behaves like a wave. Light irradiated onto a substance also generates electrons in a phenomenon called the photoelectric effect. This effect occurs because the light behaves like a particle.

Light treated as a wave is expressed by the frequency (ν) of light as shown in equation (4).

$$\nu = \frac{c}{\lambda}\ [\text{Hz}] \cdots\cdots\cdots (4)$$

c: speed of light in vacuum (2.998×10^8 m/s)
λ: wavelength [m]

For example, the frequency of light at λ=555 nm is 5.4×10^{14} Hz.

On the other hand, the particles of light we call photons possess an energy (hν) equivalent to that frequency (h: Planck's constant 6.626×10^{-34} J·s).

Laser light is coherent light with uniform direction of travel, wavelength, and phase. Laser light is used for diverse tasks such as cutting or welding steel plates, and in "stealth dicing" for cutting semiconductor wafers. In biotechnology it is used as "optical tweezers" to capture a specific cell by irradiating laser light onto a particular cell. Laser light can be used to exert a force on a material as in the case of the optical tweezers. Laser cooling is also currently being researched. In laser cooling, a laser beam is made to strike the gaseous molecules to cool the gas by lowering the speed of the molecules. Other potential uses are in "solar sail rockets" and "photon rockets" as a means to travel through outer space.

Using light to make measurements

Measurements using light are of active and passive methods. In the active method, light is directed onto an object from a light source and the light is detected as reflected light, transmitted light, or scattered light, etc. In the passive method, on the other hand, the light emitted from the object itself is detected.

Light can also be utilized to measure time and distance. Here, the distance to an object can be found by directing pulsed light onto an object and then measuring the time required for that reflected light to return. This is called the time-of-flight (TOF) method.

Other methods include investigating the state of various objects by utilizing the phase or the wavelength spectrum of the light.

[Table 1-1] Expressing the light level

Light level condition	Radiant quantity		Photometric quantity	
	Light level name	Unit	Light level name	Unit
Total radiant energy emitted from a light source in unit time	Radiant flux	W	Luminous flux	*lm* (lumen)
Quantity of energy emitted from a point light source per unit solid angle	Radiant intensity	W/sr	Luminous intensity	cd (candela)
Radiant energy per unit area of a light source having an emitting area	Radiant exitance	W/m²	Luminous emittance	*lm*/m²
Radiant energy per unit area of a light source having an emitting area per unit solid angle	Radiance	W/(m²·sr)	Luminance	cd/m²
Radiant or luminous flux striking a surface per unit area	Irradiance	W/m²	Illuminance	*lx* (lux)

[Table 1-2] Illuminance*1 unit conversion table

lux	photo	foot candle	watt per square centimeter*2
lx (*lm*/m²)	ph (*lm*/cm²)	fc (*lm*/ft²)	W/cm²
1	1.0×10^{-4}	9.290×10^{-2}	5.0×10^{-6}
1.0×10^{4}	1	9.290×10^{2}	5.0×10^{-2}
1.076×10	1.076×10^{-3}	1	5.4×10^{-5}
2.0×10^{5}	2.0×10	1.9×10^{4}	1

*1: Indicates the extent of brightness as measured by a sensor possessing spectral response (conforms to CIE) limited to the sensitivity of the human eye
*2: Total irradiance (measured value) from a CIE standard light source A (color temperature 2856 K)

1-2 Opto-semiconductors

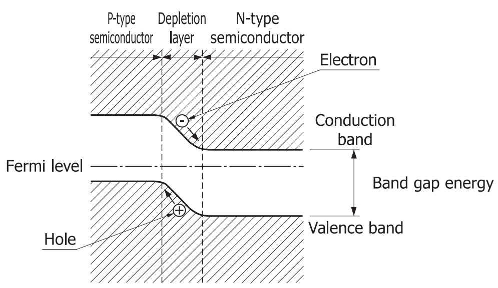
Semiconductors

Some substances such as metal are conductors since they easily conduct electricity; while others such as glass are insulators since they do not easily conduct electricity. Semiconductors have properties that are midway between conductors and insulators. Left alone they do not easily conduct electricity, however, by exposing them to light or heat or by adding dopants, the semiconductor properties change and electricity easily flows.

