

# Module 1

# Mesoscopic physics

- We are used to dividing nature into a macroscopic and a microscopic world.
- The macroscopic world contains the things we can see with our eyes.
- The microscopic world contains the building blocks of matter, the atoms and molecules. We know they are there, but we can't see them directly.
- The mesoscopic world is in between the microscopic and the macroscopic world. The boundaries are not sharp, but can be roughly indicated.
- Mesoscopic and macroscopic objects have in common that they both contain a large number of atoms.

# Mesoscopic physics(cts.)

- A first difference is that the macroscopic object can be well described by the average properties of the material from which it is made.
- The mesoscopic object, in contrast, is so small that fluctuations around the average become important.
- A second difference is that the macroscopic object obeys (to a good approximation) the laws of classical mechanics, whereas the mesoscopic object is so small that these laws no longer hold.
- Mesoscopic and microscopic systems both belong to the wonderful world of quantum mechanics.
- Mesoscopic physics addresses fundamental physical problems which occur when a macroscopic object is miniaturized.
- There is no rigid definition for *mesoscopic physics* but the systems studied are normally in the range of 100 nm (the size of a typical virus) to 1000 nm (the size of a typical bacterium):

# Protons, Neutrons, and Electrons

- Atoms are made of extremely tiny particles called protons, neutrons, and electrons.
- Protons and neutrons are in the center of the atom, making up the nucleus.
- Electrons surround the nucleus.
- Protons have a positive charge.
- Electrons have a negative charge.
- The charge on the proton and electron are exactly the same size but opposite.
- Neutrons have no charge.
- Since opposite charges attract, protons and electrons attract each other.

# proton vs photon

- Proton is a positively charged particle having a finite non zero mass ,which forms the positive part of the atom.
- Photon is assumed to be a mass less particle through which energy transfers when light propagates. Photons are discrete packets having finite energy.

# Quantum mechanics

- Quantum mechanics is the branch of physics relating to the very small.
- At the scale of atoms and electrons, many of the equations of classical mechanics, which describe how things move at everyday sizes and speeds, cannot be useful.
- In classical mechanics, objects exist in a specific place at a specific time.
- However, in quantum mechanics, objects instead exist in a base of probability; they have a certain chance of being at point A, another chance of being at point B and so on.

# History of quantum mechanics

- Isaac Newton thought that light was made of very small things that we would now call particles .
- Christiaan Huygens thought that light was made of waves.
- Scientists thought that a thing cannot be a particle and a wave at the same time.
- Scientists did experiments to find out whether light was made of particles or waves.
- They found out that both ideas were right — light was somehow both waves and particles.
- Everything behaves both like a wave and like a particle. However, this effect is much smaller in large objects

- In 1924, de Broglie used the equations of Einstein's theory of special relativity to show that particles can exhibit wave-like characteristics, and that waves can exhibit particle-like characteristics.
- Then in 1925, two scientists, working independently and using separate lines of mathematical thinking, applied de Broglie's reasoning to explain how electrons moved in atoms.
- In Germany, physicist Werner Heisenberg accomplished this by developing "matrix mechanics." Austrian physicist Erwin Schrödinger developed a similar theory called "wave mechanics."
- Schrödinger showed in 1926 that these two approaches were equivalent
- The Heisenberg-Schrödinger model of the atom, in which each electron acts as a wave (sometimes referred to as a "cloud") around the nucleus of an atom replaced the Rutherford-Bohr model.



# Heisenberg uncertainty principle

- Werner Heisenberg described the Uncertainty principle, which says that the more we know about where a particle is, the less we can know about how fast it is going and in which direction.
- In other words, the more we know about the speed and direction of something small, the less we can know about its position.
- we can never know both the location and the momentum of a particle.
- The idea shows that because these pieces are so small, whatever device you use to measure the particles will affect them.
- If you use light to examine a piece of light, won't you knock it around? Well now you just lost the idea of position.
- What if you freeze it in place? That's all very well, but now you don't know where it was going, or how much momentum it had.
- When you increase the precision of one measurement, the other measurement will suffer.
- You can not observe something naturally without affecting it in some way.

# Waves and photons

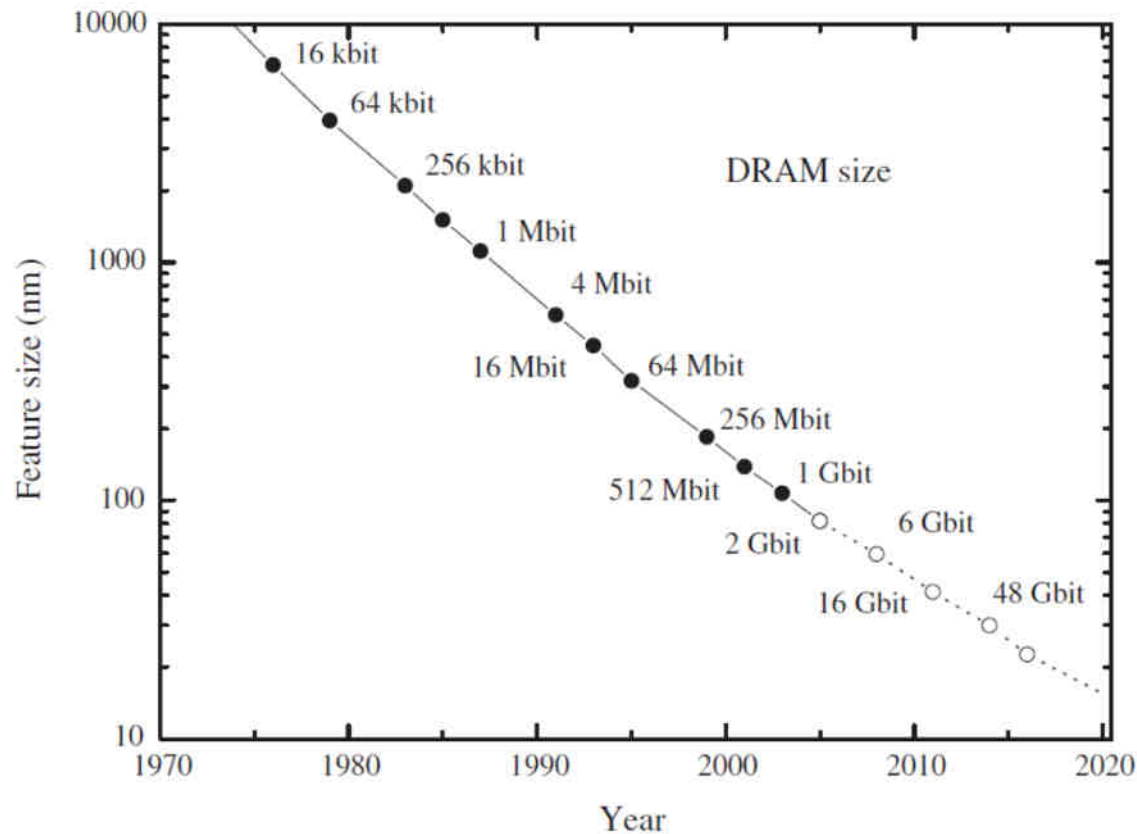
- Photons are much smaller than atoms and protons and electrons.
- The more photons a lamp shoots off, the brighter the light.
- Light is a form of energy that behaves like the waves in water or radio waves.
- Each photon carries a certain amount, or 'quantum', of energy depending on its wavelength.
- Wavelengths are not always so small. Radio waves have longer wavelengths.
- Each photon has a certain amount of energy related to its wavelength. The shorter the wavelength of a photon, the greater its energy.
- Wavelength and frequency are inversely proportional.

- Quantum mechanics started when it was discovered that a certain frequency means a certain amount of energy.
- Energy is proportional to frequency ( $E \propto f$ ).
- The higher the frequency, the more energy a photon has, and the more damage it can do.
- Max Planck discovered the relationship between frequency and energy.
- Nobody before had ever guessed that frequency would be directly proportional to energy.
- the formula that Planck worked out is  $E=h*f$ .
- his **h** is a number called Planck's constant

# TRENDS IN NANO-ELECTRONICS AND OPTOELECTRONICS

## Size

- The evolution of microelectronic devices is influenced by factors such as growing demands in memory capacity of integrated circuits, high transmission data speed, optical communications etc.
- This requires electronic devices with faster speed operation and smaller size.
- Now the transistors are fabricating around 10 nm technology



Evolution of the minimum feature size of a Si DRAM. ...

Figure shows the reduction of feature size of MOS transistors

- It seems reasonable that the rate of scaling down predicted by Moore's law will have to slow down.
- It is expected that the limits of further miniaturization, from an industrial and economic point of view, will be reached in about one decade.
- Reason- Technological limits

The amount of heat generated cannot be eliminated because of thermal conductivity limits of the materials and the increasing number of layers.

The other factor is related to the “parameter spread” in fabrication. As the size of the region to be doped is decreased to about  $0.1\mu\text{m}^3$ , the number of doping atoms becomes so low that the parameter spread cannot be controlled appropriately.

- Reason- Physical limits
  - The energy necessary to write a bit should be several times  $kT$
  - *Relativistic limit*: Signals cannot propagate faster than the speed of light.
  - *Uncertainty principle*: According to the Heisenberg's uncertainty principle, the energy and time needed to write or read a bit should be related by  $E \cdot t \geq h$ . To be safe, we ask the product  $E \cdot t$  to be  $100h$ .

Since for future circuits  $E$  could be as low as  $10^{-19}$  J, we can appreciate that we can approach the quantum limit as the frequency increases.

## Deposition Methods

- The evolution towards nanoelectronics has been possible because of advances in the deposition of very thin films to form heterostructures.
- Standard evaporation and sputtering techniques did not produce heterostructures of enough quality.
- Molecular beam epitaxy (MBE) and metal organic chemical vapour deposition (MOCVD) methods are commonly using for nanolayer deposition.
- In MBE, a film of the desired material is epitaxially grown over a substrate under ultrahigh vacuum conditions.
- Source material is heated to produce an evaporated beam of particles. These particles travel through a very high vacuum (practically free space) to the substrate, where they condense.
- This technique allows a layer-by-layer growth of films.
- Although the deposited films are of very high quality, the technique is somewhat slow and expensive.



- MOCVD is the preferred industrial technique to produce semiconductor heterostructures.
- It is a chemical vapour deposition method used to produce thin films.
- In contrast to molecular-beam epitaxy (MBE), the growth of crystals is by chemical reaction and not physical deposition.
- This takes place not in vacuum, but at moderate pressures .
- For example, GaAs can be grown over a substrate at about 500 °C by the reaction of arsine ( $\text{AsH}_3$ ) gas and trimethyl gallium  $(\text{CH}_3)_3\text{Ga}$  at sub-atmospheric pressures.
- This technique allows for simultaneous deposition on several wafers and is used for the commercial production of semiconductor lasers.

## New technologies

- superconductivity electronics, spintronics, *Molecular electronics* , *bioelectronics* and *optoelectronics* are emerging as future scopes.
- *Superconducting electronics*, which consists of two superconducting layers separated by a very thin oxide insulating film[Josephson junction] that can be tunnelled by superconducting pairs of electrons.
- The advantages of superconducting electronics are based on the fact that Josephson junctions can operate at high switching speeds (switching times between 1 and 10 ps) and the amount of dissipated power is very low.
- *Another technology, spintronics*, which exploits the spin orientation of electrons

- *Molecular electronics* is based on the different states or configurations that molecules can take, like “*trans*” or “*cis*”, as well as parallel or antiparallel alignment of the spin of unpaired electrons.
- The change between states must be fast, consume little energy and should be addressed by some external signal.
- If this technology is able to be put to work, we will have the ultimate step in miniaturization, since molecules are much smaller than present feature sizes in integrated circuits.

- Biology-inspired electronics, also called *bioelectronics* is another emerging area in nanoelectronics.
- It imitates the capabilities of biological neurons in parallel processing as well as their 3D architectures and the topology of the interconnects.
- a neuron is very large for nanotechnology standards.

- Opto-electronics devices have a great upsurge since the development of optical fibre communications.
- At present a tendency to replace, whenever possible, electronic devices by photonic ones.
- Now, laser diodes are manufactured in chips constituting the so-called *optoelectronic integrated circuits (OEIC)*.

# characteristic lengths in mesoscopic systems

- *Mesoscopic physics* deals with structures which have a size between the macroscopic world and the microscopic or atomic one.
- Above structures are also called *mesoscopic systems*, or *nanostructures* in a more colloquial way since their size usually ranges from a few nanometres to about 100 nm.
- The electrons in such mesoscopic systems show their wavelike properties and therefore their behavior is dependent on the geometry of the samples.
- In this case, the states of the electrons are wavelike and somewhat similar to electromagnetic radiation in waveguides.

- For the description of the behavior of electrons in solids it is very convenient to define a series of characteristic lengths.
- If the dimensions of the solid in which the electron is embedded is of the order of, or smaller than these *characteristic lengths*, the material might show new properties, which in general are more interesting than the corresponding ones in macroscopic materials.
- In fact, the physics needed to explain these new properties is based on quantum mechanics.
- To exhibit quantum mechanical effects, semiconductor nanostructures should construct with one or two of their dimensions of the order of, or smaller than *characteristics length*.
- In general, a mesoscopic system approaches its macroscopic limit if its size is several times its characteristic length.
- Some of the most commonly used characteristics lengths in mesoscopic systems is given

## *de Broglie wavelength*

- It is well known from quantum mechanics that for an electron of momentum  $p$ , there corresponds a wave of wavelength given by the *de Broglie wavelength*:

$$\lambda_B = \frac{h}{p} = \frac{h}{m^* v}$$

- $M^*$  is the electron effective mass, instead of the mass  $m_0$  of the electron in vacuum.
- Smaller the value of  $m^*$ , the easier will be to observe the quantum effects in nanostructures of a given size.



## *Mean free path*

- As the electron moves inside a solid, it is usually scattered by interactions with crystal imperfections like impurities, defects etc.
- These scattering events or “collisions” are inelastic, i.e. the values of energy and momentum of the system after the interaction, differ from the corresponding ones before they interact.
- The distance covered by the electron between two inelastic collisions is usually called the *mean free path*  $\ell_e$  of the electron in the solid.
- If  $v$  is the speed of the electron, then

$$\ell_e = v\tau_e$$

where  $\tau_e$  is known as the *relaxation time*.

## *Diffusion length*

- In a mesoscopic system of typical size  $L$ , the electrons can move either in the ballistic regime or in the diffusive regime.
- If the previously defined mean free path  $l_e$  is much larger than  $L$ , the particle moves throughout the structure without scattering; this is the so-called *ballistic transport* regime
- On the other hand, if  $l_e \ll L$ , transport can be explained as a *diffusion process*.
- In this case, the system is characterized by a diffusion coefficient  $D$ .
- 
- In terms of  $D$ , the *diffusion length*  $L_e$  is defined by

$$L_e = (D\tau_e)^{1/2}$$

## Screening Length

- In extrinsic semiconductors, the dopants or impurities are usually ionized and constitute a main factor contributing to scattering.
- The effect of the impurity over the distance is partially reduced.
- It is found that the variation of the potential is modulated by the term  $\exp(-r/\lambda_s)$  where  $\lambda_s$  is called the *screening length* and is given by

$$\lambda_s = \left( \frac{\epsilon k T}{e^2 n} \right)^{1/2}$$

- where  $e$  is the electronic charge,  $\epsilon$  the dielectric constant of the semiconductor, and  $n$  the mean background carrier concentration.
- In a typical semiconductor,  $\lambda_s$  is in the range 10–100 nm, and is an indication of the attenuation of charge disturbances in a semiconductor.

