Measurements, Instruments and Models of Applied Optoelectronics

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By

Yannick Deshayes

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CHAPTER I

LED DEVICES FOR OPTOELECTRONICS

The tremendous growth in optoelectronic technologies for information processing (IP) and public lighting (PL) applications available in the market in the last 20 years is mainly due to fibre optic transmission capabilities and performance of the optoelectronic components. Indeed, since the 1990s, these components have begun to replace copper-based telecommunication networks with speed limits of 100 Mbps on average. The emergence of GaN-based components in the 2000s gradually enabled the replacement of traditional lighting technologies. Currently, the performance of optoelectronic technologies for IP, already reaching more than 60 Gbps thanks to Wavelength Division Multiplexing (WDM) technologies, continues to increase and the technology has supplanted the technologies of electronic interconnections. The high bandwidth available on a single-mode optical fibre and the mastery of manufacturing processes for III-V materials are now competing with technologies developed in electronics, especially silicon semiconductor electronics.

In the case of GaN technologies, current performances have reached the order of 200 Lumen per Watt with an average lifetime of 30000 hours. However, manufacturing techniques for optoelectronic systems are more delicate than those for microelectronic technologies for two main reasons:

- The optical function requires a very precise alignment of the chip and the lens system, as well as materials whose optical properties must remain constant over time.
- Manufacturing cost for optical technologies is relatively high compared to manufacturing cost for electronic systems, especially for embedded systems. Indeed, the basic structure of a light-emitting diode (LED) may comprise more than 10 epitaxial layers far exceeding the complexity of electronic transistors.

A review of the main optoelectronic applications of near-infrared (IR) emission at visible emission is proposed in this first chapter. A state of the art of optoelectronic component and system technologies specifying the physical properties and structures of the components, as well as the architecture of the associated systems, are also proposed.

1. Optoelectronic technologies

1.1. The different materials

a) III-V semiconductors

The III-V materials consist of the elements of columns III and V of the periodic table of elements. Figure I-1 contains an extract from this classification. Thus, many binary compounds can be made.

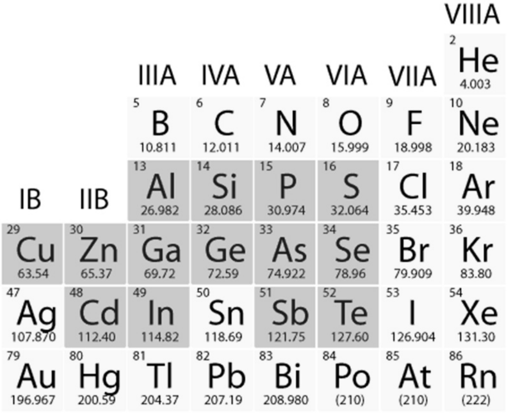


Figure I - 1 - Extract from the periodic table of elements

The study of the band structure of these elements shows that the lightest elements produce compounds whose band gap is wide and indirect, and in which the effective mass of the electrons is high. Table I-1 summarizes this situation by giving the band gap energy E_g, the effective mass m^*/m_0 (where m^* and m_0 are the effective mass and the mass of the electron in vacuo respectively) of the electrons at the bottom of the conduction band, the weak field electron mobility μ, and the lattice constant a.

III-V compound	E_g(eV)	m^*/m_0	μ(cm^{2}V^{-1}s^{-1})	a(Å)
GaN	3.36	0.19	380	a=3.189 ; c=5.185
GaAs	1.42	0.067	8500	5.6533
GaP	2.26	0.82	110	5.4512
InP	1.35	0.077	4600	5.8686

Table I - 1 - Physical properties of III-V compounds

Binary semiconductors such as gallium arsenide (GaAs), gallium nitride (GaN), indium phosphide (InP), gallium phosphide (GaP), and also the ternary and quaternary alloys of these elements have very interesting properties for optoelectronic applications. These materials have direct gaps that favour electronic transitions for the emission of light.

b) The ternary and quaternary compounds

It is possible to associate one or two substitution elements in a main matrix III-V. Ternary ($A_xB_{1-x}C$) or quaternary compounds ($A_yB_xC_{1-x}D_{1-y}$) are then obtained. The interesting thing about this technique lies in the modification of the gap of the material, the change in the optical index, and the potential steps realized by the gap difference. Two main applications can be envisaged:

- The multitude of existing ternary and quaternary materials makes it possible to create a range of components emitting at various wavelengths. We can already point out the two types of components studied in this book: $Al_{0.3}Ga_{0.7}As$ / GaAs (872 nm) and InGaN / GaN (465 nm).
- The superimposition of several layers of different materials makes it possible to create cladding zones for carriers and photons (Figure I-2). Indeed, for carriers, we can create potential wells to isolate them in the well area. For photons, the change of materials results in a difference in optical index and allows the confinement in an area of higher optical index (guide, cavity, etc.).