Si (silicon) and Ge (germanium) are well-known semiconductors. Semiconductors made just from pure Si or Ge are called intrinsic semiconductors. Adding another element as a dopant to the intrinsic semiconductor creates impurity semiconductors. These impurity semiconductors include both N (negative) and P (positive)-type semiconductors. Adding an element having more outermost electrons (valence electrons) than the atoms in the intrinsic semiconductor as the dopant having a freely moving surplus electron forms an N-type semiconductor. However, adding an element having fewer outermost electrons than the atoms in the intrinsic semiconductor as the dopant having a freely moving positive carrier (hole) with a positive charge where one electron is missing forms a P-type semiconductor.

Fabricating a single semiconductor piece where N-type semiconductor and P-type semiconductor materials are in contact with each other creates a difference in electrical potential at the PN junction which is the interface between the N-type and P-type semiconductors. This difference in potential occurs because the energy bands "bend" at the PN junction when the Fermi levels (electrical potential where the probability of electrons is 50%) of the P-type and N-type semiconductors are lined up at the same energy level [Figure 1-3]. A depletion layer (region with no electrons and holes) is formed at the PN junction. Since ionized dopants are present within this depletion layer, an electrical field is created in between. When this region is irradiated by light, electrons and holes are generated. The internal electrical field will then force these electrons and holes to move in their respective reverse directions causing electrical current to flow.

[Figure 1-3] PN junction



Besides semiconductors made from a single element such as Si or Ge, there are also semiconductors made from multiple elements. These are called compound semiconductors. InGaAs (indium gallium arsenide) and GaAs (gallium arsenide) are well-known compound semiconductors.

Compound semiconductors also include N-type and P-type semiconductors. In the GaAs semiconductor, the gallium (Ga) contains three outermost electrons and the arsenic (As) contains five outermost electrons. Adding zinc (Zn) having two outermost electrons as the dopant into the semiconductor material here forms a P-type semiconductor, and adding tellurium (Te) having six outermost electrons forms an N-type semiconductor. Moreover, adding silicon (Si) having four outermost electrons as the dopant forms an N-type semiconductor when substituted for part of the gallium (Ga) or forms a P-type semiconductor when substituted for part of the arsenic (As).

Opto-semiconductors

Some semiconductors are capable of converting light to electricity while others on the other hand can convert electricity to light. Semiconductors possessing such functions are called opto-semiconductors.

HAMAMATSU provides a wide range of opto-semiconductors. Please see the description listed in section 2, "Opto-semiconductor lineup," in this chapter.

Classification of photosensors

Photosensors or photodetectors are classified into types utilizing the photoelectric effects (where a substance absorbs light and emits electrons) and thermal types as shown in Table 1-4.

Photoelectric effects consist of internal photoelectric effects that occur internally within the opto-semiconductor and external photoelectric effects where electrons are emitted externally such as from the photocathode of photomultiplier tubes. Internal photoelectric effects can be divided into photovoltaic effects where the incident light causes a voltage to appear at the PN junction and the photoconductive effect where the incident light changes the internal resistance.

Thermal types include electromotive force types that convert heat into electromotive force, conductive types that convert heat into conductivity, and surface charge types such as pyroelectric detectors that convert heat into a surface charge. Thermal type photosensors offer the advantages that sensitivity is not dependent on the wavelength and also that no cooling is needed. However, there are drawbacks in response speed and detection capability.