## Localization Length

- The localization length can be understood in terms of transport in disordered materials
- In order to describe the hopping transport and other mesoscopic properties of the electron inside the material, it is assumed that the electron wave function is described by

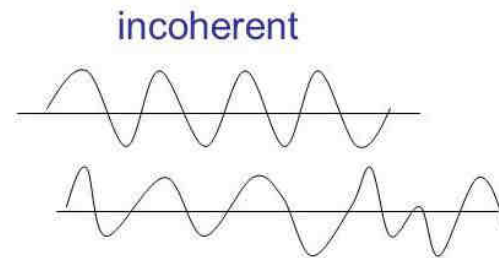
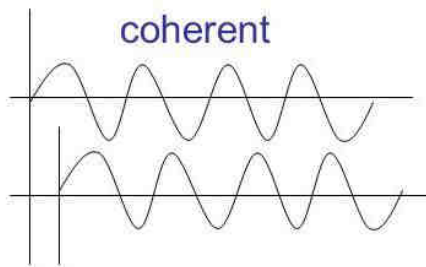
$$\psi = \exp(-r/\lambda_{\text{loc}})$$

- where  $\lambda_{\text{loc}}$  is known as the *localization length*

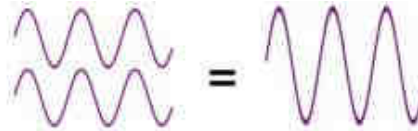
# Coherence

For two waves to show interference they must have coherence.

Two waves are coherent if one wave has a constant phase relation to the other

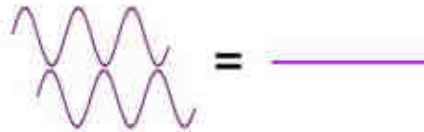


Waves that combine **in phase** add up to relatively high irradiance.



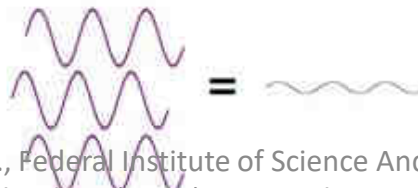
Constructive interference (**coherent**)

Waves that combine **180° out of phase** cancel out and yield zero irradiance.



Destructive interference (**coherent**)

Waves that combine with **lots of different phases** nearly cancel out and yield very low irradiance



Incoherent addition

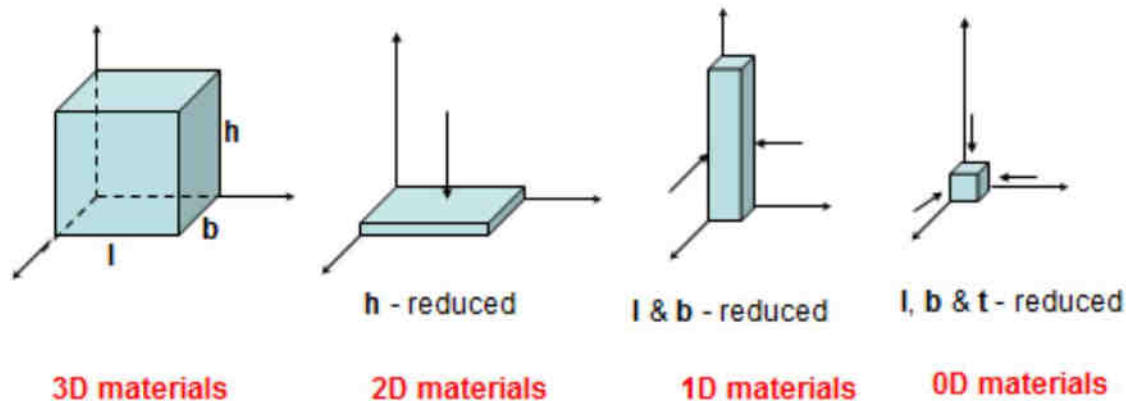
# QUANTUM MECHANICAL COHERENCE

- In a mesoscopic structure, the behaviour of the electron should be described quantum mechanically using Schrödinger equation.
- If the electron interacts inelastically with a defect, or any impurity, the electrons change their energy and momentum, as well as the phase of their wave function.
- The *phase coherence length*  $L\varphi$  is defined as the distance travelled by the electron without the carrier wave changing its phase
- *In quantum physics*,  $L\varphi$  should be a length similar to the inelastic scattering mean free path  $l_e$ .
- electrons can show *interference effects* over distances smaller than  $L\varphi$ . If electrons with phase  $\varphi_1$  interfere with electrons of phase  $\varphi_2$ , we know from the wave theory that the amplitudes can add up to each other, or they can be subtracted depending on the phase difference.

# Low dimensional structures

- When one or more of the dimensions of a solid are reduced sufficiently, its physicochemical characteristics notably depart from those of the bulk solid.
- When the dimensions of the solid get reduced to a size comparable with, or smaller than  $\lambda$ , then the particles behave wave-like and quantum mechanics should be used.
- With reduction in size, novel electrical, mechanical, chemical, magnetic, and optical properties can be introduced. The resulting structure is then called a low-dimensional structure.
- When one of the three spatial dimensions of a solid, usually a semiconductor material, is of a size comparable to  $\lambda_B$ , we say that we are dealing with a material or a structure of low dimensionality.
- The low dimensional materials exhibit new physicochemical properties not shown by the corresponding large-scale structures of the same composition.
- Suitable control of the properties and responses of nanostructures can lead to new devices and technologies

- Low-dimensional structures are usually classified according to the number of reduced dimensions they have.
- Based on reduced dimension, the low dimensional materials are in generally classified as 2D, 1D and 0D.

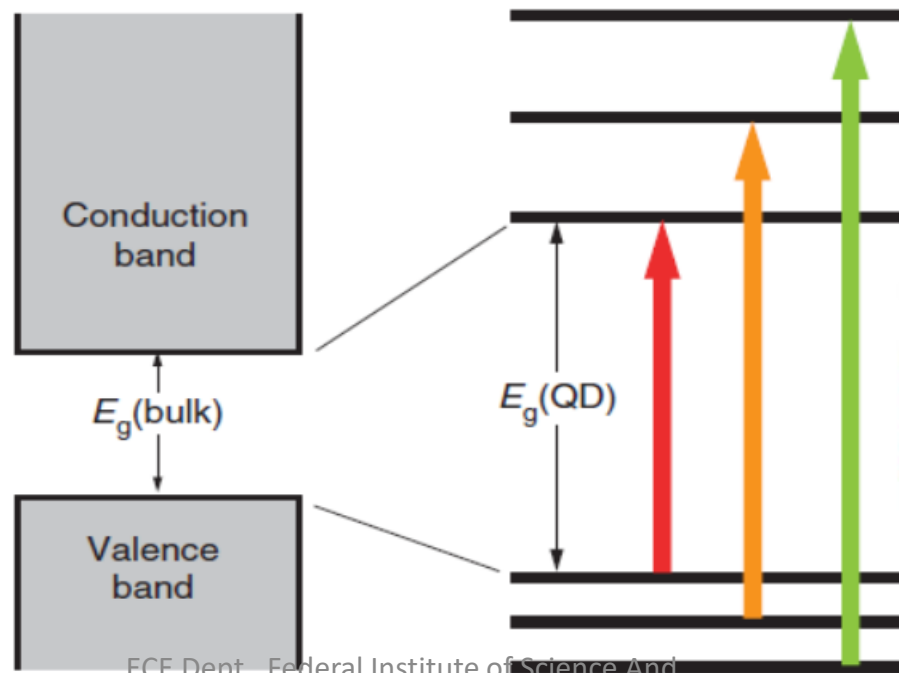




- The quantum confinement effect is observed when the size of the particle is too small to be comparable to the wavelength of the electron.

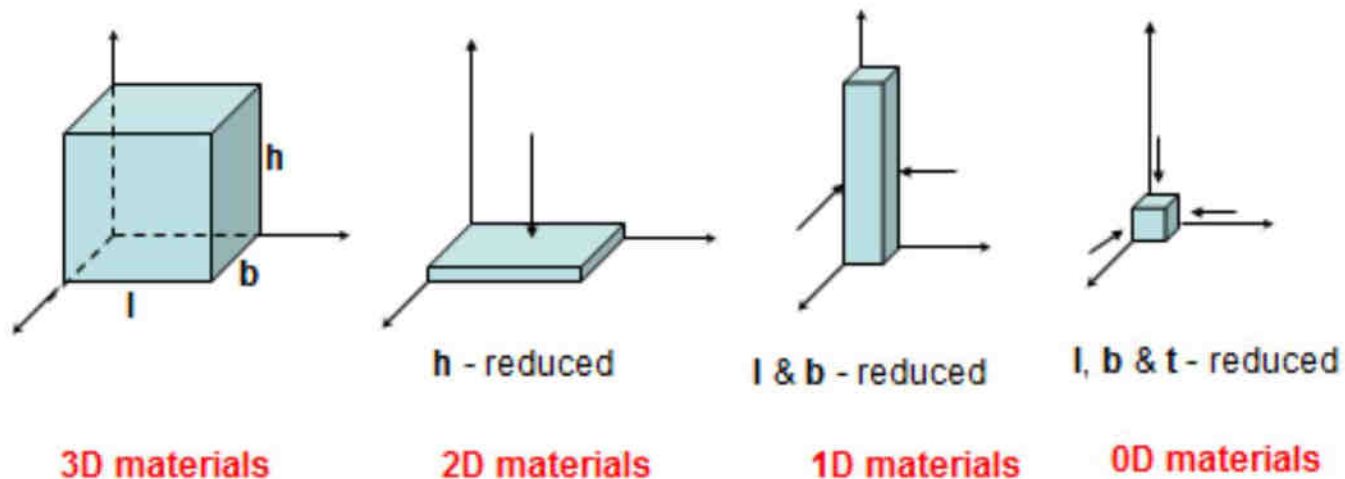
# Quantum confinement

- Quantum confinement leads to a collapse of the continuous energy bands of a bulk material into discrete, atomic like energy levels.



- A quantum confined structure is one in which the motion of the carriers (electron and hole) are confined in one or more directions by potential barriers.
- Based on the confinement direction, a quantum confined structure will be classified into three categories as quantum well, quantum wire and quantum dots

- Let us suppose that we have an electron confined within a box of dimensions  $L_x$ ,  $L_y$  &  $L_z$ . If the characteristic length is  $\lambda$ , we can have the following situations:



$$\lambda \ll L_x, L_y, L_z$$

- In this case the electron behaves as in a regular 3D bulk semiconductor.

$$\lambda > L_x \text{ and } L_x \ll L_y, L_z$$

- In this situation we have a 2D semiconductor perpendicular to the  $x$ -axis. This mesoscopic system is also called a *quantum well*.

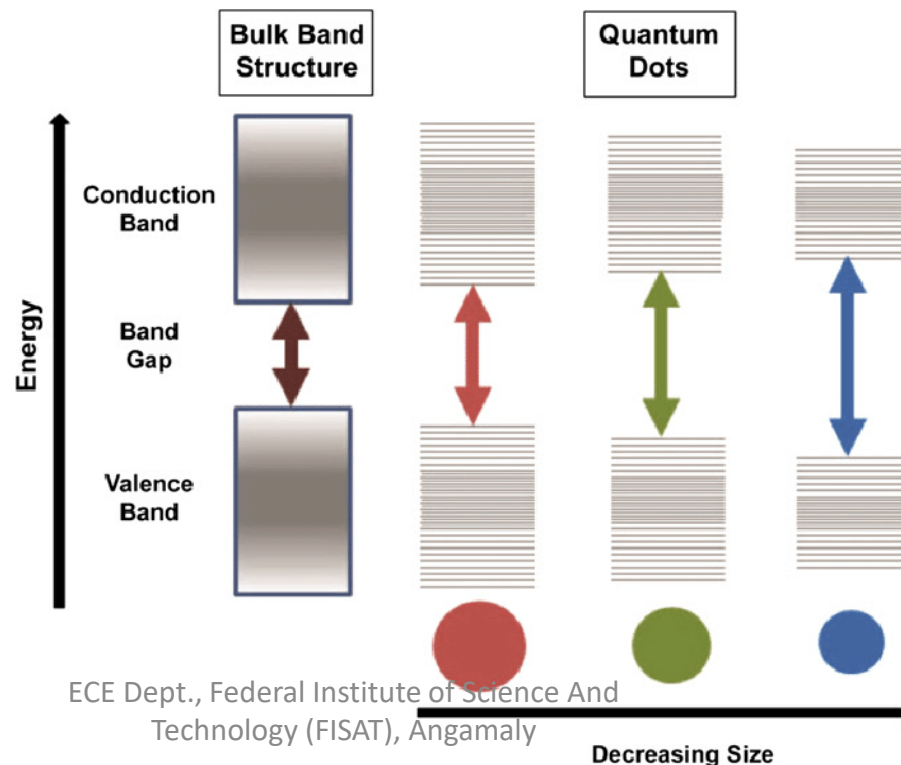
$$\lambda > L_x, L_y \text{ and } L_x, L_y \ll L_z$$

- corresponds to a 1D semiconductor or *quantum wire*

$$\lambda \gg L_x, L_y, L_z$$

- In this case it is said that we have a 0D semiconductor or a *quantum dot*

- As the size of a particle decrease till we reach a nano scale the decrease in confining dimension makes the energy levels discrete and this increases or widens up the band gap.
- This will ultimately increases the band gap energy.



# Schrodinger Wave Equation

1. Each particle in a physical system is described by a wave function  $\Psi(x, y, z, t)$ .
2. In dealing with classical quantities such as energy  $E$  and momentum  $p$ , we must relate these quantities with abstract quantum mechanical operators defined in the following way:

Classical variable	Quantum operator
$x$	$x$
$f(x)$	$f(x)$
$p(x)$	$\frac{\hbar}{j} \frac{\partial}{\partial x}$
$E$	$-\frac{\hbar}{j} \frac{\partial}{\partial t}$

and similarly for the other two directions.

3. The probability of finding a particle with wave function  $\Psi$  in the volume  $dx dy dz$  is  $\Psi^* \Psi dx dy dz$ .

$$\int_{-\infty}^{\infty} \Psi^* \Psi dx dy dz = 1$$

- Once we find the wave function of a particle, we can calculate its average position, energy, and momentum, within the limits of the uncertainty principle.

The classical equation for the energy of a particle can be written:

Kinetic energy + potential energy = total energy

$$\frac{1}{2m} p^2 + V = E$$

In quantum mechanics we use the operator form for these variables (postulate 2); the operators are allowed to operate on the wave function  $\Psi$ . For a one-dimensional problem Eq. (2-22) becomes<sup>3</sup>

$$-\frac{\hbar^2}{2m} \frac{\partial^2 \Psi(x, t)}{\partial x^2} + V(x) \Psi(x, t) = -\frac{\hbar}{j} \frac{\partial \Psi(x, t)}{\partial t}$$

which is the Schrödinger wave equation. In three dimensions the equation is

$$\boxed{-\frac{\hbar^2}{2m} \nabla^2 \Psi + V \Psi = -\frac{\hbar}{j} \frac{\partial \Psi}{\partial t}}$$

where  $\nabla^2 \Psi$  is

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial^2 \Psi}{\partial z^2}$$



# DENSITY OF STATES AND DIMENSIONALITY

- Most physical properties significantly depend on the DOS function  $\rho$ .
- It is the number of energy states existing in a region.
- The DOS function, at a given value  $E$  of energy, is defined such that  $\rho(E)VE$  is equal to the number of states (i.e. solutions of Schrödinger equation) in the interval energy  $E$  around  $E$ .
- In quantum level, the DOS function becomes discontinuous.
- Each of the above states is also called as Bloch state and is designated by a quantum number  $k$  (Bloch state).

- let us remind that for bulk solids  $\rho(E)$  varies with energy in the form  $\sqrt{E}$

$$\rho_{3D}(E) = \frac{V}{2\pi^2} \left( \frac{2m^*}{\hbar^2} \right)^{3/2} \sqrt{E}$$

$$\rho_{2D}(E) = \frac{A}{\pi} \left( \frac{m^*}{\hbar^2} \right)$$

$$\rho_{1D}(E) = \frac{L}{2\pi} \left( \frac{2m^*}{\hbar^2} \right)^{1/2} \frac{1}{\sqrt{E}}$$

$$\rho_{0D}(E) = \sum_i \delta(E - E_i)$$

- Some important considerations can already be made: the DOS function in 3D semiconductors is proportional to  $\sqrt{E}$ , in 2D is constant, and in 1D varies inversely proportional to  $\sqrt{E}$ .