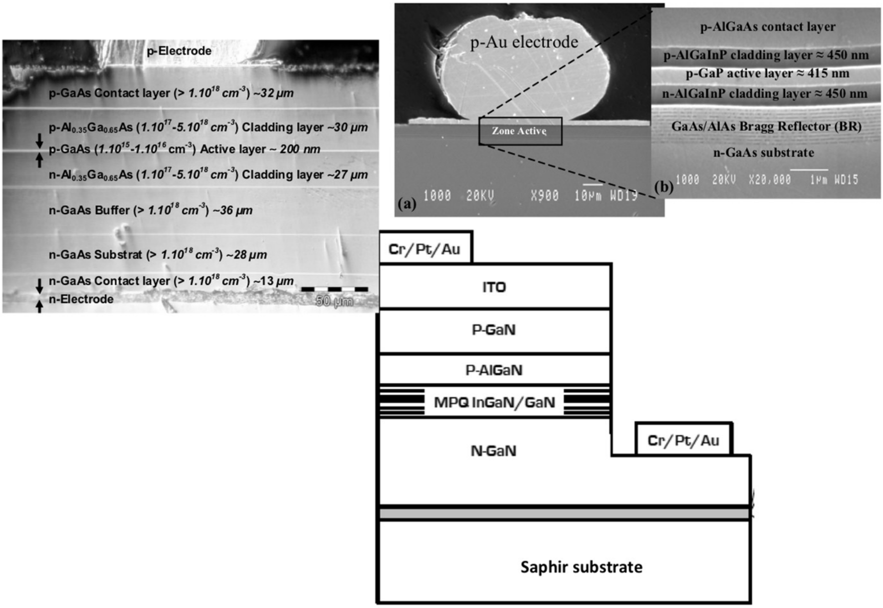


Figure I - 2 - Examples of multi-material structure

c) Wavelength domain and optical properties

Figure I-3 shows, in a non-exhaustive way, the correspondence between materials, their wavelengths, and their applications. We note that two major domains are treated:

- The field of fibre optic telecommunications: this field, to a large extent, is made up of laser diode technologies of wavelengths 980, 1310, and 1550 nm. The materials used are InP for the longer wavelengths and GaAs for the wavelength of 980 nm. This area will not be treated more specifically in this book.
- The consumer domain: this has two main applications – the recording of data based on laser diodes and public lighting. Other applications such as remote controls for electronic devices or auto-focus cameras are part of this domain.

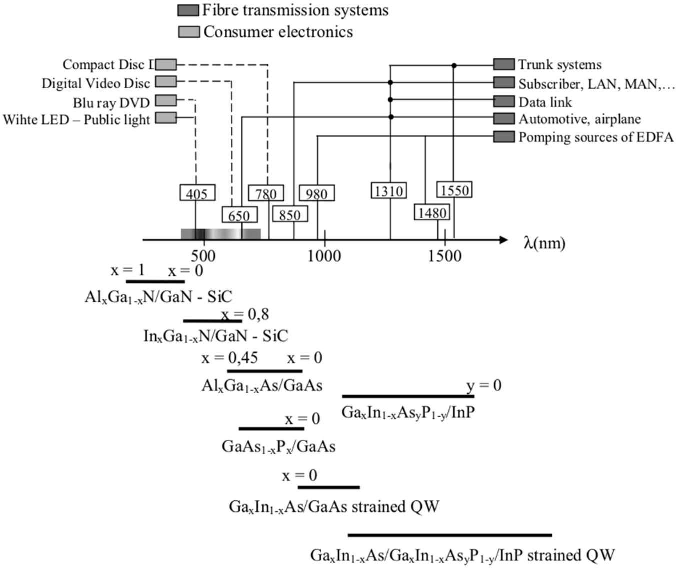


Figure I - 3 - The wavelength domain associated with the applications

Note that all applications cover the wavelength range from visible to near-infrared (less than 2000 nm). We will focus on this area, bearing in mind that the different materials shown in Table I-1 can cover this wavelength range using the ternary and quaternary compounds.

The essential property of III-V materials responsible for light emission is related to the fact that they have direct gaps. Recall the different conditions for obtaining a photon from electronic transitions:

- We define the element of the matrix $W_{n,k,n',k'}$ of band n and wave vector $\vec{k}$ optically excited on a band n' of wave vector $\overrightarrow{k'}$ as:

$$W_{n,k,n',k'} = -\frac{qE}{\Omega_i} I\delta\left(k' - k_{op} - k\right) \qquad (1)$$

E is the electric field, Ω_i is the volume of cluster, k_{op} is the wave vector of light, δ is the Kronecker's function, and I is an integral whose calculation is detailed in chapter 5. The term of Kronecker's function expresses the conservation of moments in the electron-photon interaction:

$k' = k + k_{op}$

However, the wave vector of the electron and the wave vector of the photon are distinct: the wave vector of the Brillouin zone is of the order of $k = 2\pi/a = 10^8 cm^{-1}$ (a is the lattice constant) while the optical wave vector can be evaluated as $k_{op} = 2\pi/\lambda = 10^4 - 10^6 cm^{-1}$. The wave vector of light is therefore negligible compared to that of the different bands where $k' = k$. This last relationship imposes vertical electronic transitions.

- The energy of the photons emitted is close to the gap of the material:

$$\hbar\omega = E_c(k) - E_v(k) = \frac{\hbar^2 k^2}{2m} + E_g \qquad (2)$$

$\hbar\omega$ is the energy of the photon, E_g is the band gap, m is the electron mass, $E_c(k)$ is the energy of the conduction band, and $E_v(k)$ is the energy of the valence band.

It is then found that materials with direct gaps are preferred for light emissions from electronic transitions. In addition, the gap is close to the emission wavelength.

The band structure of III-V materials such as GaAs or GaN has a greater gap bandwidth than silicon and a direct transmission gap. Indeed, these properties find special application in optoelectronic components because:

- the photon absorption coefficient of the material is high,
- the radiative recombination efficiency can reach 100%,
- the lifetime of the minority carriers is relatively high.

The emission of photons is thus made possible by promoting transitions with a constant wave vector. This condition is realized to the extent that the valence band is preferably populated by holes and the conduction band by electrons. The presence of both types of carriers is necessary to obtain photon emission. For low carrier density, spontaneous emission is favoured, and when the density becomes important, stimulated emission becomes predominant.

Figure I-4 is the energy diagram of GaAs and GaN materials. We note that the valence bands have three degenerations corresponding to heavy holes and split-band interactions. It will be seen in Chapter 5 that only the first two bands contribute to the optical properties. Note also that the shape of the GaAs bands is almost parabolic, whereas it is quite different for GaN bands. This difference will be highlighted when modelling the spectrum of the two types of components: GaAs and GaN LEDs.