[Table 1-3] Classification of semiconductors

Type	Semiconductor examples	Features
Single element semiconductor	Si, Ge	• Large amount of deposit (Si) • Simple crystal structure • Relatively simple process • High purity possible
Compound semiconductor	InGaAs, GaAs, GaAlAs, InP	• High-speed response • Includes light-emitting substances • Band gap controllable

[Table 1-4] Classification of photosensors

Type		Photosensor examples	Features
Internal photoelectric effect	Photovoltaic type	Photodiode Photo IC PSD (position sensitive detector) Image sensor	• High-speed response • Spectral response range: UV to near IR • Small size • Integration is easy.
	Photoconductive type	PbS/PbSe photoconductive detector MCT photoconductive detector Image pickup tube (camera tube)	• Spectral response range: visible or IR • Response is generally slow.
External photoelectric effect		Phototube Photomultiplier tube Image tube	• High sensitivity • High-speed response • Spectral response range: UV to near IR • Large active area possible
Thermal type	Electromotive force type	Thermopile	• Sensitivity is not wavelength-dependent. • Response is slow.
	Conductive type	Bolometer	
	Surface charge type	Pyroelectric detector	

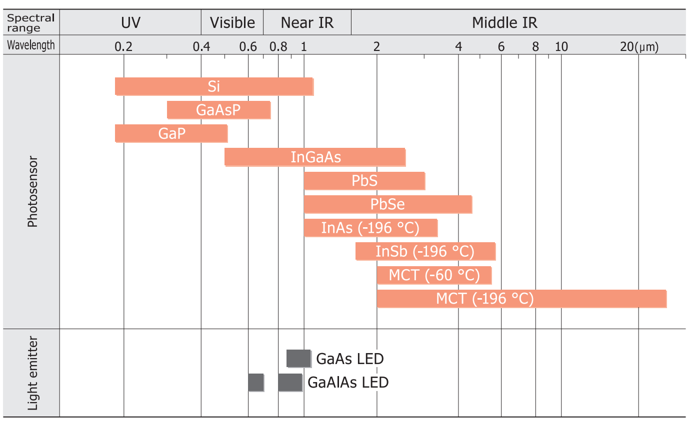
[Table 1-5] Physical constants relating to light and opto-semiconductors

Constant	Symbol	Numerical value	Unit
Electron charge	q	1.602×10^{-19}	C
Speed of light in vacuum	c	2.998×10^{8}	m/s
Planck's constant	h	6.626×10^{-34}	J · s
Boltzmann's constant	k	1.381×10^{-23}	J/K
Thermal energy at room temperature	kT	0.0259 (T=300 K)	eV
Energy of 1 eV	eV	1.602×10^{-19}	J
Wavelength equivalent to 1 eV in vacuum	-	1240	nm
Permittivity of vacuum	ε_0	8.854×10^{-12}	F/m
Relative permittivity of silicon	ε_{si}	Approx. 12	-
Relative permittivity of silicon oxide film	ε_{ox}	Approx. 4	-
Band gap energy of silicon	Eg	Approx. 1.12 (T=25 ℃)	eV