- In more accurately the DOS can define as below

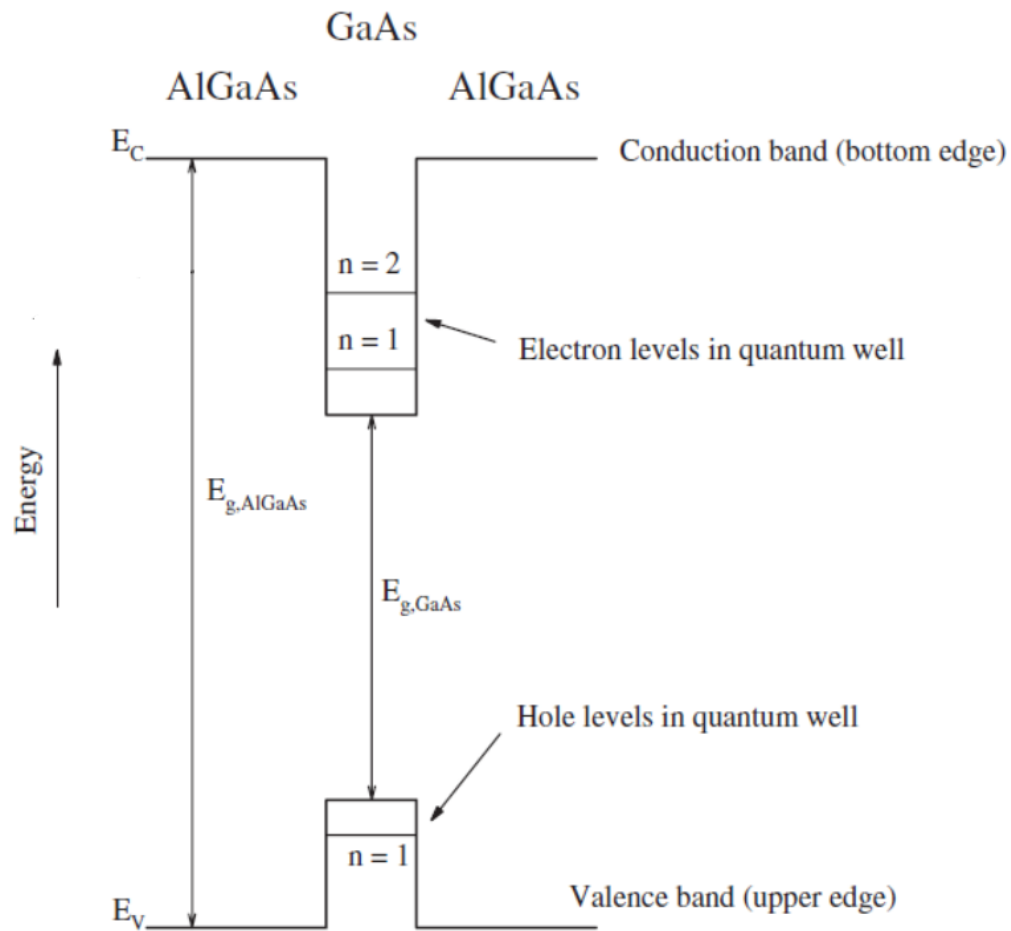
$$\rho_{2D}(E) = \frac{A}{\pi} \left( \frac{m^*}{\hbar^2} \right) \sum_{n_z} \theta(E - E_{n_z})$$

$$\rho_{1D}(E) = \frac{L}{2\pi} \left( \frac{2m^*}{\hbar^2} \right)^{1/2} \sum \frac{1}{\sqrt{E - E_{n_x, n_y}}}$$

- where  $n_z$  refers to the quantization in the confined z-axis and  $\theta$  is the step function.
- Similarly  $n_x$  and  $n_y$  refers to the quantization in the confined  $x$  and  $y$  axis

# Basic properties of two dimensional semiconductor nanostructures

- One of the most practical two-dimensional semiconductor structures consists of a sandwich of gallium arsenide (GaAs), with a thickness in the nanometre range, surrounded on each side by a semiconductor such as aluminium gallium arsenide ( $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ) of higher bandgap.
- The bandgap of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  ( $x \sim 0.3$ ) is close to 2.0 eV while that of GaAs is 1.4 eV.
- As a consequence, the potential energy profile has the shape of a square well.



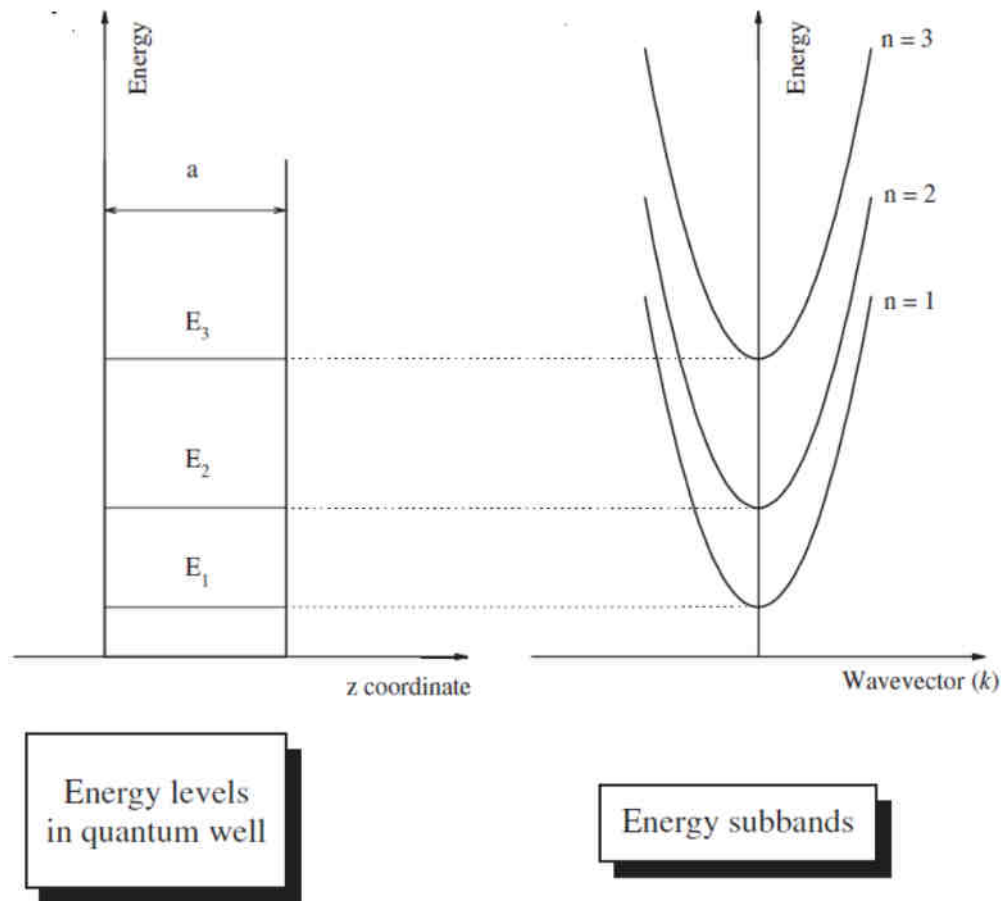
- Carrier motion for both electrons and holes is not allowed in the direction perpendicular to the well, usually taken as the  $z$ -direction because of the potential walls.
- However in the other two spatial directions ( $x, y$ ), parallel to the semiconductor interfaces, the motion is not restricted.
- The behavior of electrons when their motion is restricted along one direction in the wells of infinite height corresponds to a well-known problem in quantum mechanics, the so-called particle in a box of infinite wells.

- Solving Schrodinger equations for the case of infinite potentials barriers, the wave functions and energy levels of the bound electrons are given by

$$\psi_n(z) = \left(\frac{2}{a}\right)^{1/2} \sin\left(\frac{\pi n z}{a}\right)$$

$$E_n = \frac{\hbar^2 \pi^2}{2m_e^* a^2} n^2, \quad (n = 1, 2, \dots)$$

- where  $m_e^*$  is the effective mass of the electrons in the well material for the motion along the z-direction and  $a$  is the width of the well.
- From above expression, it is observed that, quantum size effects will be more easily observable in quantum structures of very small size  $a$ , and for materials for which the electron effective mass is as small as possible.
- GaAs nanostructures are very convenient since  $m_e^* \sim 0.067m_0$ , where  $m_0$  is the free electron mass.



- It is interesting to observe that the lowest energy of electrons,  $E_1$ , is different from zero, in contrast with classical mechanics.



- Motion of electrons in the quantum well is confined only in one direction,  $z$ , but in the  $(x, y)$  planes the electrons behave as in a three-dimensional solid.
- Therefore the electron wave function is separable as the product of  $\psi_x$ ,  $\psi_y$ , and  $\psi_z$ .
- $\psi = \psi_x \psi_y \psi_z$

- In our simple model,  $\psi_x$  and  $\psi_y$  satisfy the Schrödinger equation for a free electron, while  $\psi_z$  is given by the Schrödinger equation with a square well potential  $V(z)$  and therefore can be expressed as in our previous equation.
- The expression for the total energy of electrons in the potential can be written as

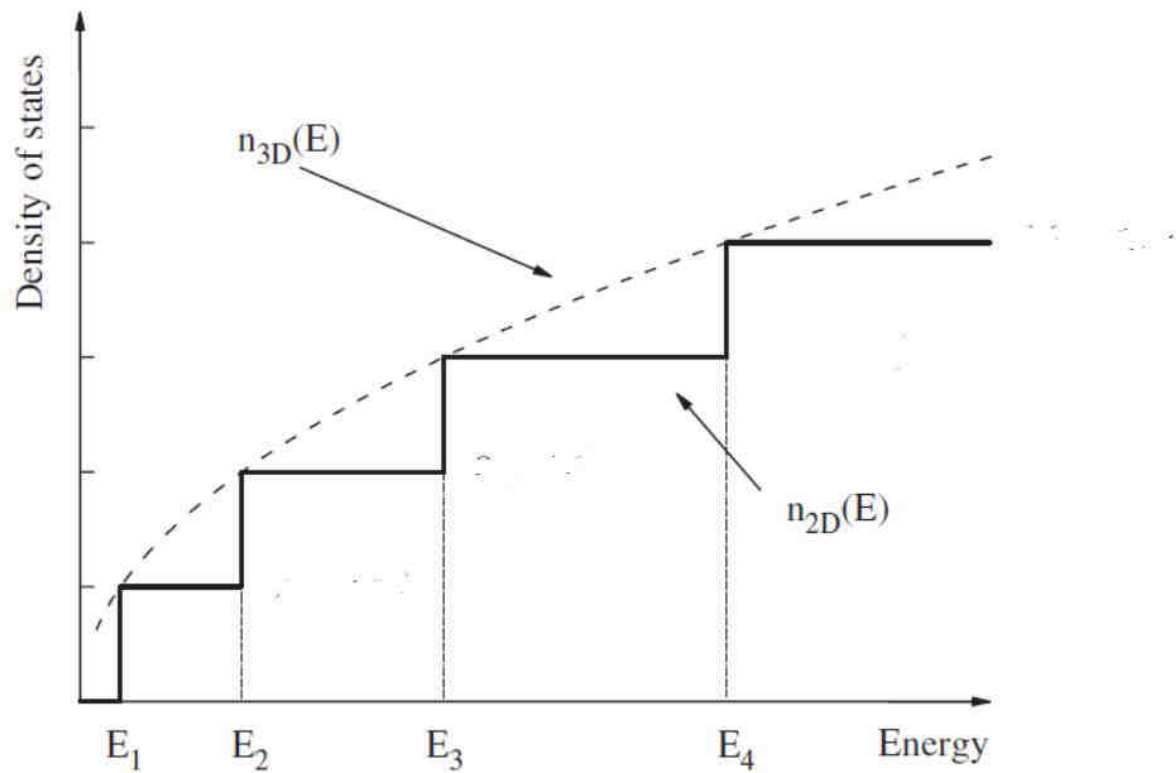
$$E(k_x, k_y, n) = \frac{\hbar^2}{2m_e^*} (k_x^2 + k_y^2) + E_n = \frac{\hbar^2}{2m_e^*} (k_x^2 + k_y^2) + \frac{\hbar^2 \pi^2}{2m_e^* a^2} n^2, \quad (n = 1, 2, \dots)$$

- Where  $k_x, k_y$  represents the quasi-continuous values as in the case of a free electron in the bulk.
- $E_n$  corresponding to the discrete values of energy in the  $z$ -direction.

- The densities of states in energy is given by'

$$n_{2D}(E) = \frac{m_e^*}{\pi \hbar^2}$$

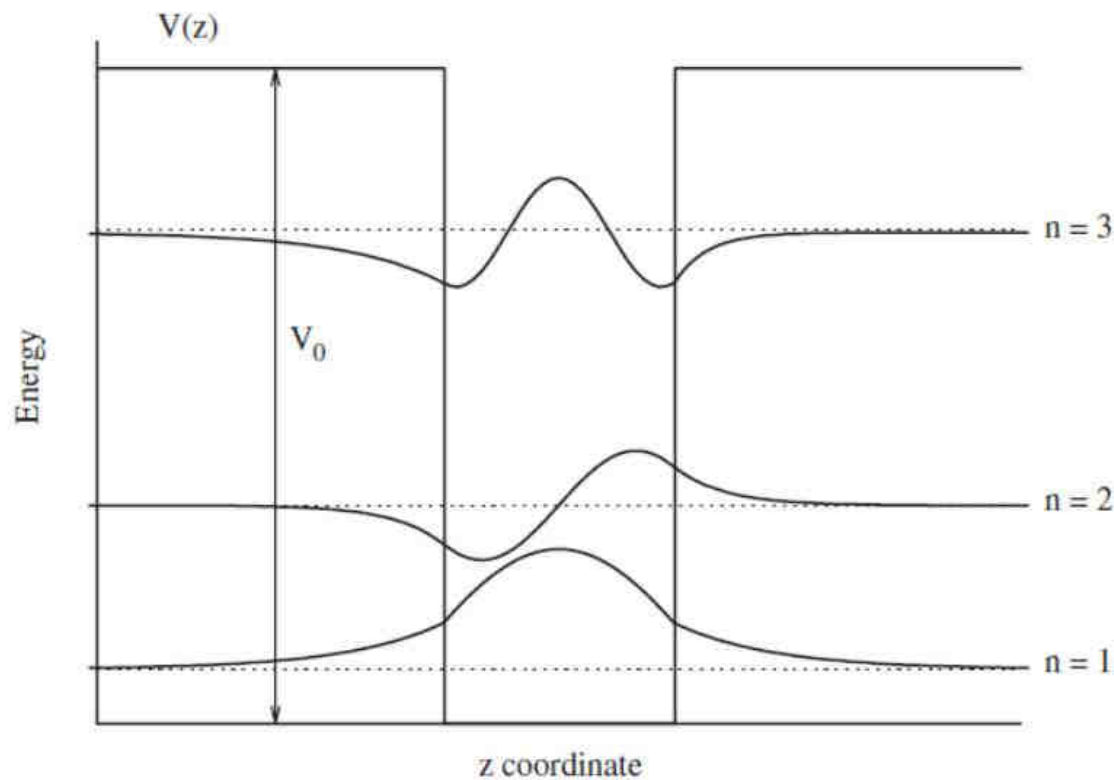
- DOS function, for the two-dimensional case, exhibits a staircase-shaped energy dependence in which all the steps are of the same height, but located at energies  $E_n$  given by previous Eq.



Density of states function for a 2D electron system, as a function of energy.