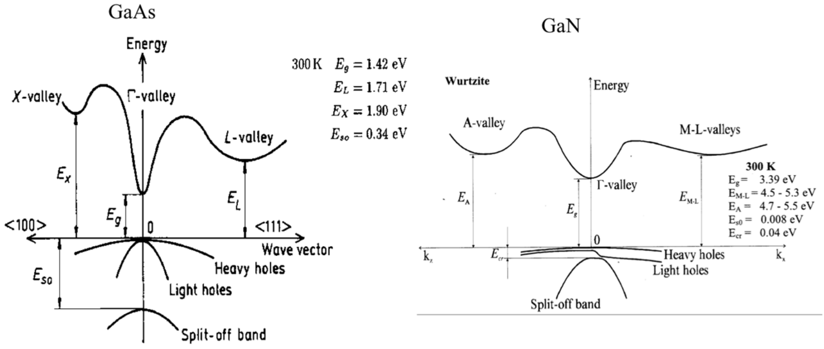


Figure I - 4 - Energy diagram of GaAs and GaN

1.2. The elaboration techniques

The different techniques for developing an optoelectronic component are mainly applied in vacuum to keep the surface to be treated free of defects and pollutants. The main parameter to remember is the pressure of the enclosure in which the component is developed. It is measured in Torr (1Torr = 1mmHg = 1/756 bar = 1/1013 hPa). There are several types of vacuum:

- the primary vacuum that extends over a range from 10 to 10^{-3} Torr,
- the secondary vacuum whose ultimate pressure is 10^{-7} Torr,
- the ultra-high vacuum (UHV) whose pressure start at 10^{-7} Torr and is, on average, of the order of 10^{-11} Torr in the laboratory.

The different vacuums are mainly characterized by their pressures and are used in the development of components for controlling the pollution of the surface of a semiconductor (Table I-2).

Pressure (hPa)	**Strength per unit area**	**Freeway (m)**	**Time to form a single layer**
1013	1 kg/cm^2	0.1 µm	3.4.10^{-9} s
1	1 g/cm^2	0.1 mm	3.4.10^{-6} s
10^{-3}	1 mg/cm^2	10 cm	3.4.10^{-3} s
10^{-6}	1 µg/cm^2	100 m	3.4 s
10^{-9}	10 µg/m^2	100 km	1 hour
10^{-12}	0.01 µg/m^2	10^5 km	40 days
10^{-16}	1 µg/km^2	10^9 km	1000 years

Table I - 2 - Impact of environmental pressure on the surface of a sample

Note that to avoid the oxidation or pollution of a semiconductor, it is preferable to work in a vacuum with relatively low pressure, i.e. a secondary or ultra-high vacuum. Another important parameter for the development of optoelectronic components is the average free path of the particles. This parameter gives an estimate of the distance to maintain between the source of material to be added on the substrate and the target sample. The greater the distance, the more precise and uniform the deposit or engraving. It is necessary to use mask techniques per polymer resin in order to make several components on the same substrate. In this case, the complete substrate is called the wafer.

d) Epitaxy

It is necessary to control the deposition of thin layers from one material to another while preserving the physical properties. The technique used to achieve this is the epitaxial technique. This technique makes it possible to deposit thin layers, with thicknesses ranging from 50 Å to 1000 Å as the case may be, of a different or an identical material on the substrate while preserving the physical properties of the substrate and, in particular, the semiconducting properties (crystal order).

The constant improvement in epitaxial techniques has made it possible to obtain even thinner layers. The techniques of molecular beam epitaxy (MBE or MBE) and organometallic vapor deposition (MOCVD) are at the origin of the growth in the manufacture of dual heterostructure and multi-quantum well components. Indeed, it is possible to deposit on the semiconductor material the desired composition of atomic layer by the atomic layer deposition method.

The main advantage of these techniques is the ability to obtain thin layers with a thickness of a few nanometres useful in the production of quantum wells. With certain substrate orientations (111 for example), it is possible to produce quantum dots. These last elements have dimension restriction along three axes. The advantage of such systems is their ability to reduce the threshold current in the laser diodes to values as low as 10 μA.

The limit of the techniques outlined above is given by the difference of the lattice constants of each layer. Figure I-5 shows the different compounds according to their lattice constants and possible associations with acceptable lattice constant difference to achieve epitaxy under the best conditions.

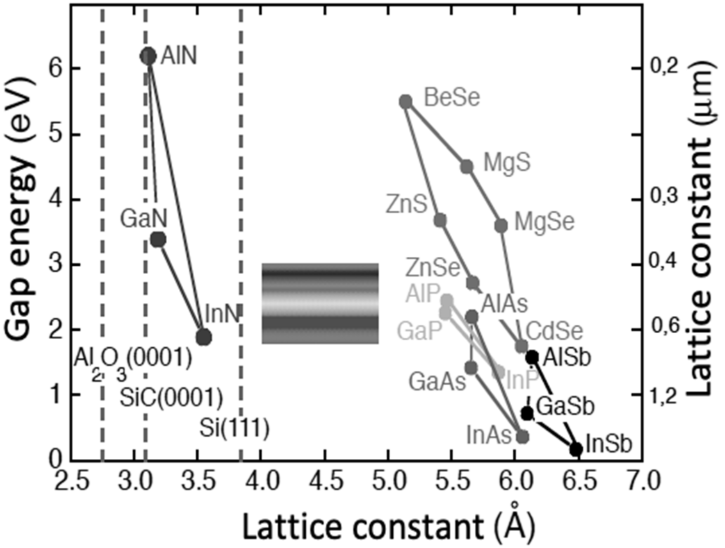


Figure I - 5 - Representation of the band gap value according to the lattice constant

Epitaxial techniques are essential in the manufacturing of optoelectronic components. Methods for obtaining thin films or quantum dots can influence the physical parameters of light-emitting diodes and laser diodes. The main parameter that has been greatly improved is the luminescence efficiency. The improvement in this performance allowed the emergence of emitting optoelectronic systems. Currently, mastering the technique of molecular beam epitaxy (MBE) is at the core of the production of quantum wells and quantum dots that constitute the active zone of most emitting components. An example of a molecular beam epitaxy frame is shown in Figure I-6.

