Semiconductor Photonics

Semiconductor substrates offer the opportunity of integrating electronic devices with photonic components. Si is ideal for electronic circuits but it has limited function for photonics. It is an excellent detector for wavelength less than 1 micron but it doesn't work in the transmission window of glass fiber. It doesn't generate light efficiently except in the form of porous silicon. The emission wavelength doesn't match with fiber either. Compound semiconductors containing group III and group V elements are best candidates. III-V compound semiconductors include binary (2 elements), ternary (3 elements), and quarternery (4 elements) materials. Examples are GaAs, Al$_x$Ga$_{1-x}$As, In$_x$Ga$_{1-x}$As$_y$P$_{1-y}$. By integrating electronic devices with photonic components, it is possible to realize single-chip transceivers with low cost and high reliability. The effort of integrated photonic circuit started twenty years ago using GaAs as the substrate.

There are quite a few combinations to form III-V and II-VI compounds, e.g., GaAs, InGaAs, InGaAsP, GaN, CdSe, HgTe, etc. Some of the binary compounds are available commercially as substrate materials. However, ternary and quarternery materials can only be grown epitaxially. The growth of planar films on a substrate is called epitaxy. To grow high quality films with low defect, the lattice structure and dimension must match. If the dimensions do not match, there is strain. Only very thin layers can be grown. It is called strained-layer films. There are two binary substrates of great importance, namely, GaAs and InP. GaAs is reasonably well matched to AlAs, therefore, AlGaAs can be grown on GaAs perfectly. It forms the basis of many novel electronic devices. On the other hand, InGaAs and InGaAsP can be grown on InP with no lattice mismatch. It is the basis of photonic components used in optical communications systems. The newest development is GaN. It may become the material system for optical memory and display in the near future. GaN can emit at short wavelengths and may be extended to cover most of the visible region. The AlGaAs-GaAs system covers 800-900 nm while InGaAsP-InP works in the 1100-1550 nm.

In AlGaAs, the aluminum concentration determines the energy bandgap. The more Al, the higher is the bandgap. It also determines the index of refraction. The higher the Al concentration, the lower is the index. By forming an AlGaAs-GaAs-AlGaAs structure, the GaAs layer which has a lower energy bandgap and a higher energy becomes the waveguide for photons and the well for electrons. The overlapping photons and electrons can interact effectively in light generation and detection. The index of refraction follows the Selmeier’s relation:

$$n^2 = A(x) + \frac{B}{\lambda^2 - C(x)} - D(x)\lambda^2$$

- $A = 10.906 - 2.92x$
- $B = 0.97501$
- $C = (0.52886 - 0.735x)^2 \quad x < 0.36$
- $(0.30386 - 0.105x)^2 \quad x > 0.36$
- $D = 0.002467 \cdot (1.41x + 1)$
x is the Al concentration. The relation is found empirically.

To grow compound semiconductor films, molecular beam epitaxy (MBE), metalorganic chemical vapor deposition (MOCVD), and liquid phase epitaxy (LPE) are used. MBE involves a high vacuum system. The source material is heated up until an adequate vapor pressure is established. The evaporated molecules travel through the vacuum and get deposited on the substrate. The molecules migrate and relax on the surface until a crystalline site is found. If the substrate is too hot, it may also re-evaporate from the surface. Since high vacuum is used, there are many diagnostic tools available for in-situ control, for example, high energy electron diffraction (HEED). From the diffraction pattern, one can monitor the growth process and the quality of the film. MBE is a slow but extremely well-controlled process. You can grow films with a single-layer accuracy.

MOCVD can be performed at low pressure or at the atmospheric pressure. The source materials include arsine, phosphine, organometallic compounds, such as tri-methyl gallium, di-ethyl indium, etc. They are either extremely toxic or highly flammable. Precaution must be exercised in performing MOCVD. It can be scaled up for industrial production. Using low pressure MOCVD, the film accuracy can be controlled to within two monolayers.

LPE is a low-cost approach to growing compound semiconductors. A graphite boat carries the substrate to different wells containing molten liquids of various compositions. It is only good for film thickness above 1000 Å. Since most advanced photonic components involve quantum wells with a thickness below 20 nm, it is no longer a viable epitaxial system.

By stacking layers of different compositions together, we can form a periodic structure. If the period is too thick, there is no interaction among electrons residing in different layers. However, if the layers are below 20 nm, electrons in different layers may tunnel and interact. Such an artificial, periodic structure is called a superlattice. Quantum wells and superlattices offer new electrical and optical properties not available from traditional solid state materials. For example, excitons exist in solid only at low temperature but in quantum wells, the effect of exciton can be observed even at room temperature.

An exciton consists of an electron-hole pair. It behaves similarly to a hydrogen atom which has one electron and one proton. However, the separation between the positive and negative charges is very different. In hydrogen, the radius is approximately 5 Å. The exciton in solid, however, has a radius of 300 Å. The Coulomb interaction is much weaker. Except at very low temperature, excitons dissociate due to thermal agitation. However, in a quantum well, the thickness of the well limits the separation between the electron and hole. The thinner the well, the stronger is the interaction. Excitons may persist even at room temperature. Quantum well has interesting electronic characteristics and optical properties. Like atomic energy levels in an atom, electronic states of a quantum well are quantized. The number of available states to accommodate electrons is also different from that of a solid. The efficiency of light generation and absorption is increased. Further enhancements can be expected from quantum wires and quantum dots.
However, the uniformity among wires and dots must be strictly controlled. Multiple layers may be needed to increase the interaction region.

Excitons appear in the absorption spectrum as additional peaks near the band edge. There is a series of peaks corresponding to excitons associated with different quantized states of the quantum well. There are also fine structures because of details in the configuration of the valance band. The excitons are used to realize optical bistability, two-dimensional spatial modulator, and picosecond pulse generation from semiconductor lasers. Specially designed quantum-well structures, i.e., bandgap engineering, have also led to many novel devices, e.g., fast electronic switches, low threshold semiconductor lasers, staircase detector designs, short wavelength lasers.

Under an applied field, the excitonic states can be modulated. If the applied field is in the plane of the quantum well, its main effect is to pull electron and hole apart leading to the dissociation of the exciton. The absorption peak becomes broadened and eventually disappears. If the field is along the direction of film growth, it tilts the energy levels. The absorption peak shifts its position. As the wavelength shifts, modulation by absorption or by index can be achieved at a fixed wavelength. Since the field can be affected by resistance in a current loop. A self-electrooptic device has been realized. With no light, the entire voltage is applied through the quantum well structure. When light is turned on, there are carriers generated. The resistance drops and the field also drops. The light absorption changes accordingly. This can lead to hysteresis or bistability. In general, electric field-induced modulation in quantum-confined structures forms the basis of quantum-confined Stark effect (QCSE) devices.

In addition to QCSE, there are other effects which can also provide means for modulation. The Franz-Keldysh effect represents a shift in the effective bandgap under an applied electric field. The applied field tilts the energy diagram. Even when the photon energy is not sufficient to cross the bandgap directly, electron may gain enough energy and tunnel through the remaining gap. The effect is strongest at slightly below the nominal bandgap. The absorption is very weak when no field is applied. It becomes very strong when an electric field is applied. Another effect is the free carrier effect. The density of free carriers can affect the index of refraction just like the density of plasma determines the index of the plasma. An increase in the number of free carriers leads to a lower index of refraction. In addition to a change in index which is the real part of the dielectric constant, there is also a change in the imaginary part of the dielectric constant, i.e., the absorption coefficient. Excess carrier can increase the loss of an optical waveguide.