2. Opto-semiconductor lineup

			[Product name]	[Applications]
Photosensor	Point sensor	High energy particle	Si detector	High energy physics, nuclear medicine, industrial measurement
		X-ray	Si photodiode for X-ray	X-ray baggage inspection, non-destructive inspection, medical use
		UV	Si photodiode for UV light	Pollution analysis, spectroscopy, medical use, UV detection, colorimetry
			Schottky type GaAsP photodiode	Pollution analysis, spectroscopy, colorimetry, UV detection
			Schottky type GaP photodiode	UV detection
		Visible	Si photodiode with compensation filter	Exposure measurement, auto-strobes, illuminometry, copiers, color sensors
			Diffusion type GaAsP photodiode	Exposure measurement, auto-strobes, illuminometry, flame eyes (monitors)
			Illuminance sensor	Energy-saving sensors for TV, etc., light dimmers for liquid crystal panels, backlight dimmers for cell phones, optical power measurements
			Color sensor	Display color adjustment, color detection
		Near IR	Si photodiode	Optical communication devices, information equipment, automatic control systems, general electronics, car electronics, photometric equipment, medical equipment, high energy physics
			Si APD (avalanche photodiode)	Optical communication devices, information equipment, automatic control systems, general electronics, car electronics, photometric equipment, medical equipment, high energy physics
			Photo IC	Optical switches, office automation equipment, rotary encoders, optical fiber communications
			InGaAs PIN photodiode	Optical communication, IR laser monitoring, radiation thermometry, industrial measurement
		IR	PbS/PbSe photoconductive detector	Radiation thermometry, flame eyes (monitoring), moisture analysis, gas analysis, spectroscopy
			InSb photoconductive detector, InSb/InAs photovoltaic detector	IR laser detection, spectroscopy, radiation thermometry
			MCT (HgCdTe) photoconductive/ photovoltaic detector	Thermal imaging, radiation thermometry, FTIR, gas analysis, CO_2 laser detection
			Photon drag detector	CO_2 laser detection
	Image sensor	2D	Area image sensor	Fluorescence spectroscopy, Raman spectroscopy, scientific measurement, X-ray imaging
			X-ray image sensor	Dental X-ray imaging, non-destructive inspection
			Flat panel sensor	Radiography, X-ray diffractometers, non-destructive inspection
		1D	Linear image sensor	Multichannel spectroscopy, spectrum analysis, optical measurement
			Photodiode array	Multichannel spectroscopy, color analysis, spectrum analysis, position detection
	Position sensor	Segmented type	Multi-element photodiode	Optical disk pickup, position detection
		Non-segmented type	PSD (position sensitive detector)	Rangefinding, displacement sensing, laser optics, automatic control systems, high energy physics
Light emitter		Visible	Red LED (light emitting diode)	Optical switches, optical fiber communications
		IR	Infrared LED (light emitting diode)	Optical switches, light sources for measurement devices, optical communication, automatic control, rotary encoding
Module product			Mini-spectrometer, photosensor amplifier, APD module, distance sensor, etc.	

[Figure 2-1] Selection guide by wavelength



3. Manufacturing process of opto-semiconductors

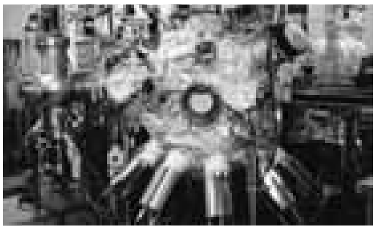
Design

- Design of new products
- Design of custom products

[Example of custom orders]
- Electrical and optical characteristics
- Active area
- Number of elements
- Package
- Reliability

Epitaxial growth process

[Typical compound semiconductor fabrication process]

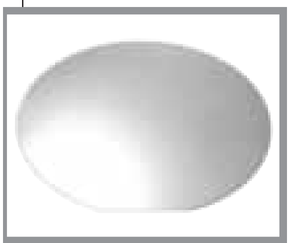


Thin-film crystal growth under ultra-high vacuum in MBE equipment

Thin-film crystal growth with MOCVD equipment

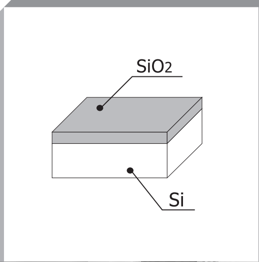
Wafer process

[Typical process of Si photodiode fabrication]



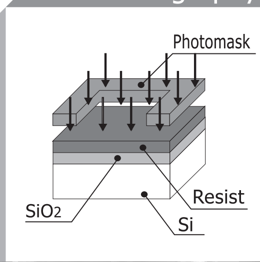
Si wafer (before process)

Oxidation



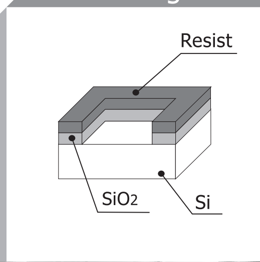
Thin films are formed on wafers by oxidation or CVD process.