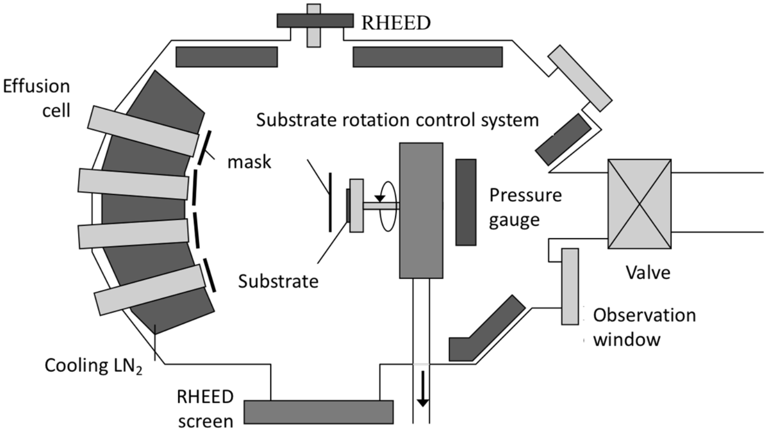


Figure I - 6 - Diagram of a molecular beam epitaxy frame

The effusion cells are elements that contain the different pure materials for the elaboration of the layers. Gallium, arsenic, aluminum, and silicon are contained in the GaAs die. The right dosage of each material is applied by controlling the opening, the temperature, and the flow rate of each effusion cell.

The limit of thin film epitaxy techniques of a few tens of nanometres is fixed by the difference in the lattice constants of each layer (about 1%). For ultra-thin layers or quantum wells, strain levels may be higher (1.5 to 2%). In this case, the interfacial stresses between the layers are relatively important. There is therefore a so-called critical thickness such that below this thickness, mechanical stresses of lattice constants in the structure are induced. Beyond this critical thickness, such that the lattice constant mismatch is greater than 1%, the epitaxial film may tear under the effect of a stress greater than the breaking stress of the layer. As long as the thickness of the quantum well is small, the energy of the stresses remains elastic and therefore lower than the energy of the interatomic bonds within the well. The stresses, induced by the lattice constant mismatch, essentially change the shape of the valence bands of the material, as shown in Figure I-7. These changes in valence bands cause a modification in the electro-optical behaviour of the active area of the component.

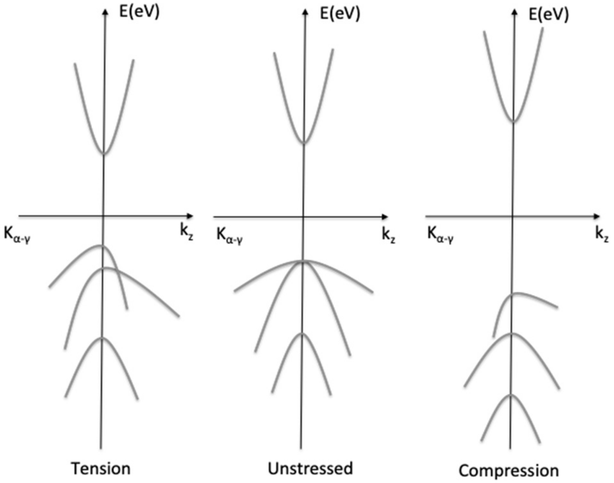


Figure I - 7 - Deformation of the band diagram depending on the type of stress: impact on the strain of the valence band and on the value of the gap

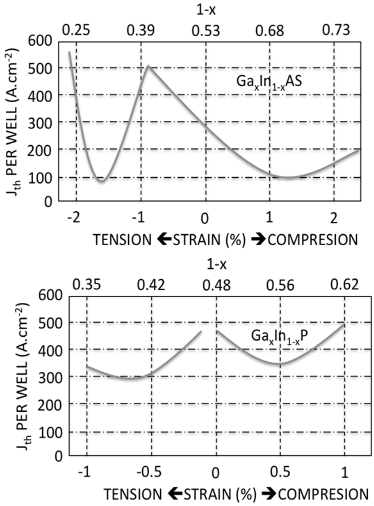


Figure I - 8 - Threshold current density obtained in the quantum well as a function of strain: (a) DL GaInAs/GaAsInP/InP at 1.5 µm and (b) DL GaInP/AlGaInP/GaAs at 633 nm

e) Etching techniques

Etching is a process in optoelectronics that involves the removal of one or more layers of material from the surface of a wafer. Etching is a critical step that is extremely important in the manufacture of microelectronic components; one wafer can undergo many etching steps.

Most of the time, the protective layer of a wafer is a photosensitive resin that has been deposited using photolithographic techniques. Specifically, after depositing the resin by spin coating, the photosensitive resin is exposed through a mask (which represents the pattern to be etched on the substrate: Figure I-9 – step1) to a light radiation (ultraviolet in general, which allows penetration as far as 45 nm; X-ray cannot penetrate that far. Step 2 consists in revealing the resin in order to remove the parts exposed to light (for a negative resin). Positive resins exist in which parts not exposed to light are removed.