# SQUARE QUANTUM WELL OF FINITE DEPTH

- If we call  $V_0$  in Figure as the height of the finite square well, it is evident that for states with energy  $E < V_0$  we have *bound states*, i.e. the electrons are trapped inside the well of width  $a$ .
- For  $E > V_0$ , we have continuous *propagation states*, in which the electrons are free to move from  $z = -\infty$  to  $z = +\infty$ .
- The wave functions inside the well should have the same shape as in the case of the infinite well.
- Solutions outside the well, which are obtained from the Schrödinger equation with a potential energy equal to  $V_0$ , are exponential decay functions



Finite potential square well. The first three energy levels and wave functions are shown.

$$\psi_n(z) = \begin{cases} D \exp(kz), & z < -a/2 \\ C \cos(kz), C \sin(kz), & -a/2 < z < a/2 \\ D \exp(-kz), & z > a/2 \end{cases}$$

where  $k = \left( \frac{2m_e^* E}{\hbar^2} \right)^{1/2}$  inside the well

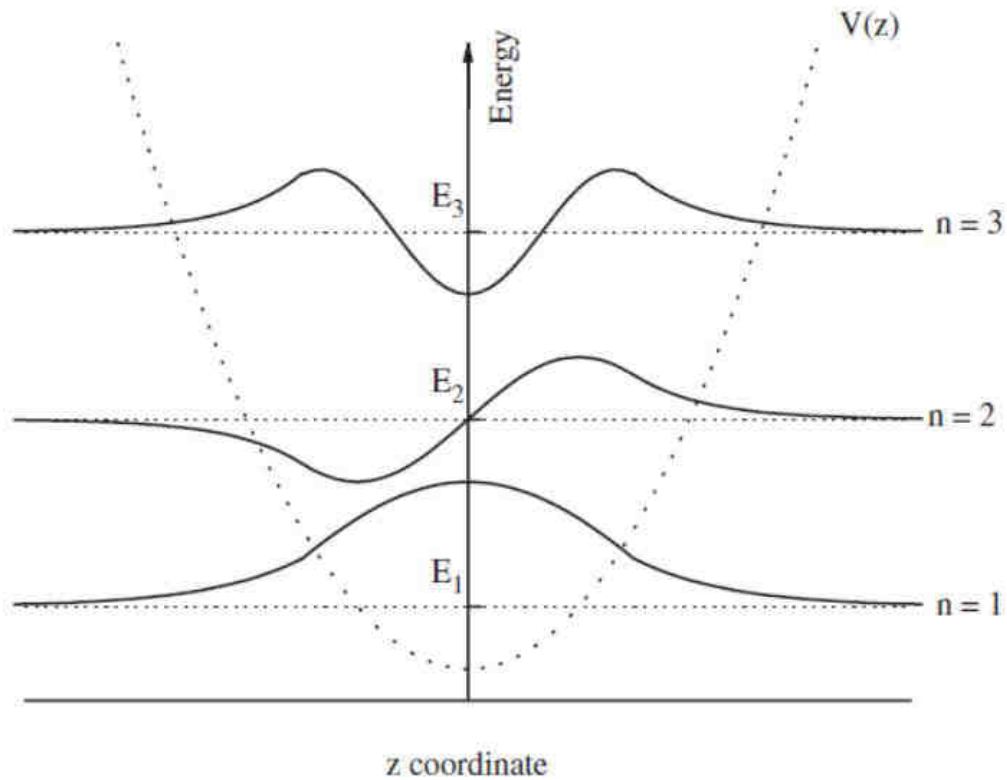
and  $k = \left( \frac{2m_e^* (V_0 - E)}{\hbar^2} \right)^{1/2}$  outside the well

# Parabolic Quantum Wells

- Parabolic quantum well profiles can be produced by the MBE growth technique.
- Alternate layers of GaAs and  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  of varying thickness are deposited.
- Increasing the thickness of the AlGaAs layer quadratically with distance, while the thickness corresponding to the GaAs layer is proportionally reduced.
- potential energy of the system is given as

$$V(z) = \frac{1}{2}k^2z^2$$

- Wave functions are mostly symmetrical



- Harmonic oscillator potential well  $V(z)$ . The first three levels and corresponding wave functions are shown.



# Triangular wells

- The potential profile across quantum heterojunctions , such as the well-known modulation doped AlGaAs–GaAs heterojunction, is almost triangular in shape for electrons within GaAs.
- For simplicity, it is assumed that the left barrier is infinite in energy and it increases linearly for  $z > 0$ :

$$V(z) = eFz, \quad \text{for } z > 0$$

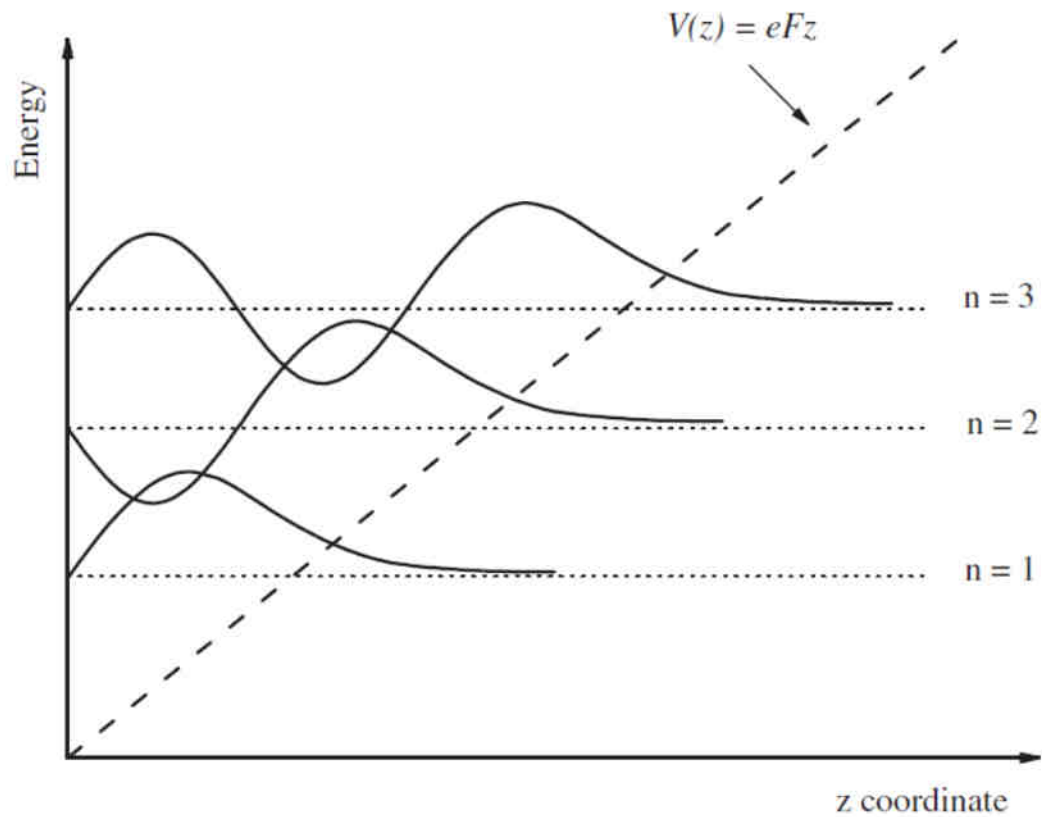
$$V(z) = \infty, \quad \text{for } z \leq 0$$

- where  $e$  is a constant equal to the electron charge and  $F$  is a uniform electric field.

- Electron energies and states are found by solving the Schrödinger equation.

$$E_n \approx \left[ \frac{3}{2} \pi \left( n - \frac{1}{4} \right) \right]^{2/3} \left( \frac{e^2 F^2 \hbar^2}{2m} \right)^{1/3}, \quad n = 1, 2, \dots$$

- in contrast to the square well where the levels become further apart as  $n$  increases.
- As  $n$  increases, the wave functions add one more halfcycle.
- The wave functions are neither symmetric or antisymmetric due to the asymmetry of the potential well.



- i. Triangular potential well  $V(z)$ . The first three levels and corresponding wave functions are shown.

# QUANTUM WIRES

- Electrons should be confined in two directions,  $(x, y)$ , and can freely propagate along the  $z$ -direction
- Total energy of the electrons in the quantum wire should be of the form:

$$E_{n_1, n_2}(k_z) = E_{n_1, n_2} + \frac{\hbar^2 k_z^2}{2m_e^*}$$

- where the last term represents the kinetic energy of the electron propagating along the  $z$ -direction.

$$E_{n_1, n_2} = \frac{\hbar^2 \pi^2}{2m_e^*} \left( \frac{n_1^2}{a_x^2} + \frac{n_2^2}{a_y^2} \right), \quad n_1, n_2 = 1, 2, 3, \dots$$

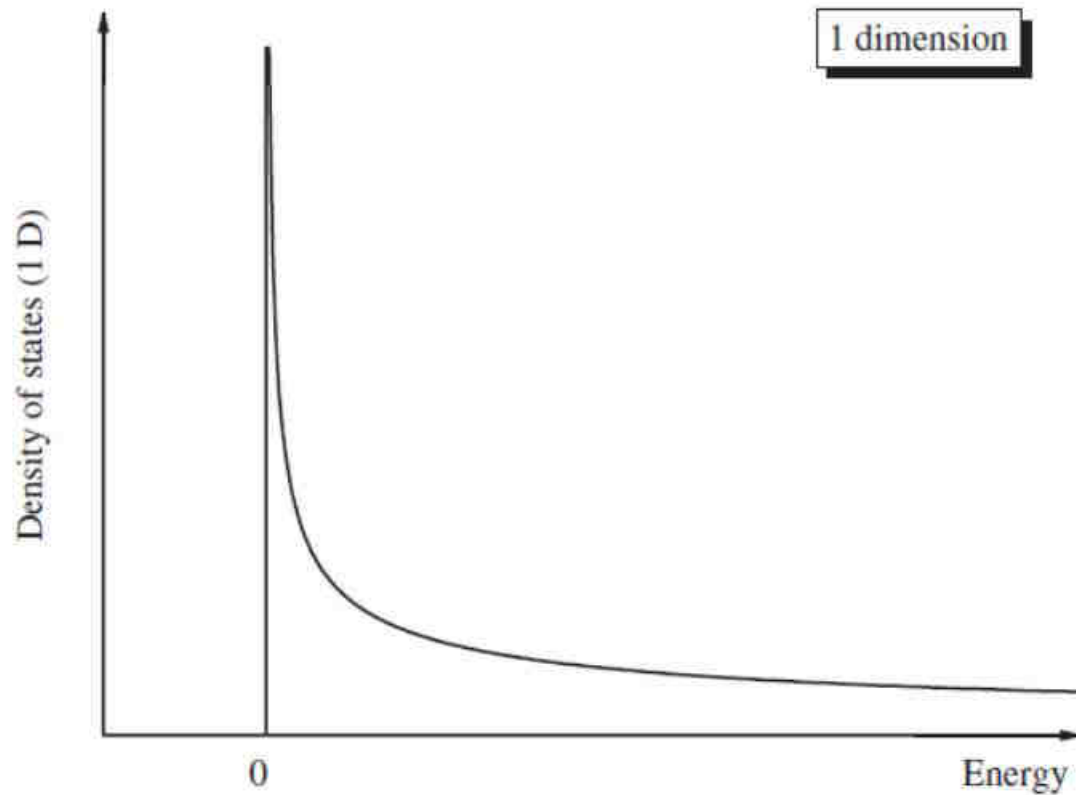
Density of states for the one-dimensional material may defined as,

$$n_{1D}(E) = \frac{1}{\pi \hbar} \sqrt{2m_e^*/E}$$

which diverges for  $E = 0$

- The expression of the total DOS per unit length for a quantum wire can be expressed as

$$n_{1D}(E) = \sum_{n_1, n_2} \frac{1}{\pi \hbar} \sqrt{\frac{2m_e^*}{E - E_{n_1, n_2}}}$$



. Density of states function for a 1D electron system, as a function of energy.

# QUANTUM DOTS

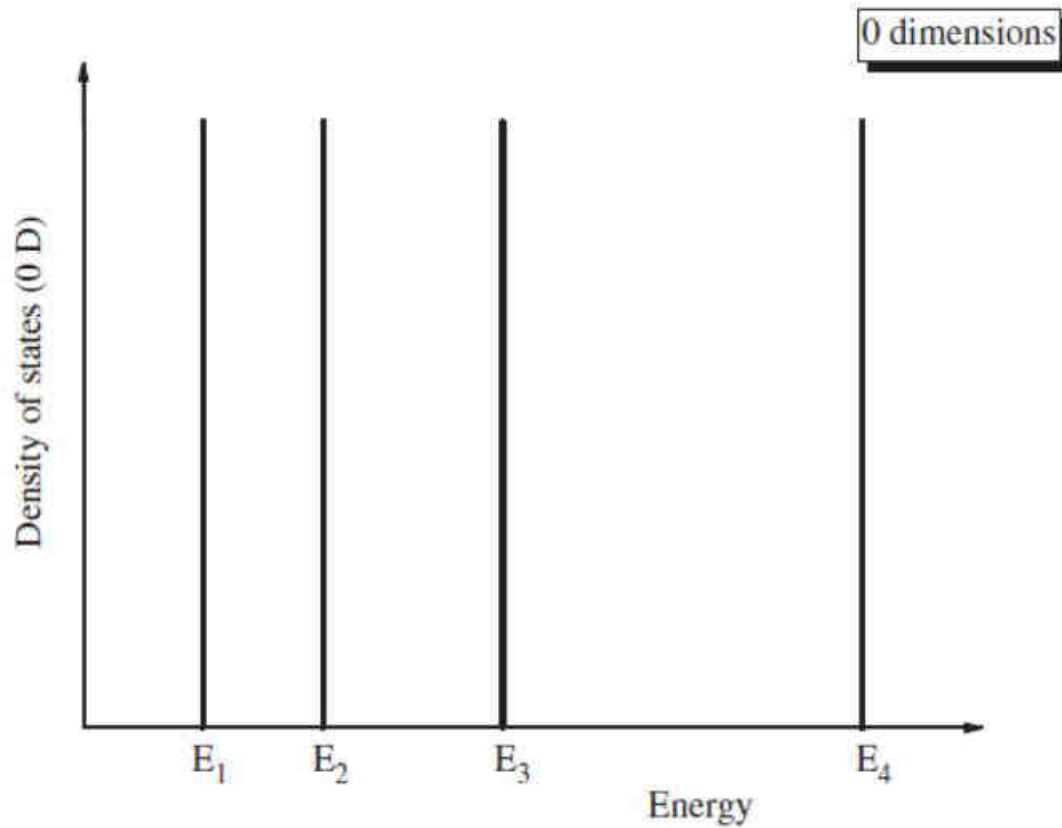
- Quantum dots are often nanocrystals with all three spatial dimensions in the nanometre range.
- Although the word “dot” implies an infinitely small size, in practice dots might have a large number of atoms:  $10^4$ – $10^6$ .
- Quantum dots are often referred to as *artificial atoms* *because* the spectrum of the energy levels resembles that of an atom.
- Even the introduction or removal of one single electron in quantum dots, in contrast to the case of 2D or 1D systems, produces dominant changes in the electrical characteristics.

- The electron wave function and the energy levels are given by

$$E_{n_1, n_2, n_3} = \frac{\hbar^2 \pi^2}{2m_e^*} \left( \frac{n_1^2}{a_x^2} + \frac{n_2^2}{a_y^2} + \frac{n_3^2}{a_z^2} \right), \quad n_1, n_2, n_3 = 1, 2, 3, \dots$$

- In contrast to the 2D and 1D cases, now the energy is completely quantized
- There is no free electron propagation.
- Since in the case of quantum dots the electrons are totally confined, the energy spectrum is totally discrete and the DOS function is formed by a set of peaks in theory with no width and with infinite height.





Density of states function for a 0D electron system.