Photolithography



Device patterns are formed by photolithographic technique.

Etching



Selective etching is performed on the thin film on wafers.

Evaluation systems

Process

SEM

Checks patterning performance

CD-SEM

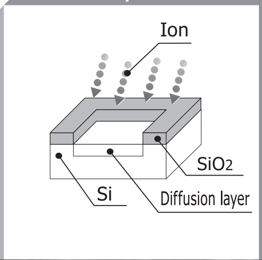
Measures pattern size

TRXF

Measures metal electrode thickness

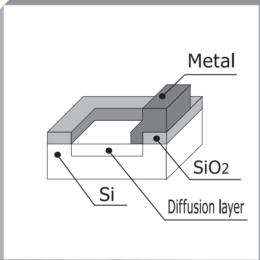
Main factory (Ichino)

Ion implantation



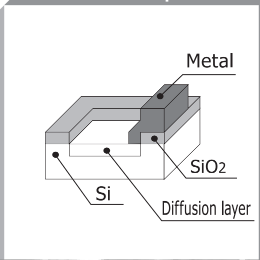
Doping impurities are injected into wafers.

Metallization

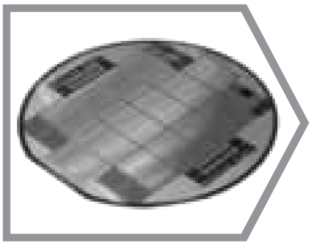


Metal pattern is formed.

Wafer inspection

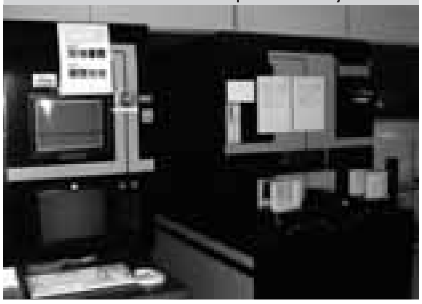


Devices on the wafer are inspected electrically and optically.



To assembly process

Patterned wafer inspection system



Checks pattern accuracy and particles

FIB (focused ion beam)

Observes cross section of devices

IR-OBIRCH analysis system

Locates failure points of chip patterns

Assembly process

[Typical process]

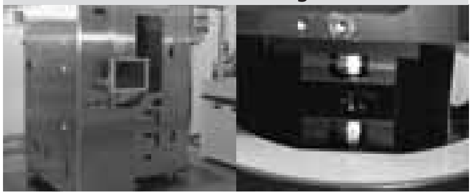
Metal package

Dicing

Blade dicing

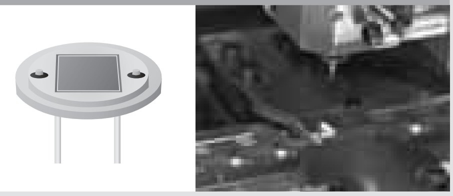
Wafers are cut by a dicing wheel.

Stealth dicing



A laser cuts a wafer by irradiating the interior of the wafer.

Die bond

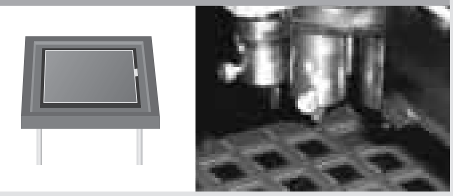


Chips are bonded to metal bases.

Ceramic package

Dicing (see above)

Die bond



Chips are bonded to ceramic bases.

Plastic package

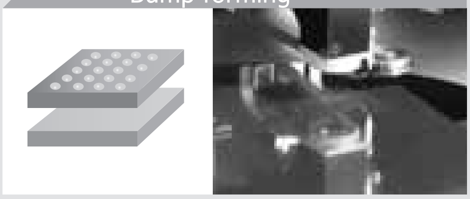
Dicing (see above)

Die bond

Chips are bonded to lead frames.