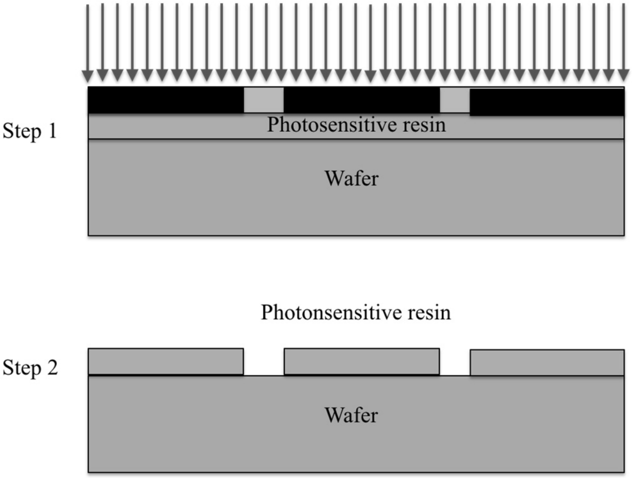


Figure I - 9 - Lithography process

The main technique of chemical etching is the so-called "wet etching". Here, the partially protected substrate is immersed in a solution that will etch the surface of the unprotected wafer. The solution is, in general, an acid: hydrofluoric acid for a silicon substrate (HF is the only acid capable of reacting with the layer of silicon dioxide that naturally forms on the surface of the silicon substrate), hydrochloric acid for a substrate of gallium arsenide (chloride ion reacts strongly with gallium), or a weaker acid, such as citric acid.

This technique has several advantages:

- It is relatively easy to implement and can be easily industrialized.
- The etching rate is particularly high, which makes for fast burning to avoid destroying the protective layer and etching areas that should not be burnt.
- It has good selectivity of materials. In the case of substrates composed of different layers, which is often the case, a chemical etching will tend to react only with certain layers. For example, in the case of a substrate composed of layers of gallium arsenide and aluminium arsenide, the hydrochloric acid will tend to attack mainly the layer of gallium arsenide.

It has a major drawback: this etching technique is highly isotropic, that is to say that the acid will attack the substrate in all directions, giving an almost semi-spherical etching profile (Figure I-10). This isotropy causes problems on a very small scale (<50 nm); if the areas to be engraved are too close to each other, it is common that not only these areas would be etched, but also the interstitial spaces.

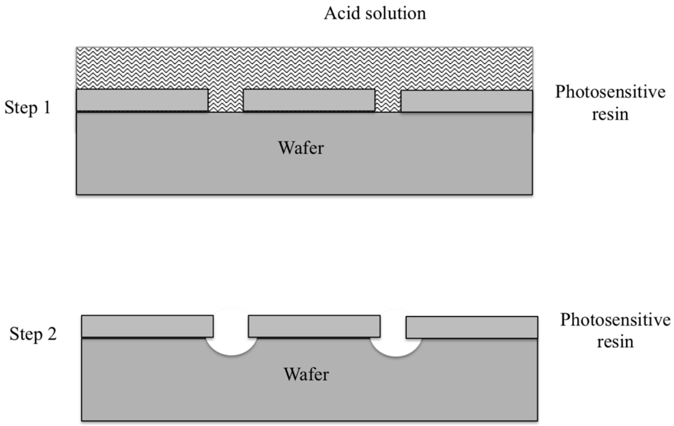
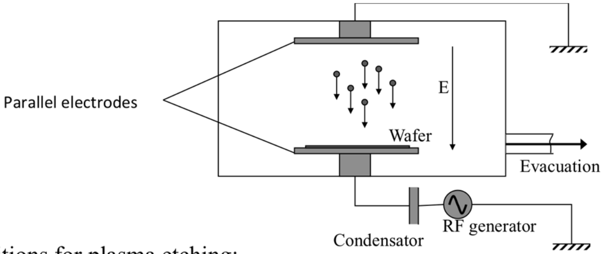


Figure I - 10 - Typical wet etching profile

To improve this result, dry etching techniques were developed. They rely for the most part on the bombardment of the surface to be etched by ions from a plasma. The partially protected substrate is placed in a vacuum chamber (figure I-11). This chamber is provided with two horizontal and parallel electrodes, the lower electrode serving as a plateau for the wafer. Once the vacuum in the chamber is ready, a gas is introduced – oxygen (O_2) or argon (Ar) – then a strong electric field (a hundred or more volts per meter) at radio frequency is applied to the lower electrode, generating in the chamber a plasma, that is to say a gas-ionized part, because some electrons of the gas molecules have been torn off by the electric field. The substrate then undergoes ion bombardment which disintegrates it.



Conditions for plasma etching:

- Substrate temperature: 5 ° C Pressure: 0-5 Torr
- Preparation: Deposit of photoresist (protection of non-etched area)
- Ion: O or Ar

Figure I - 11 - Schematic diagram of plasma etching

This technique has the advantage of a strong anisotropy of the engraving: the border between the engraved and unengraved areas will mostly be rectilinear and vertical (Figure I-12). However, it has many disadvantages, viz.:

- The implementation is much more difficult than for wet chemical etching, and it is difficult to use in industry.
- The etching rate is relatively low, which lengthens the etching process and therefore increases the chances of destroying the protective layer.
- Physical etching has no selectivity.
- Ion bombardment strongly damages the surface, changing its electrical characteristics. It is possible, however, in the case of silicon, to anneal, thus reforming the crystal lattice, but it is impossible to do so for composite semiconductors, which dissociate at high temperatures.