# Carbon nano Tube

# Graphene

# Module\_2

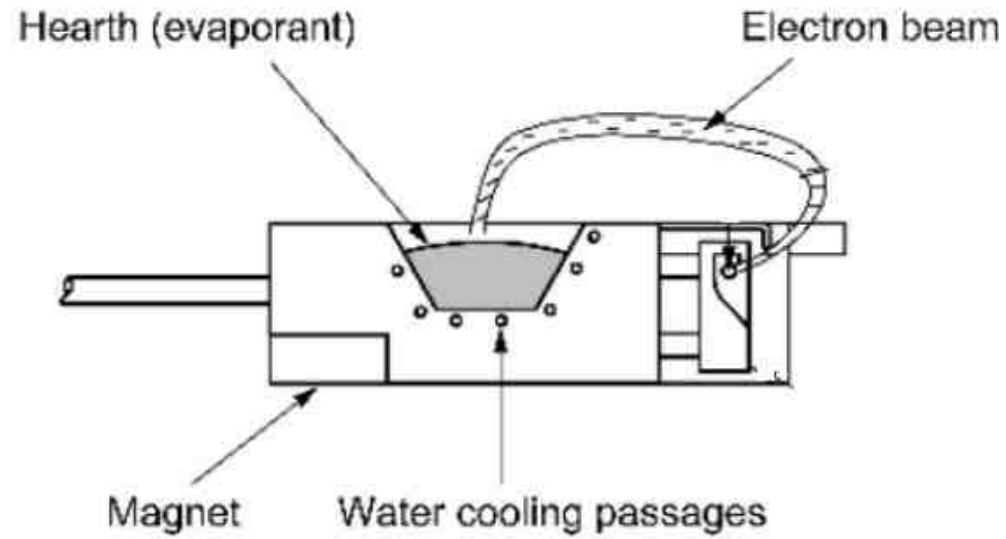
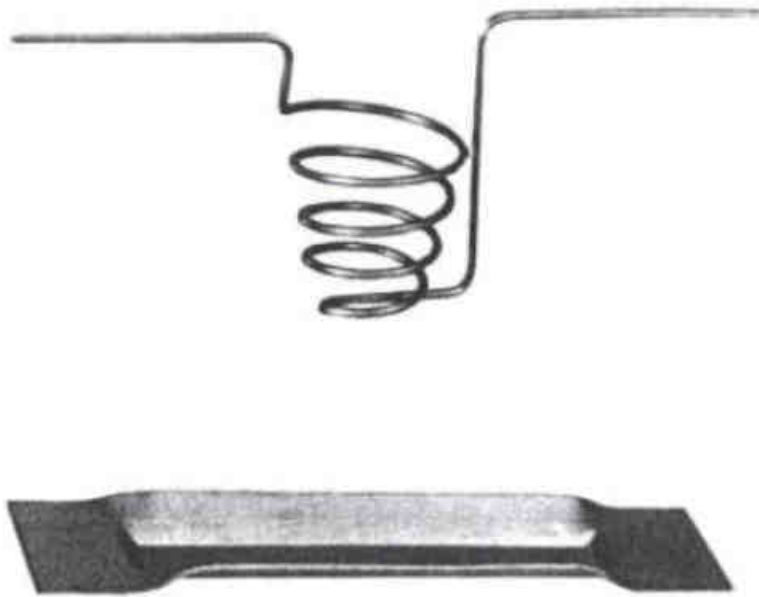
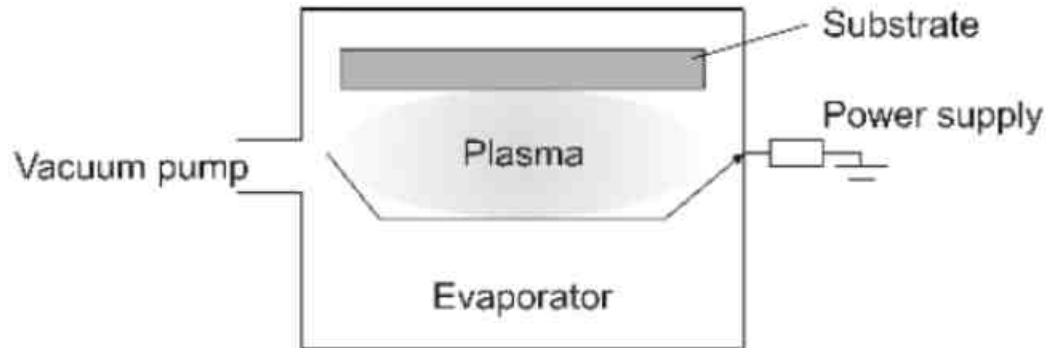
# Production of Nanolayers

## Physical Vapor Deposition (PVD)

- **Physical Vapor Deposition (PVD)** is a process by which a thin film of material is deposited on a substrate.
- (i) evaporation
- (ii) sputtering
- (iii) ion plating
- (iv) laser ablation.

# Physical Vapor Deposition (PVD) by Evaporation

- 1) the material to be deposited is converted into vapor by physical
- 2) the vapor is transported across a region of low pressure from its source to the substrate
- 3) the vapor undergoes condensation on the substrate to form the thin film.



- A crucible is heated up by a resistance or an electron gun until a sufficient vapor pressure develops.
- As a result, material is deposited on the substrate.
- There are several ways by which heating is achieved in PVD by evaporation.
  - Technically, the resistance is wrapped around the crucible, or a metal wire is heated up by a current and vaporized.
  - Or an electron beam is directed at the material intended for the deposition on the substrate
  - In electron beam evaporation, a high kinetic energy beam of electrons is directed at the material for evaporation.
  - Upon impact, the high kinetic energy is converted into thermal energy, heating up and evaporating the target material,



# Advantages

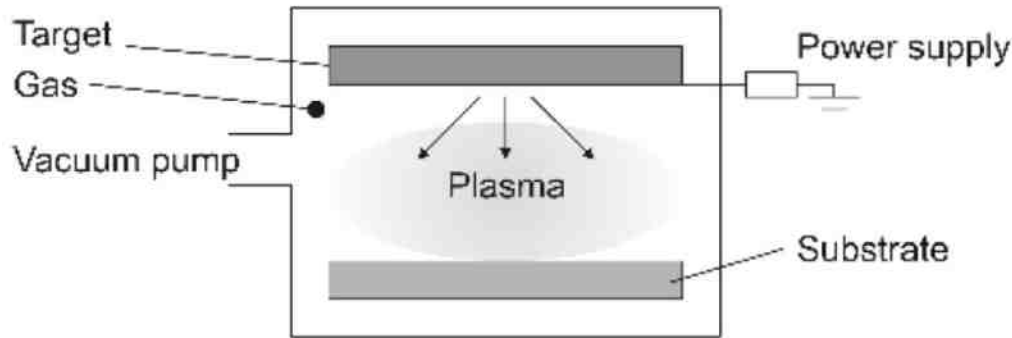
- 1) high film deposition rates
- 2) less substrate surface damage unlike sputtering that induces more damage because it involves high-energy particles;
- 3) excellent purity of the film because of the high vacuum condition used by evaporation;
- 4) less tendency for unintentional substrate heating.

# disadvantages

Difficult control of film composition

# Sputtering

- **Sputter deposition** is a physical vapor deposition (PVD) method of thin film deposition.

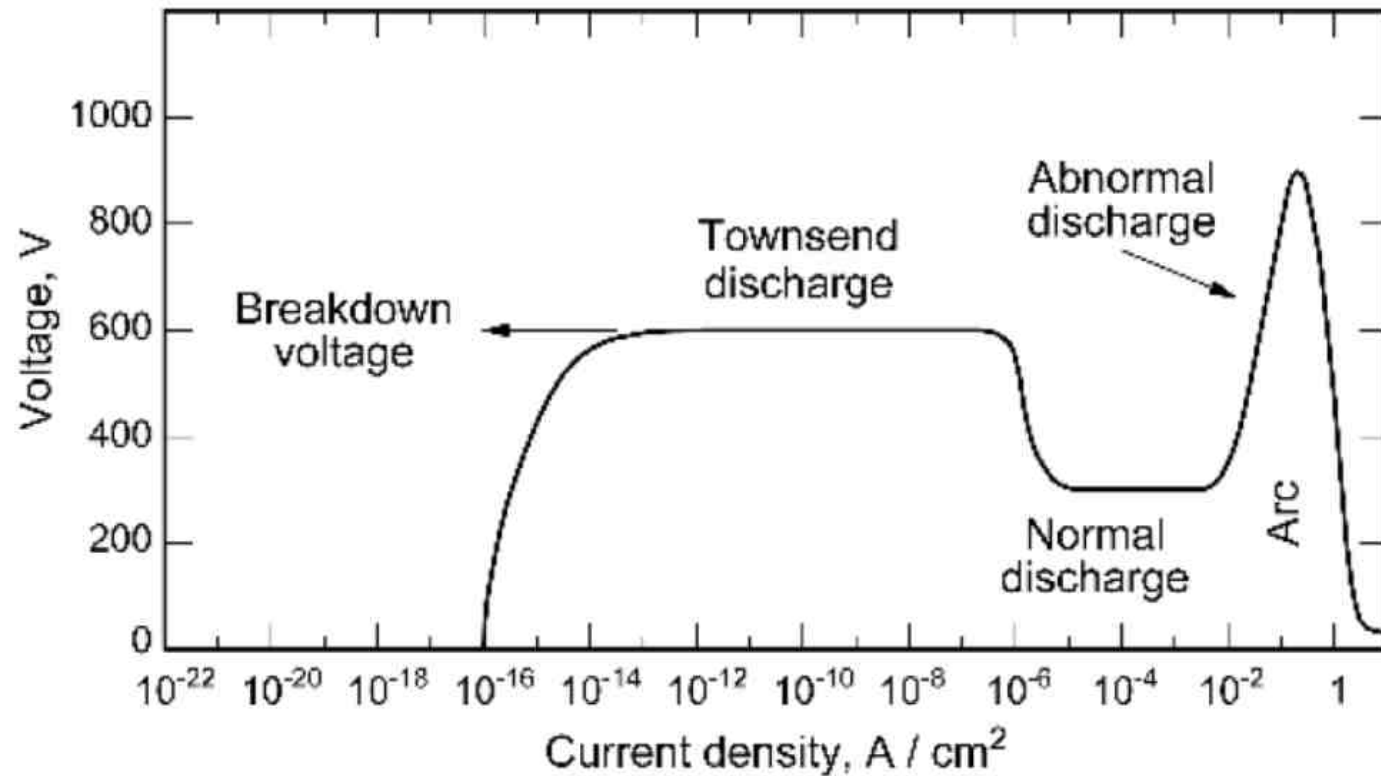


- An atom or a molecule, usually in its ionized form, hits a solid state(*target*) and knocks out surface atoms. This will be deposited on a solid state substrate.
- Sputtering involves ejecting material from a "target" that is a source onto a "substrate" such as a silicon wafer.

- Mainly two types
  - Glow discharge [ DC sputtering] .
  - High frequency discharge [ RF sputtering].

# Glow discharge

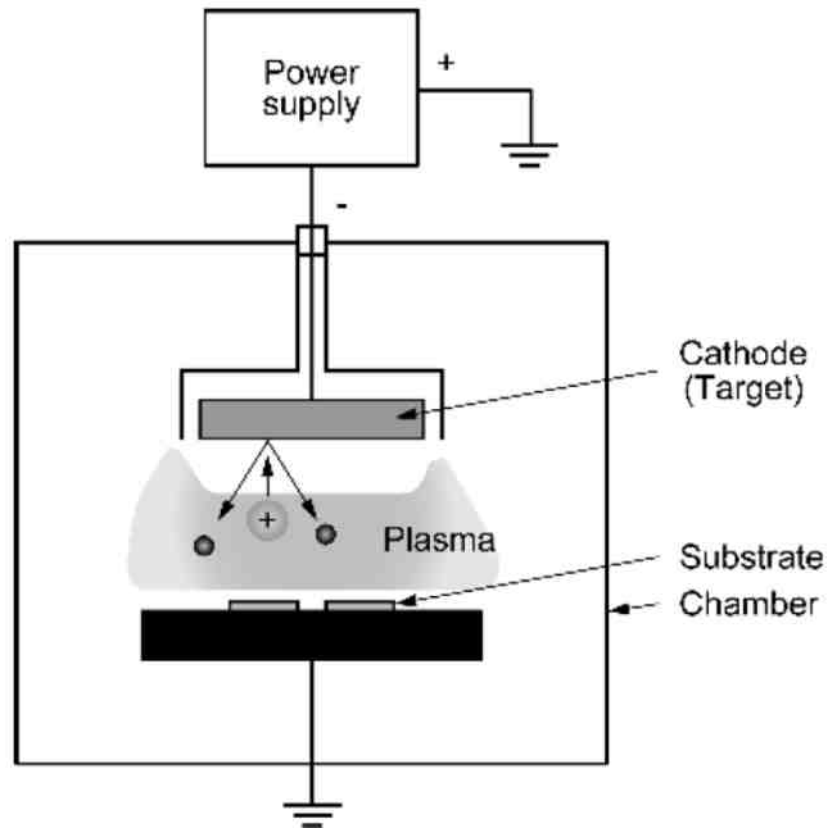
- It is created by applying a voltage between two electrodes in a glass tube containing a low-pressure gas.
- When the voltage exceeds a value called the striking voltage, the gas ionization becomes self-sustaining, and the tube glows with a colored light.
- The color depends on the gas used.
- Glow discharges are used as a source of light in devices such as neon lights, fluorescent lamps, and plasma-screen televisions.
- They are also used in the surface treatment technique called sputtering.



Applied voltage vs. discharge current

# Glow discharge Sputtering

- Sputtering is achieved by glow discharge with dc voltage.
- The chamber is supplied with Ar and a constant gas pressure of some 100 mPa is built up.
- The target, being attached a few centimeters above the substrate, is raised to a negative dc potential from -500 to -5000 V, while both chamber and substrate are grounded.
- When the voltage is slowly increased, a small current flows over the two electrodes.



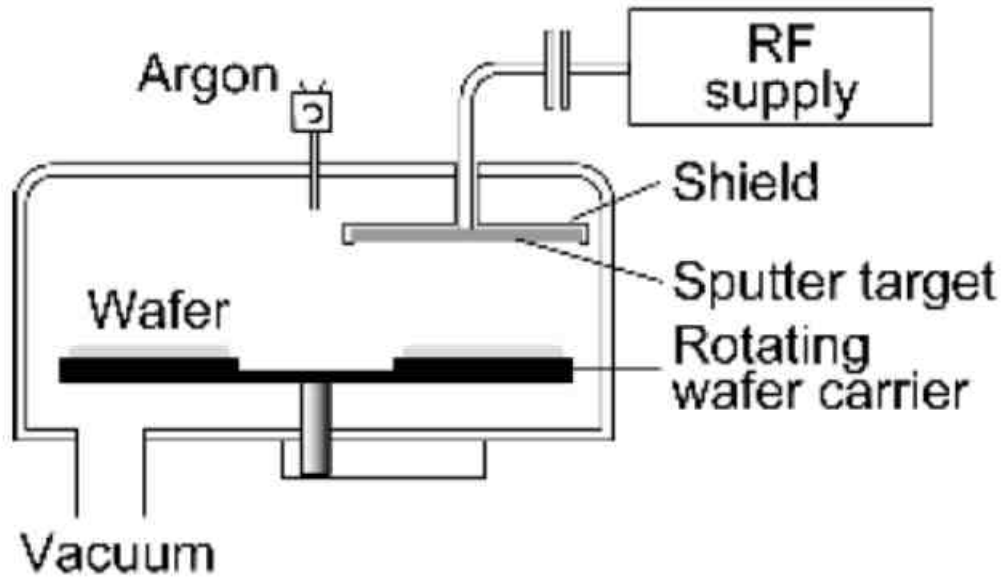
DC voltage sputtering



- At higher voltages across the anode and cathode, the gas in the chamber become ionized.
- The freed carriers can gain enough energy so that additional carriers are freed during collisions; the process is a Townsend avalanche or multiplication.
- The ionised atom will hit the target and knock out atoms.
- This will be deposited on a solid state substrate.