Chip size package

Bump forming



Gold bumps are formed on wafers.

Dicing

Blade dicing
or
Stealth dicing

Evaluation systems

Assembly

X-ray fluorescence thickness meter

Measures plating thickness of materials

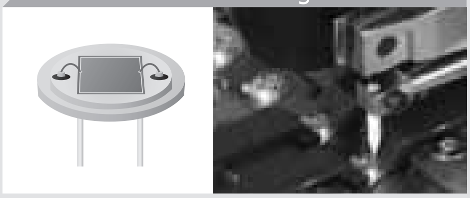
Warpage measurement system

Measures surface warpage of large-area chips

Ultrasonic observation equipment

Observes internal structures by ultrasonic wave

Wire-bonding

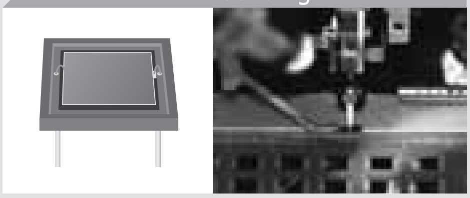


Chips are connected to metal bases using gold wires.

Cap sealing

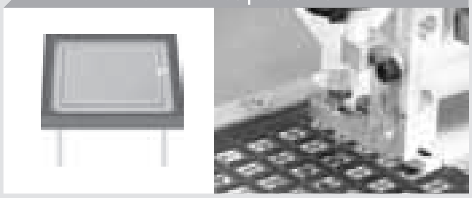
Metal caps are welded to metal bases.

Wire-bonding



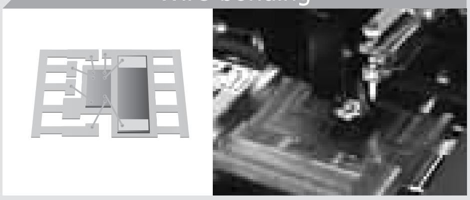
Chips are connected to ceramic bases using gold wires.

Resin encapsulation



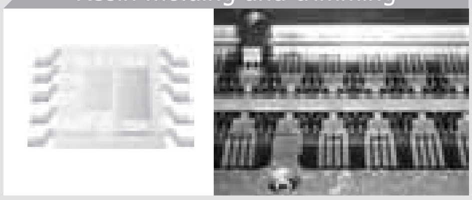
Resin is encapsulated into ceramic bases.

Wire-bonding



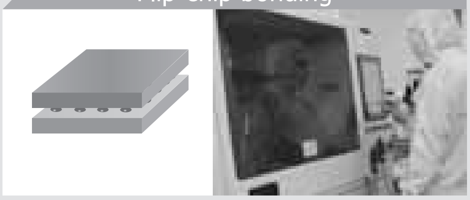
Chips are connected to lead frames using gold wires.

Resin molding and trimming



Resin is molded along lead frames and chips.

Flip-chip bonding



Chips with bumps are bonded to substrates by being flipped (inverted).

Underfill filling

The space between the substrate and chip is filled in with resin.

Test

Metal package test equipment

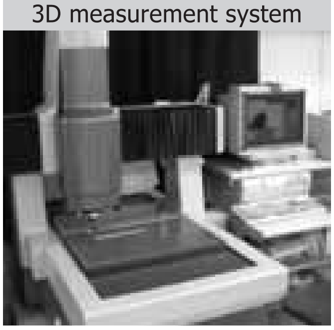
Electrical & optical characteristics and appearance are tested.

Plastic package test equipment

X-ray observation system

Observes internal state using X-rays

3D measurement system



Measures dimensions of materials

X-ray fluorescence analyzer

Analyzes components of material to check RoHS compliance