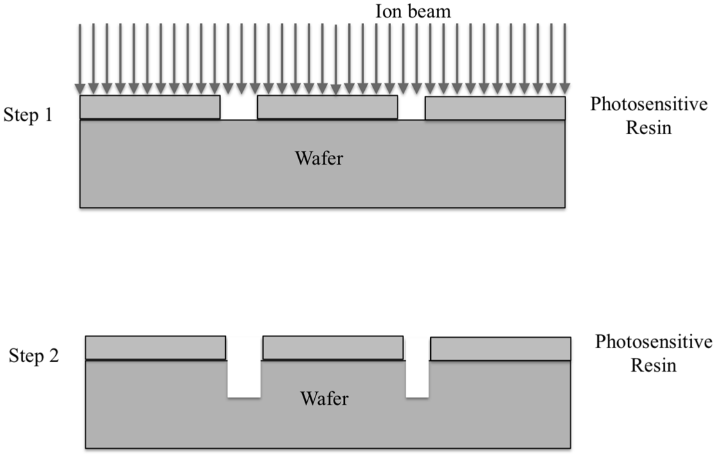


Figure I - 12 - Typical dry etching profile

Reactive ion etching (RIE) is a technique derived from plasma etching. It is also a highly physical engraving technique (like plasma etching) to which is incorporated dry chemical etching. Basically, the implementation is similar to that of plasma etching, at least in its simplest form (parallel plate system). A chamber equipped with two electrodes is evacuated, then injected with a gas that will be ionized, before bombarding the surface of the substrate with the ions. However, to this relatively inert gas (chemically) a highly reactive gas is added, usually a fluorine derivative for silicon substrates (sulfuric hexafluoride (SF_6), carbon tetrafluoride (CF_4), etc.) or a chlorine derivative for gallium arsenide substrates (boron trichloride (BCl_3), dichloride (Cl_2), silicon tetrachloride ($SiCl_4$), etc.).

This reactive gas is ionized and transported to the substrate by a potential difference in the chamber, created in a parallel plate system by another electric field in a triode system, or even by a magnetic field in a plasma torch system. The ions then chemically react with the surface of the substrate, forming a volatile compound.

This technique thus integrates the advantages of physical etching (anisotropy) and chemical etching (higher etching rate than plasma etching which is associated with a form of selectivity), but remains difficult to implement, particularly in industry.

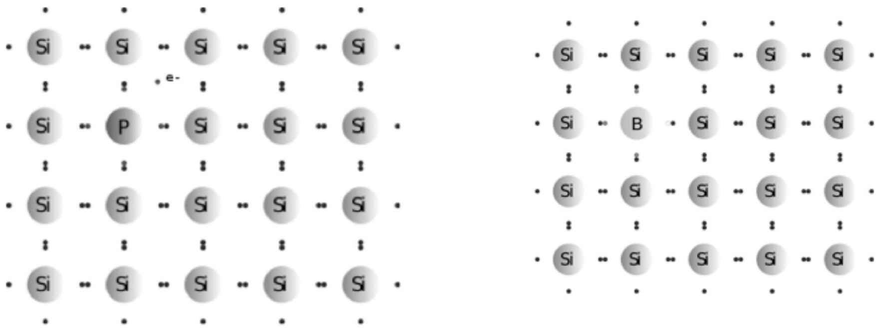
f) Doping techniques

Doping techniques are used to modify the electrical properties of a semiconductor without changing the other physical properties. There are three main types of doping technique:

- doping by diffusion,
- doping by implantation,
- doping by epitaxy.

The doping of a material consists in introducing into its matrix atoms of another material (Figure I-13). If column IV of the periodic table is considered to be that of semiconductors whose valence layer is of type ns^2np^2, an atom of column III will behave as an electron-accepting atom. Indeed, the atoms of column III are characterized by an upper layer of type ns^2np^1, and for an atom of this column to be comparable to an atom of column IV, it must gain an electron – hence the name "atom acceptor." For the V-column atoms, the reverse is the case – this time the atom has to lose an electron to be comparable to an atom in column IV, thus it is a "donor atom."

The atoms of a doping material are also called impurities, and are in a dilute phase: their concentration remains negligible compared to that of the atoms of the original material.



N-type doping (phosphorus in silicon)

P-type doping (Boron in silicon)

Figure I - 13 - Basic principle of doping

To develop emitting optoelectronic technologies, doping during epitaxy is performed by assaying the dopant and the main semiconducting matrix. A device for performing this very precisely is shown in figure I-5. The doping profile is abrupt and has a constant concentration of dopants in each layer (figure I-14).

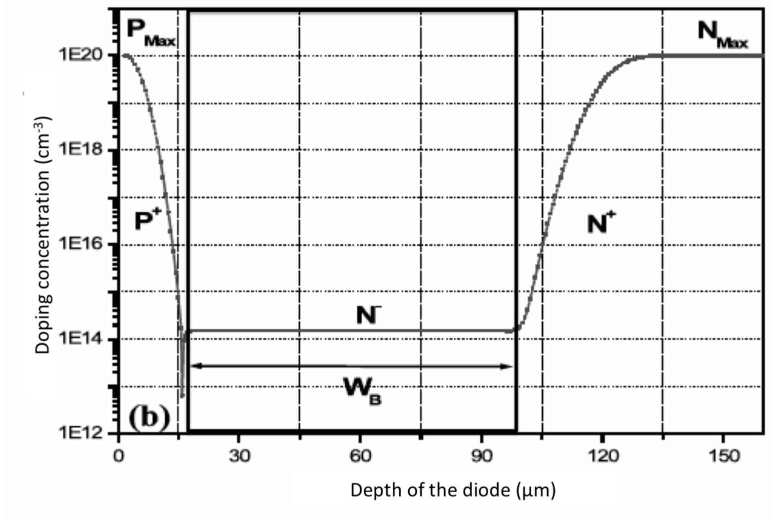


Figure I - 14 - Epitaxial doping profile

Diffusion doping techniques, mainly used for detectors, are carried out in doping furnaces at a temperature of up to 1200 °C (Figure I-15).