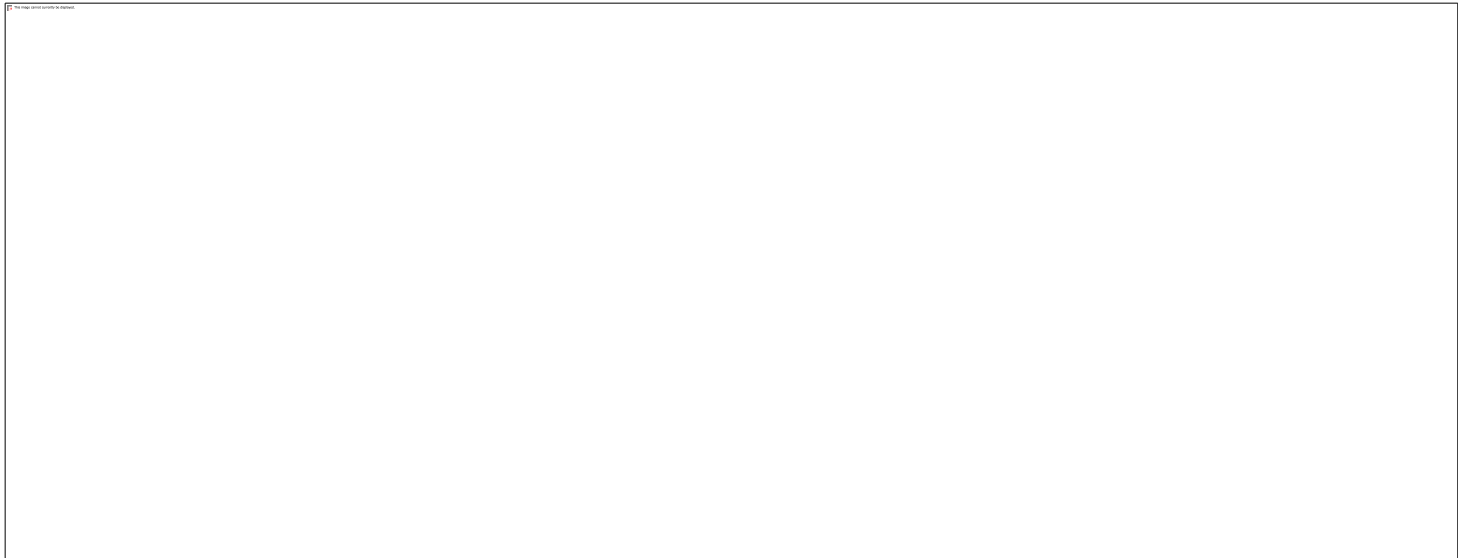
# High frequency discharge

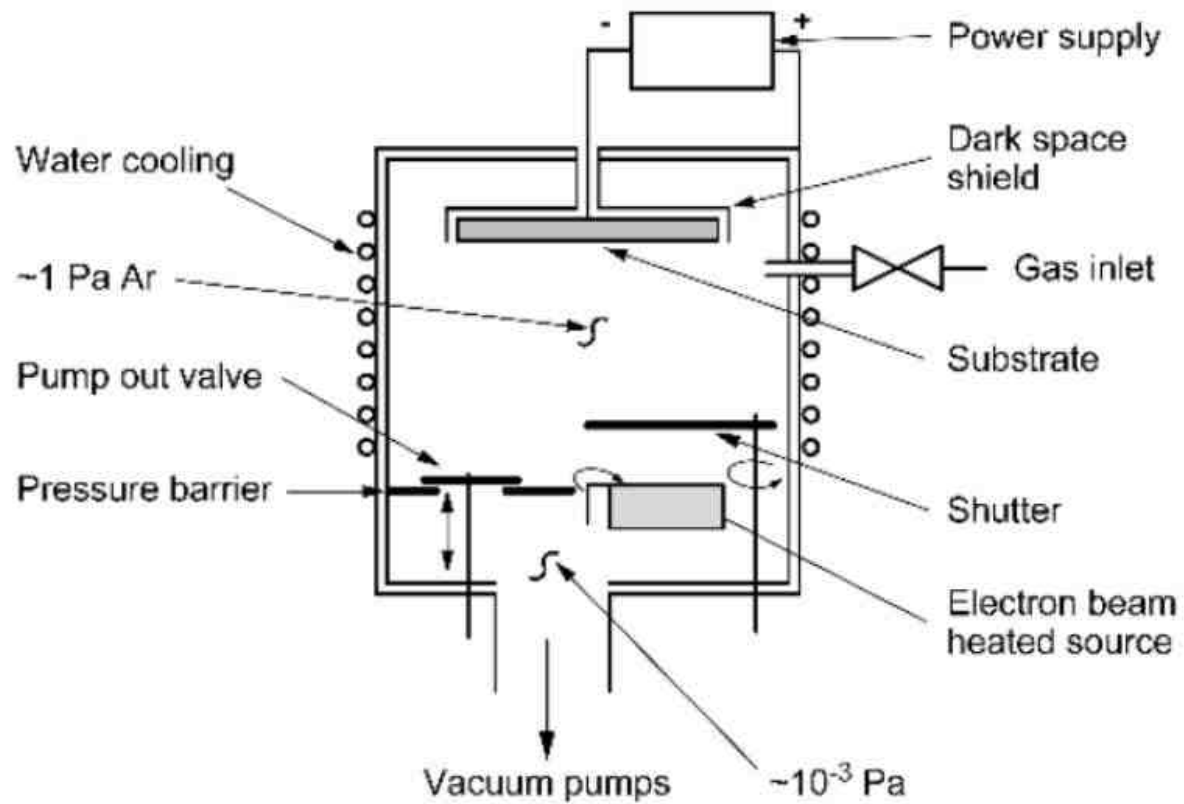
- It replaces the dc voltage source to a high frequency generator.
- during DC sputtering, the working gas will be ionized. As a result, many positive ions will be produced within the chamber and accumulate on the surface of target.
- In order to avoid this problem, we can use AC power instead of DC.
- In the first cycle, the source or target material is given -ve charge which causes polarization of atoms and the sputtering gas atoms are attracted to the source where they knock off source atoms.
- However, the source atoms may remain at the target surface
- During the second cycle, when target is given positive charge, the sputtering gas ions are ejected due to reverse polarization.



# *Ion plating.*

- This process is a combination of resistance evaporation and glow discharge
- A negative voltage is applied to the substrate, while the anode is connected with the source of the metal vaporization.
- The chamber is subsequently filled with Ar with a pressure of a few Pa, and the plasma is ignited.
- The material is vaporized with the help of e-gun .
- The growing of the layer on the substrate is improved by the plasma.
- The advantages of ion plating are higher energies of the vaporized atoms and therefore better adhesion of the produced films.
- The disadvantage is heating of the substrate.

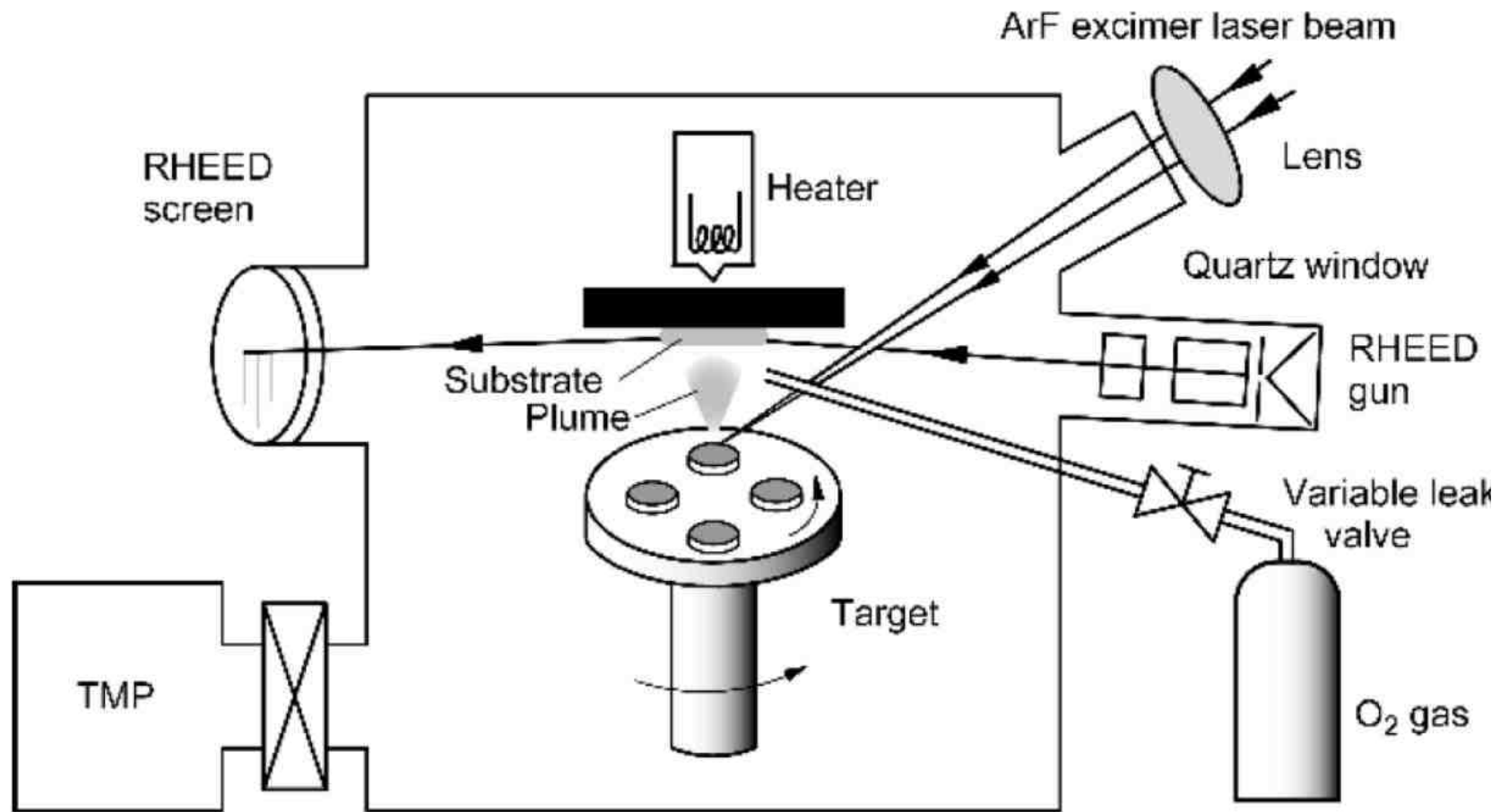




**Ion plating system**

# *Laser ablation.*

- A high-energy focused laser beam is capable of gradually remove the surface of a target rotating with a velocity of one revolution per second.
- The material is vaporized on the substrate, and as a result, a film is produced on it.
- The growth can be supported by heating the substrate (750 °C) and by chemical reactions.



Typical laser ablation system under O<sub>2</sub> partial pressure. Note the so-called plume, a luminous cloud close to the irradiated target surface. RHEED: reflection high-energy electron diffraction



# Reflection high-energy electron diffraction (RHEED)

- Reflection high-energy electron diffraction (RHEED) is a technique used to characterize the surface of crystalline materials
- A RHEED system consist an electron source (gun), detector screen and a sample with a clean surface.
- The electron gun generates a beam of electrons which strike the sample at a very small angle relative to the sample surface.
- Incident electrons diffract from atoms at the surface of the sample and form regular patterns on the detector.
- The electrons interfere according to the position of atoms on the sample surface, so the pattern at the detector is a function of the sample surface.

# Advantages

- Deposition of materials of high-melting points
- Good control over impurities.

# Chemical Vapor Deposition (CVD)

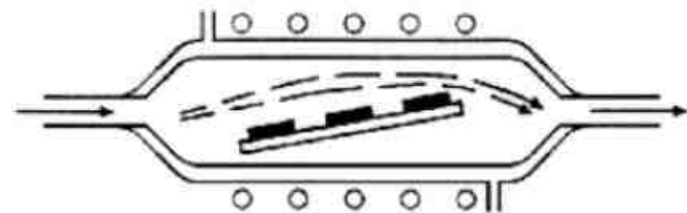
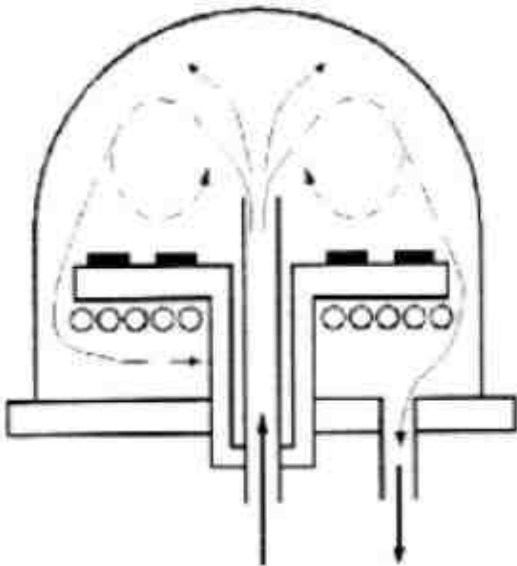
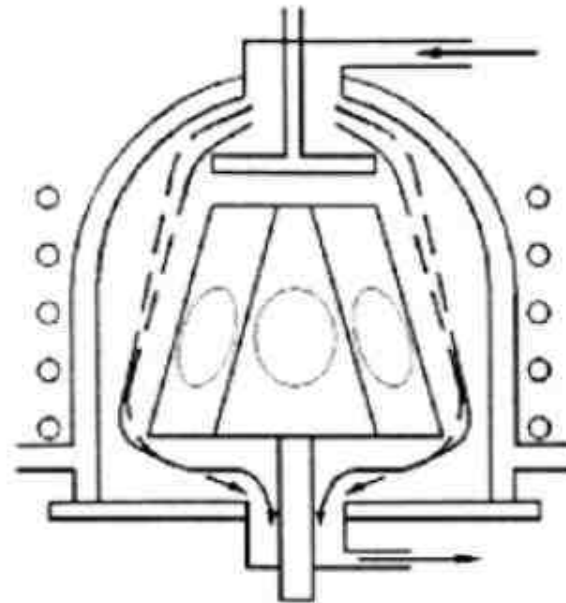
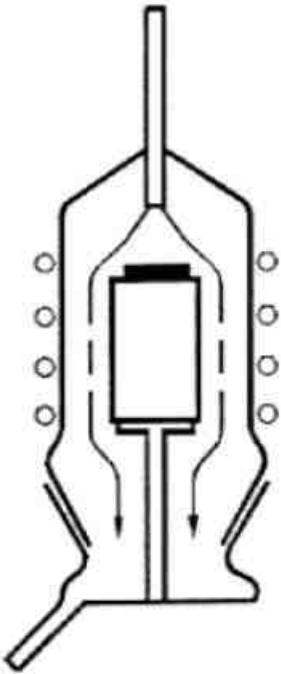
- **Chemical vapor deposition (CVD)** is a deposition method used to produce high quality, high-performance, solid materials, typically under vacuum.
- The wafer is put on a carrier and heated to a temperature between 350 and 800C.

# Types of CVD

CVD is practiced in a variety of formats.

- *Atmospheric pressure CVD (APCVD)*
  - CVD at atmospheric pressure.
- *Low-pressure CVD (LPCVD)*
  - CVD at Reduced pressures tend to reduce unwanted gas-phase reactions and improve film uniformity across the wafer.
- *Ultrahigh vacuum CVD (UHVCVD)*
  - CVD at very low pressure, typically below  $10^{-6}$  Pa
- *Plasma-Enhanced CVD (PECVD)*
  - CVD that utilizes plasma to enhance chemical reaction rate.

# Types of CVD Chamber



- One or several species of gases are let in so that a gas pressure is formed between very low and normal pressure.
- The gas flow hits the wafer at a normal or a glancing incidence.
- Now a dissociation (in the case of a single gas species) or a reaction between two species takes place.
- In both cases, a newly formed molecule adheres to the wafer surface and participates in the formation of a new layer.

# Examples

- Silane ( $\text{SiH}_4$ )

On impact, it disintegrates into elementary silicon, which partly adheres to the surface, and to hydrogen, which is removed by the pumps.

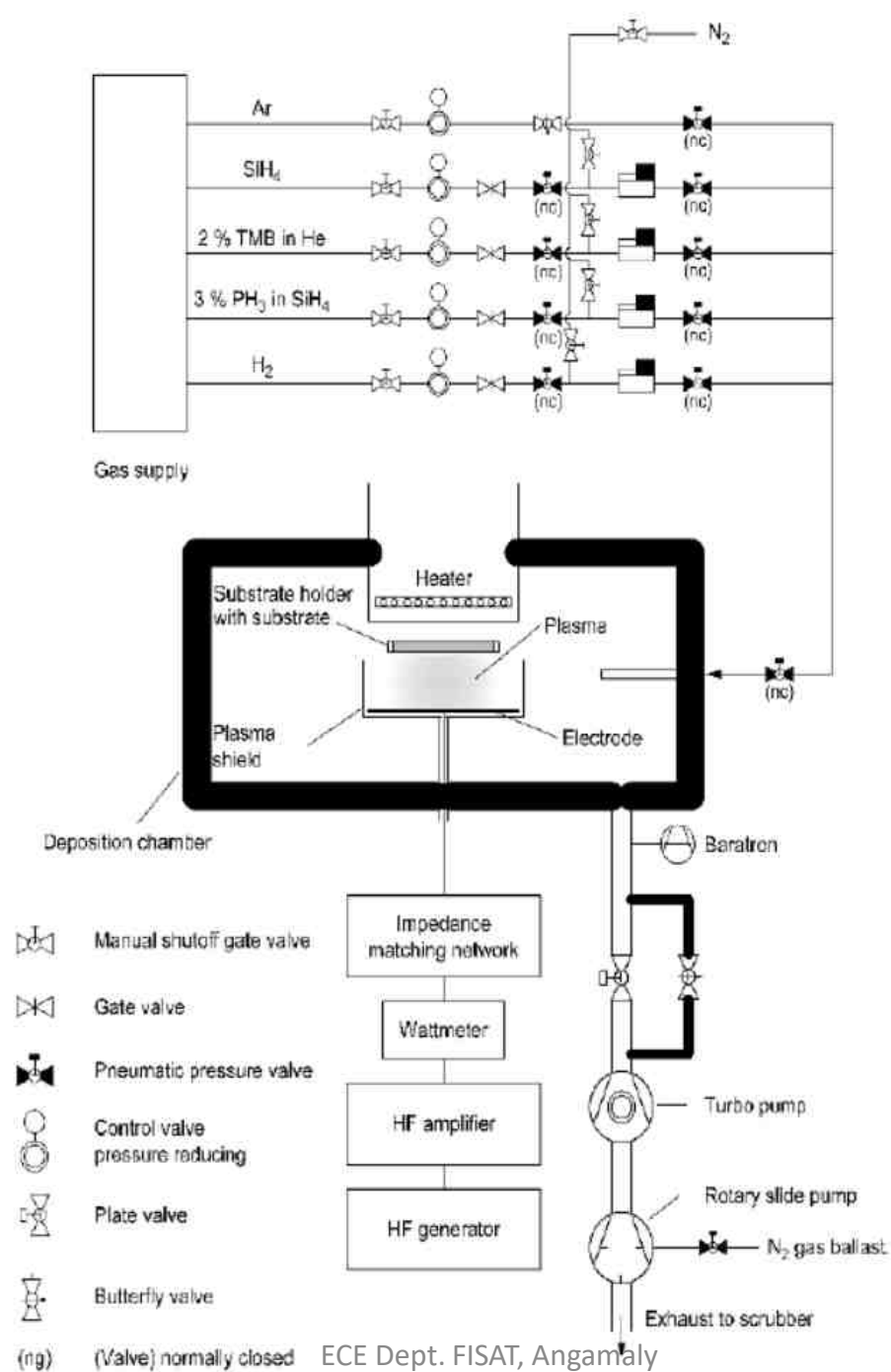
- $\text{SiH}_4$  &  $\text{N}_2\text{O}$

$\text{SiH}_4$ , reacts with  $\text{N}_2\text{O}$  to form  $\text{SiO}_2$ .

# PECVD

- CVD deposition can be supported by an RF plasma.
- An example of an amorphous or micro-crystalline silicon deposition.
- The major difference to the conventional CVD is the addition of Ar for the ignition of the plasma and of H<sub>2</sub>.
- The degree of the SiH<sub>4</sub> content in H<sub>2</sub> determines whether amorphous or microcrystalline silicon is deposited





Block diagram of a PECVD system

# Epitaxy

- The term epitaxy comes from the Greek roots epi, meaning "above", and taxis, meaning "in ordered manner". It can be translated "to arrange upon."
- Epitaxy means the growth of a single crystal film on top of a crystalline substrate.

# Types of Epitaxy

- Homoepitaxy

The film and the substrate are the same material.

Often used in Si on Si growth.

Epitaxiallygrown layers are purer than the substrate and can be doped independently of it.

- Heteroepitaxy

Film and substrate are different materials.

Eg: AlAs on GaAs growth

Allows for optoelectronic structures

Epitaxy is also classified based on the phase from which the film is made:

- **vapor phase epitaxy**

- In vapour phase epitaxy the deposition atoms come from a vapour, so that growth occurs at the interface between gaseous and solid phases of matter.
- A subclass of vapor phase epitaxy is **molecular beam epitaxy (MBE)**.

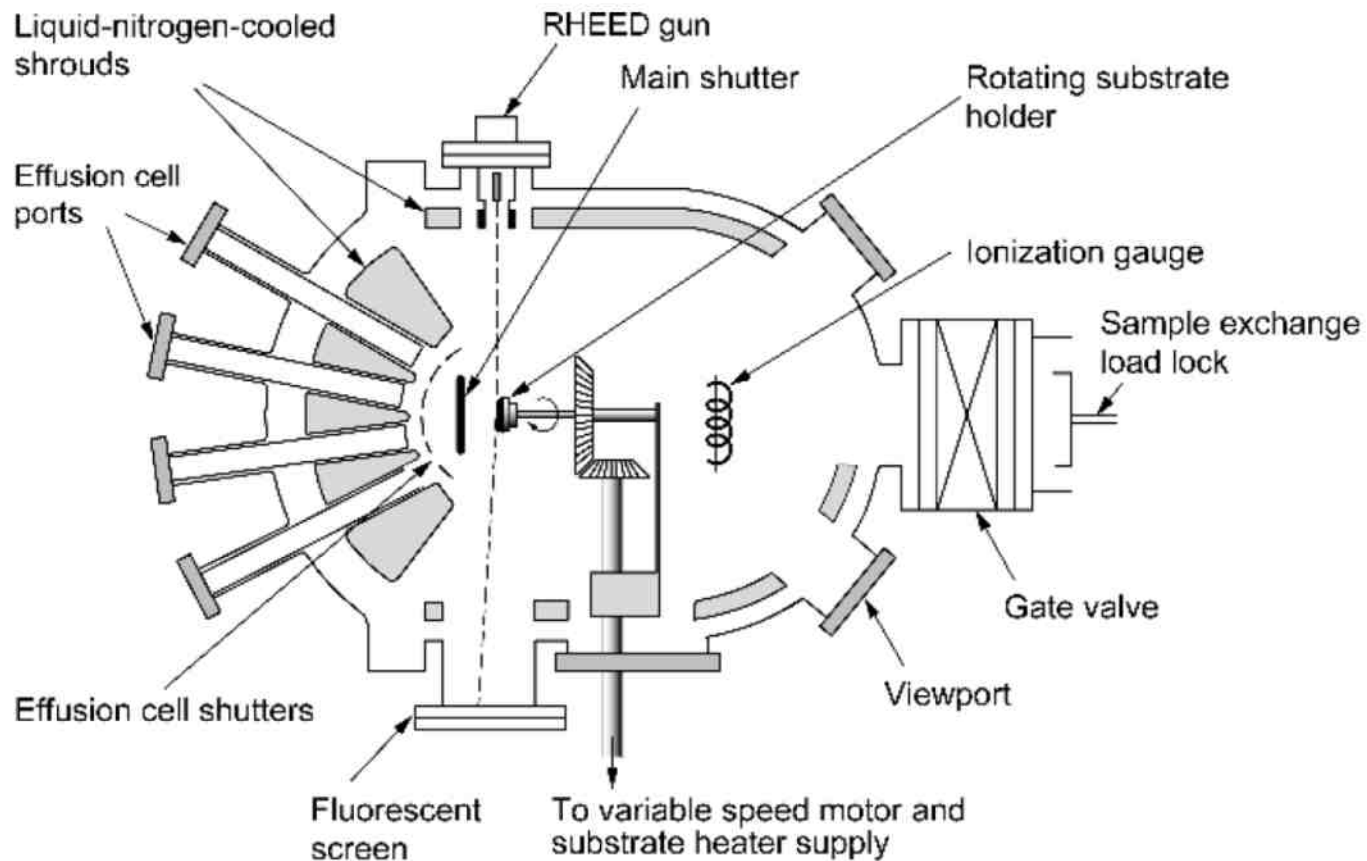
- **liquid phase epitaxy (LPE)**

- Liquid-phase epitaxy (LPE) is a method to grow semiconductor crystal layers from the melt on solid substrates.

- **solid state epitaxy**

- Solid-phase epitaxy (SPE) is a transition between the amorphous and crystalline phases of a material.
- a thin amorphous (noncrystalline) film layer is first deposited on a crystalline substrate, which is then heated to convert the film into a crystalline layer.

# molecular beam epitaxy (MBE)

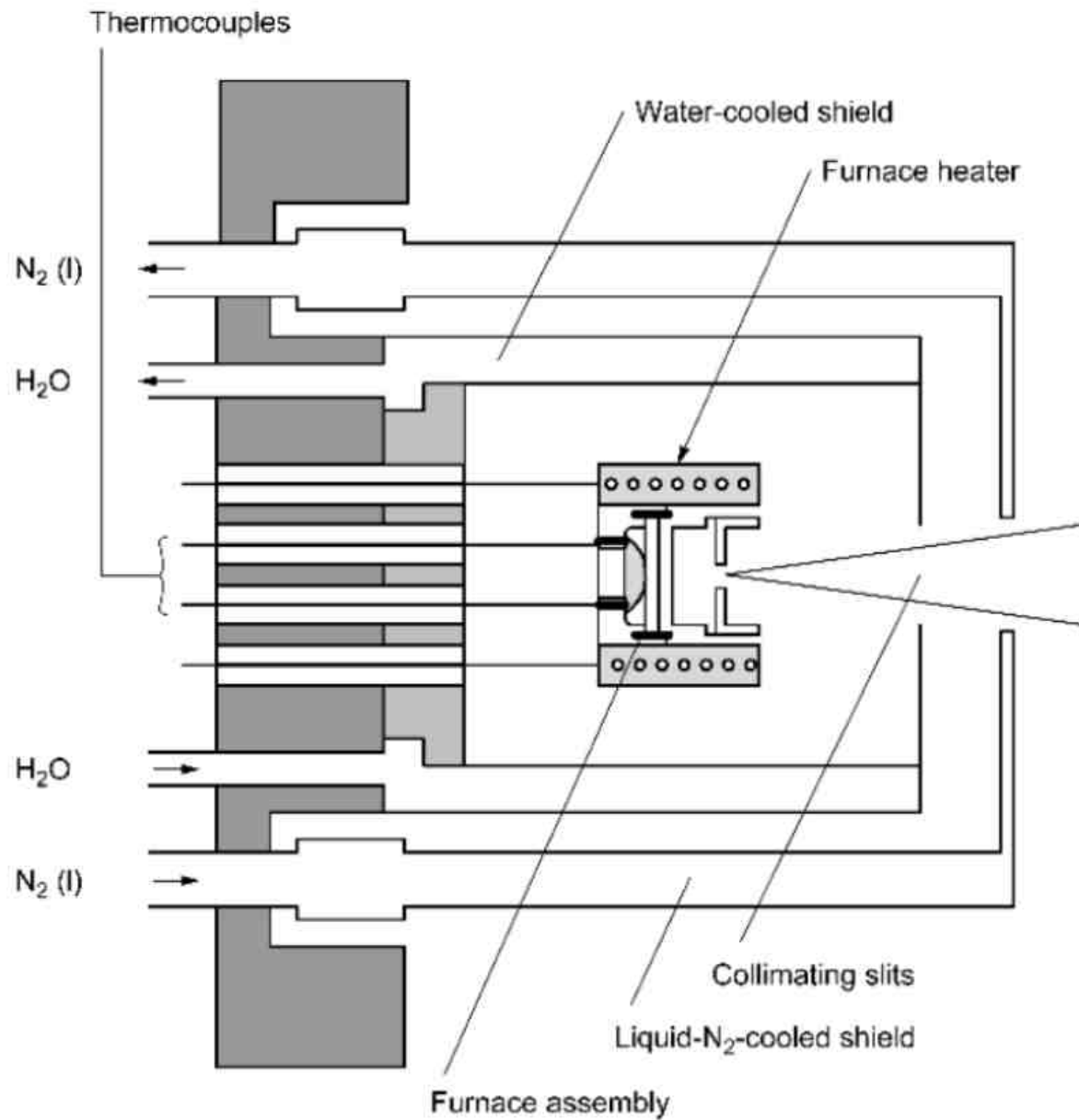


Schematic structure of the MBE as in [59]

- The constituents of the deposited film are contained in mini furnaces as elements, the so-called Knudsen cells.
- During heating some vapor pressure develops and an atom beam is emitted, which is bundled by successive apertures.
- The beam hits the wafer surface to which the atoms remain partially adhered.
- There, they can react with atoms of a second or third beam, which is also directed towards the wafer surface.
- A favorable reaction and finally the film deposition depend on the selection of the parameters.
- The parameters are: wafer temperature, the ratios of the beam densities, the purity of the surface, ..etc

# effusion (Knudsen) cell

- The material to be deposited is contained in the innermost cell which is heated up.
- Its temperature is controlled by a set of thermocouples and resistance heaters.
- A screen cooled with liquid air is installed around the internal cell to avoid high thermal flows to the furnace.



Effusion cell (schematic)



# Liquid Phase Epitaxy (LPE)

- The mixture of Ga and As in a ratio of 50:50 takes over the role of a constituent.
- In other words: GaAs forms a stable compound which is not subjected to any chemical change during the change of temperature.
- Pure GaAs freezes out on the already available solid GaAs by decreasing the temperature and the melt becomes richer in Ga until finally only pure Ga remains.