Figure I - 15 - Diffusion doping furnace

The dopant can be obtained from:

- a solid source: Here, the sample to be doped is placed in an oven in front of a solid compound containing the dopant. The doping atom is then transported from the sublimating solid compound to the sample by an inert carrier gas. Example: P_2O_5 (N-doping of silicon).
- a liquid source: Here, the carrier gas bubbles into the liquid or nears its surface at a given temperature. The partial pressure of the compound in the gas is equal to the vapor pressure of the liquid. Example: $POCl_3$ (N-doping of silicon).
- a gaseous source: Here, the gas containing the doping species is introduced into the furnace. Examples: PH_3 (silicon N-doping), B_2H_6 (silicon P-doping), AsH_3 (silicon N-doping).

The doping takes place at a temperature between 850 °C and 1150 °C in order to allow the dopant species to diffuse into the material (sample to be doped). An example of a doping profile is given in Figure I-16. The doping profile P^+ is therefore a diffusion profile since the doping varies according to the complementary error law (3).

$$D(x,t) = D_0 erfc\left(\frac{x}{2\sqrt{Dt}}\right) \qquad (3)$$

$$erfc(u)1-\frac{2}{\sqrt{\pi}}\int_{0}^{u} exp(-x^2)dx$$

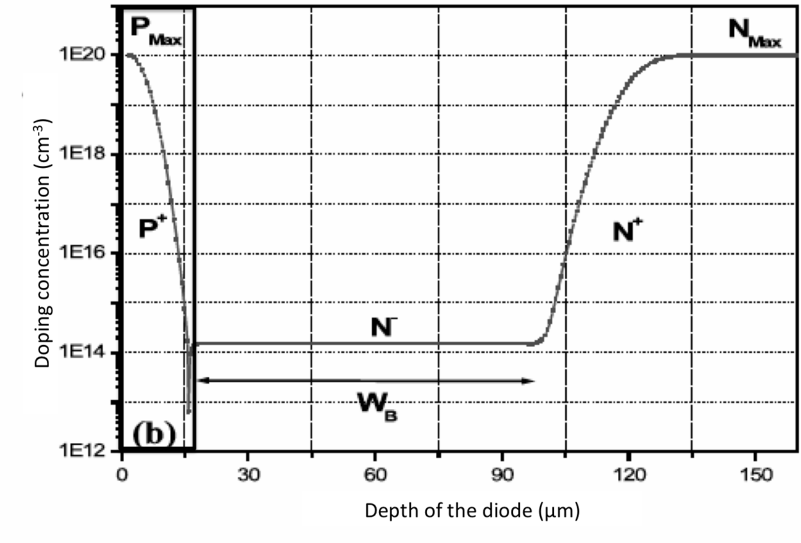


Figure I - 16 - Doping profile by diffusion

Ion implantation doping consists in accelerating ionized impurities by means of an electric field in order to give them the energy necessary to enter the material to be doped. This method makes it possible to use a wide variety of doping elements. The mono-energetic beam and the vacuum chamber make possible great reproducibility and localized doping. The more an ion is accelerated, the greater its kinetic energy, and therefore the deeper it will sink into the crystal lattice of the substrate being doped. Thus, by controlling the dose and the energy, the doping profile is determined. One of the drawbacks of ion implantation doping is the strong crystalline disorder caused by the shocks between the incident ions and the atoms of the material. This causes defects that increase the probability of collision and decrease the mobility of the charge carriers. The evolution of the dopant concentration after ion implantation is of Gaussian type (4).

$$D(x,0) = D_{t=0}^{max} exp\left(-\frac{\left(x - R_p\right)^2}{2\Delta R_p^2}\right) \tag{4}$$

R_p is the average projected course and ΔR_p^2 is the standard deviation. If R_p is large enough so that the impurity profile does not interact significantly with the surface during diffusion, and if the diffusion coefficient can be considered constant, the profile obtained after a time t is always Gaussian and centred in $x = R_p$, given by equation (5).

$$\begin{gathered} D(x,t) = D_t^{max} exp\left(-\frac{\left(x - R_p\right)^2}{2\Delta R_p^2}\right) \\ D_t^{max} = D_{t=0}^{max} \frac{\Delta R_{p(t=0)}}{\Delta R_{p(t)}} ; \Delta R_{p(t)}^2 = \Delta R_{p(t=0)}^2 + 2Dt \end{gathered} \tag{5}$$

An example of implantation doping profile is given in Figure I-17.

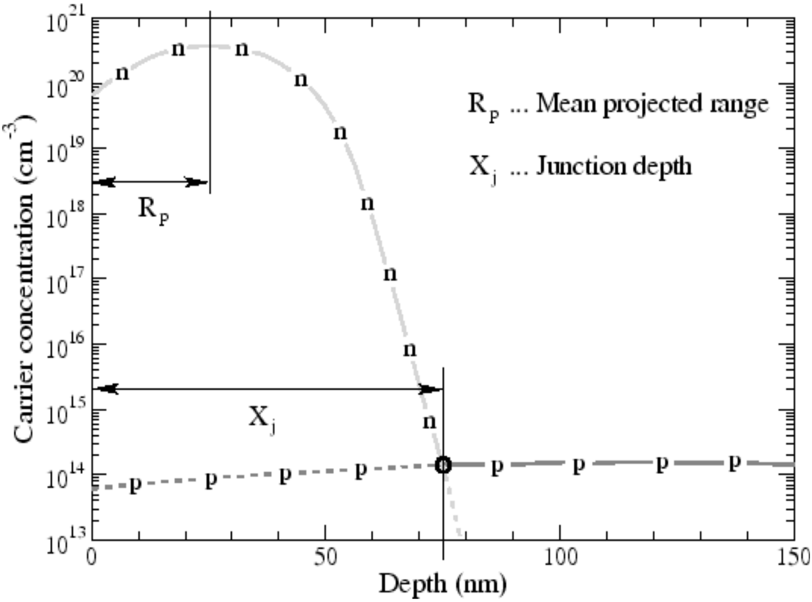


Figure I - 17 - Doping profile by implantation

g) Metallization

The application of a potential difference between the target and the reactor walls in a rarefied atmosphere allows for the creation of a cold plasma composed of electrons, ions, photons, and neutral particles in a ground or excited state. Under the effect of the electric field, the positive species of the plasma are attracted to the cathode (target), where they collide with it. They then communicate their momentum, thus causing atoms to atomize in the form of neutral particles that condense on the substrate. The formation of the film takes place according to several mechanisms that depend on the interaction forces between the substrate and the film.

The discharge is self-sustained by the secondary electrons emitted from the target. Indeed, during inelastic collisions, these transform some of their kinetic energy to the potential energy of the argon atoms that can ionize.

Sputtering sources are usually magnetrons that use intense electric and magnetic fields to trap electrons near the surface of the magnetrons representing the target. Electrons follow helical paths around magnetic field lines, undergoing more ionizing collisions with gaseous neutral elements near the target surface than would otherwise occur. The sputtering gas is inert, typically argon. The supplementation of argon ions created as a result of these collisions leads to a higher deposition rate. It also means that the plasma can be kept at a lower pressure. The atomized atoms are electrically neutral and therefore insensitive to the magnetic trap. Charge accumulation on insulating targets can be avoided by the use of RF sputtering in which the sign of anode-cathode polarization is changed at high frequencies. RF sputtering works well to produce highly insulating oxide films. Permanent magnets of strong magnetic induction are often used to compensate for the magnetic reaction of the main circuit. This makes it possible to keep a very important part of the field lines within the surface of the target.

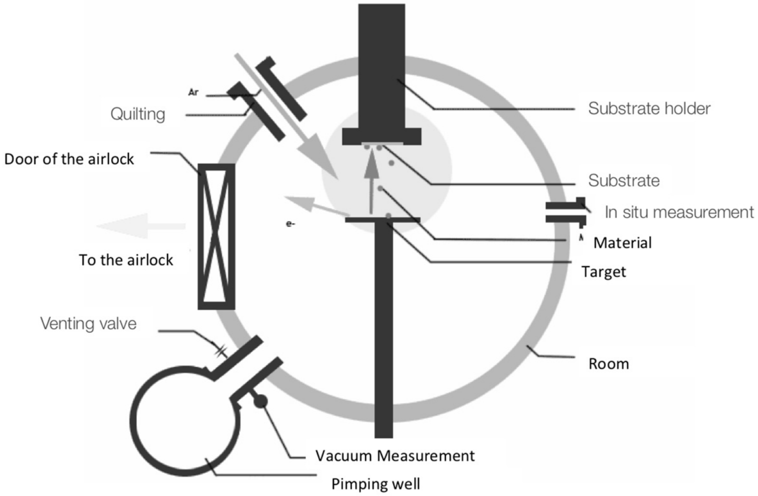


Figure I - 18 - Principle of a sputtering machine

Vacuum evaporation relies on two basic processes: the evaporation of a heated source and the solid-state condensation of the evaporated material on the substrate (Figure I-19). This is somewhat similar to the process through which liquid water appears on the lid of a saucepan of boiling water: the liquid water evaporates and condenses on the lid, which is the equivalent of the deposit target.

The evaporation takes place without vapor deposition in a vacuum, that is to say in a gaseous environment, containing extremely few particles. Under these conditions, the particles of matter can propagate to the target without collision with other particles. The heated objects produce parasitic vapors which limit the quality of the vacuum in the deposition chamber. Under these conditions, the material to be deposited is purified by heating below the evaporation temperature. When the pressure goes down again, the deposited material is free of pollutants.

The evaporated material is not uniformly deposited on an uneven surface, as is generally the case for an integrated circuit. Also, during deposition on a complex micro-structured surface, shading effects may occur when a surface of the support is hidden from the unidirectional radiation of the source.

All evaporation systems are equipped with a chamber in which are placed the source and target of the deposit, a pump for evacuation, and a source of energy for evaporation (Figure I-19). There are different sources of energy, viz.:

- in the thermal method, the material to be deposited is placed in a crucible which is heated by an electric filament; it is also possible that the filament itself is the source;
- in the electron beam method, the source is heated by an electron beam of energy up to 5 keV;
- in the flash evaporation method, the material to be deposited is in the form of a wire which is continuously unwound and evaporated by contact with a very hot ceramic bar.

In some systems, the medium is mounted on a platter that rotates during deposition to improve the regularity of the deposit and to limit shading effect.

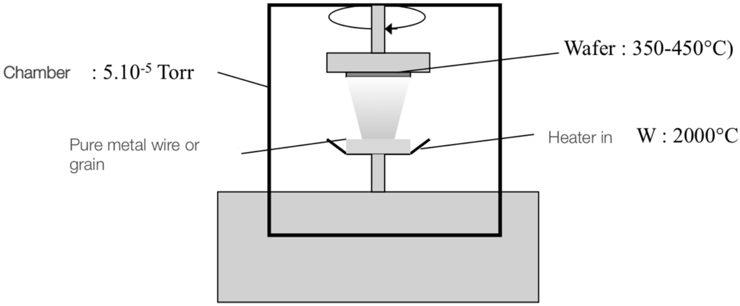


Figure I - 19 - Principle of a vacuum evaporator

1.3. Packaging techniques

In this part, we will discuss the assembly and integration of dedicated LED systems by showing the multiple processes required to manufacture them. Depending on the complexity of the system to be achieved, the degree of integration of the components used, and the assembly technology applied, several levels of integration may be required. Figure I-20 shows the hierarchy and arrangement of these levels for optoelectronic applications.