# Comparison

- LPE VS VPE vs MBE

Do as homework

Process characteristic	LPE	VPE	MBE
Possibility of in situ etching	Yes, through melt back	Yes, through halide reaction with substrates above growth temperatures	No
Further cleaning and monitoring of substrate surface	Not possible	Possible by heat treatment in inert gas, but surface cannot be monitored except by ellipsometry	Yes, by ion bombardment or thermally in UHV. Can be monitored by AES, LEED or RHEED, but there may be electron beam effects
Typical growth rate range	0.1–1.0 $\mu\text{m}/\text{min}$	0.05–0.3 $\mu\text{m}/\text{min}$	0.001–0.03 $\mu\text{m}/\text{min}$
Layer thickness control	$\pm 50\text{ nm}$	$\pm 25\text{ nm}$	Easily $\pm 5\text{ nm}$ , can be $\pm 0.5\text{ nm}$
Substrate temperature (for growth of GaAs on GaAs)	1120 K	1020 K	820 K
Interface control	Segregation and outdiffusion can occur	Autodoping and outdiffusion can occur	Only outdiffusion, but this may occur at enhanced rates under some conditions
Topography	Very difficult to obtain uniformly smooth surfaces over large areas	Can be very smooth but conditions for success are somewhat critical	Extremely smooth surfaces obtained under not very critical conditions. Even initial surface roughness is smoothened out.
Composition control of ternaries and quaternaries	Composition determined by process chemistry	Composition determined by process chemistry	Group III element ratio determined by thermal stability of the source. Group IV ratio by surface chemistry
Total carrier concentration in undoped film	Very low, $(N_D + N_A) \approx 10^{13}\text{ cm}^{-3}$	Low, $(N_D + N_A) \approx 10^{14}\text{ cm}^{-3}$	Rather high, $(N_D + N_A) \geq 10^{16}\text{ cm}^{-3}$

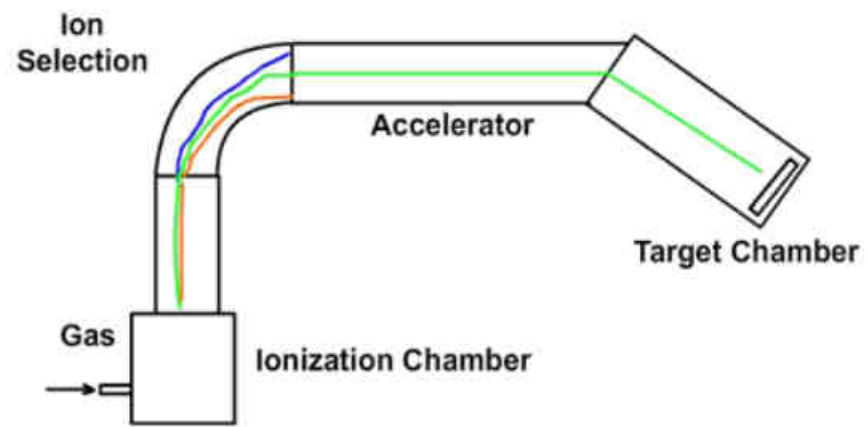
# Ion Implantation

- The depth of doping and the quantity of doping can precisely control.
- Ion implantation is a doping technique with which ions are shot into a substrate (e.g., a silicon wafer) using an accelerator.
- The desired ion species is let in as a gaseous compound through a needle valve
- The compound is ionized with an electron beam.
- The arising ions are pulled out of the source area and brought to an energy of 30 keV by a preliminary acceleration .
- Then, the ions pass through a magnetic field filter which is adjusted in such a way that only the desired ion type can run into the acceleration tube.
- At the end of the accelerator tube the ions acquire a total energy of 360 keV.

- The beam can be scanned upwards and downwards or left and right.
- The beam current is measured by an ammeter, which is connected to the substrate.

Equipment can divide into four sections

- Ionizing chamber
- Ion selection chamber
- Acceleration chamber
- Doping chamber



• Schematic of the ion implanter

# Ionizing chamber

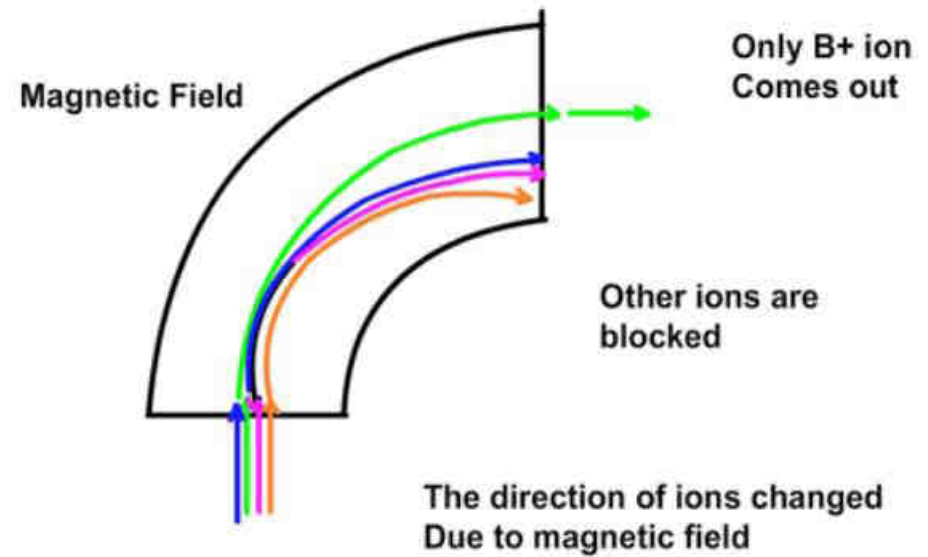
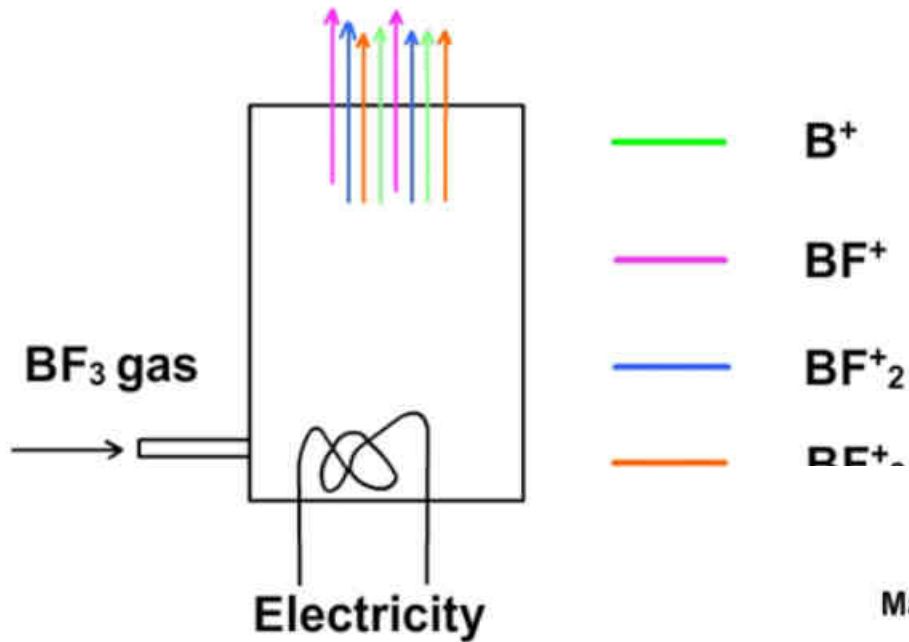
- For doping boron, boron trifluoride ( $\text{BF}_3$ ) is used. It has to be heated and evaporated.
- The atoms in  $\text{BF}_3$  must be converted to ions. In the ionizing chamber, a low pressure is maintained and a tungsten filament is heated using electricity
- When it is very hot, electrons are emitted from the filament in a process called thermionic emission.
- Some of the electrons hit the  $\text{BF}_3$  molecules and create ions such as  $\text{BF}_3^+$ ,  $\text{BF}_2^+$ ,  $\text{BF}^+$  and  $\text{B}^+$ .
- Thus ions are created from the gas.

# Ion selection chamber

- We would like to dope the wafer with boron only and not with fluorine.
- Hence only  $B^+$  must be selected from the mixture of ions and added to the wafer.
- In order to select the required ion ( $B^+$ ), electric field and magnetic field are used.
- If we send the stream of ions between two electric plates, which have positive and negative connection, the ions will be attracted to the negative plate and move towards the negative plate.
- If a magnetic field is also applied at the same time, the direction of the movement will change.
- The speed and the direction of the movement will depend on the charge and the mass of the ions.
- A plate with a hole in the appropriate place can be used to block all the ions except the desired one.
- Thus  $B^+$  ion can be separated from the mixture of ions.

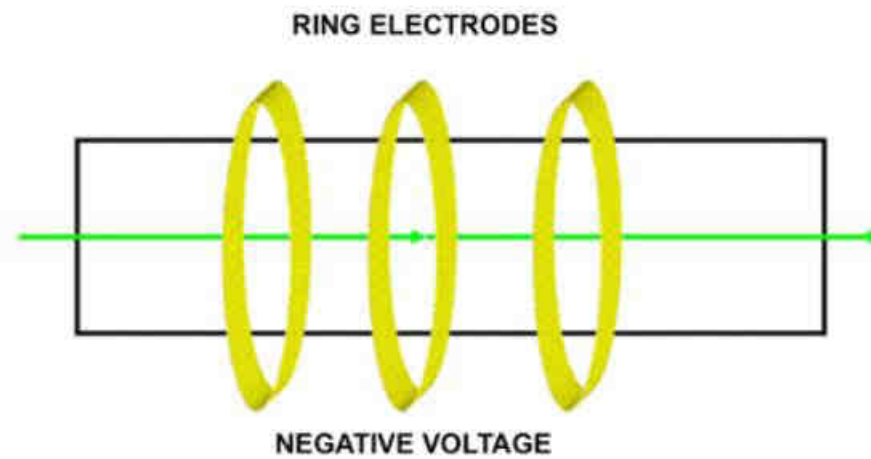


## Many Types of ions



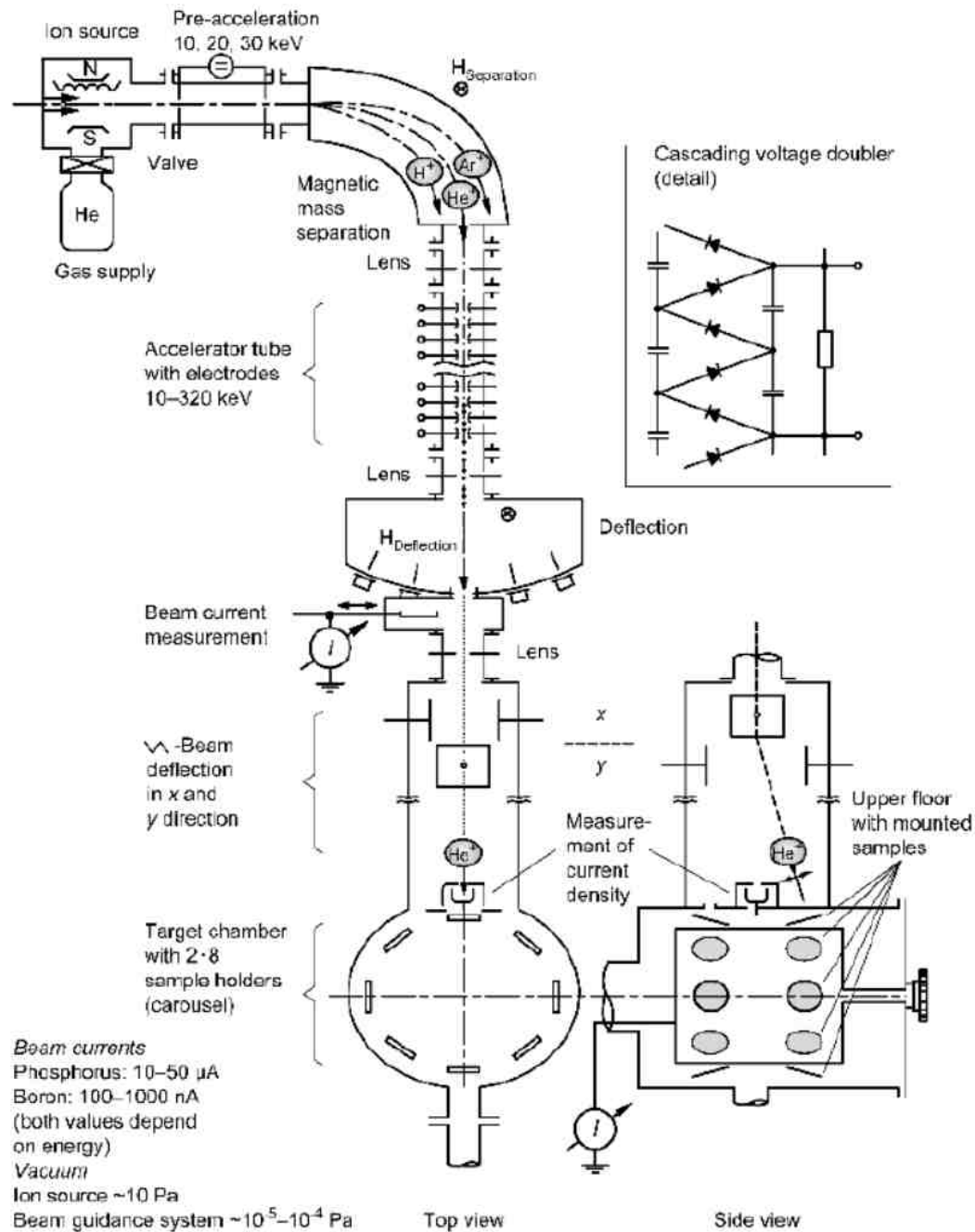
# Accelerating chamber;

- In order to ensure that they penetrate the wafer, they must be accelerated.
- For this, a set of ring electrodes are used .
- If negative charge is applied on the plates, the ions will get accelerated considerably.
- They form what is called as “ion beam”.
- The ionizing chamber must be kept under high vacuum.



# Doping chamber

- Ions will fall on the wafer
- using electrodes, the beam is moved by applying suitable positive and negative voltages.



# ***Calculation of the Implantation Time***

- Typical required dose values  $N_I$  lie between  $10^{12}$  and  $10^{16}$  cm<sup>2</sup>.
- The necessary implantation time depends on the available beam current,  $I$ , substrate surface,  $A$ , and on the charge of the ions.

$$Q = q N_I A,$$

$$t = \frac{Q}{I} = \frac{q N_I A}{I}.$$

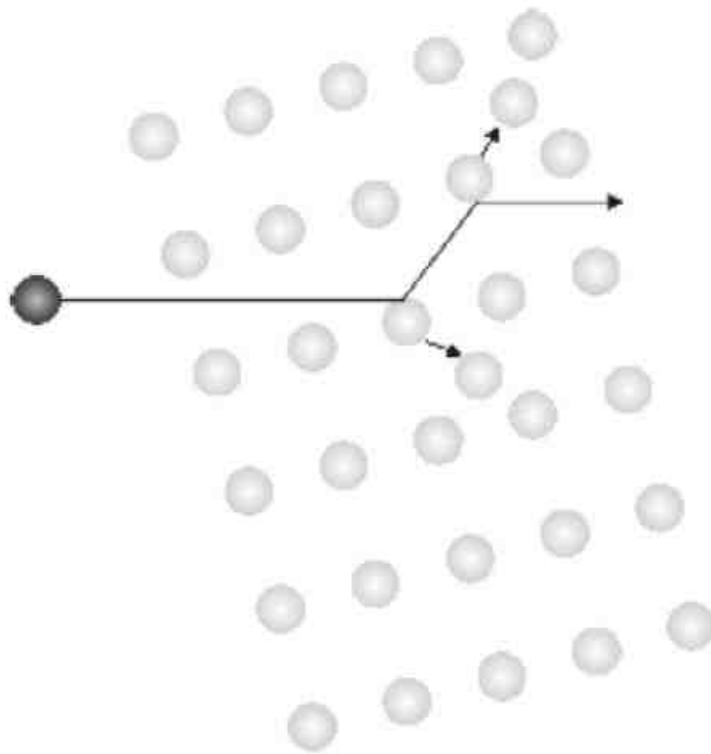
- As an example, an ion current of 1  $\mu$ A, a substrate surface of 100 cm<sup>2</sup>, and a dose of  $10^{13}$  cm<sup>2</sup> deliver a time of 160 s.

# ***Radiation Damage***

- The penetrating ions pass through the lattice depending on the ion mass/lattice atom mass ratio and the momentary velocity in a zigzag path.
- At the path, the ions collide on host lattice atoms, which leave their places and go to the interstitial site. Thus, lattice defects of different nature develop.
- The defect produced by the displacement of a lattice atom into an interstitial site is called Frenkel defect.
- Double vacancies can be formed if the ion dislodges two nearest neighbor lattice atoms
- Dislocation lines anneal only at high temperatures (1000 °C), and very often they do not anneal at all in implanted layers.

- If many lattice atoms are displaced by an impact ion in a considerably small volume, a locally amorphized area develops. Often, this area is known as cluster.
- Annealing is applied for both the annealing of lattice defects and for the relocation of the doping atoms from interstitial sites into lattice sites.
- Annealing is the process of thermal treatment of the implanted samples at approximately 900–1100 °C in a suitable atmosphere like nitrogen or hydrogen gas.





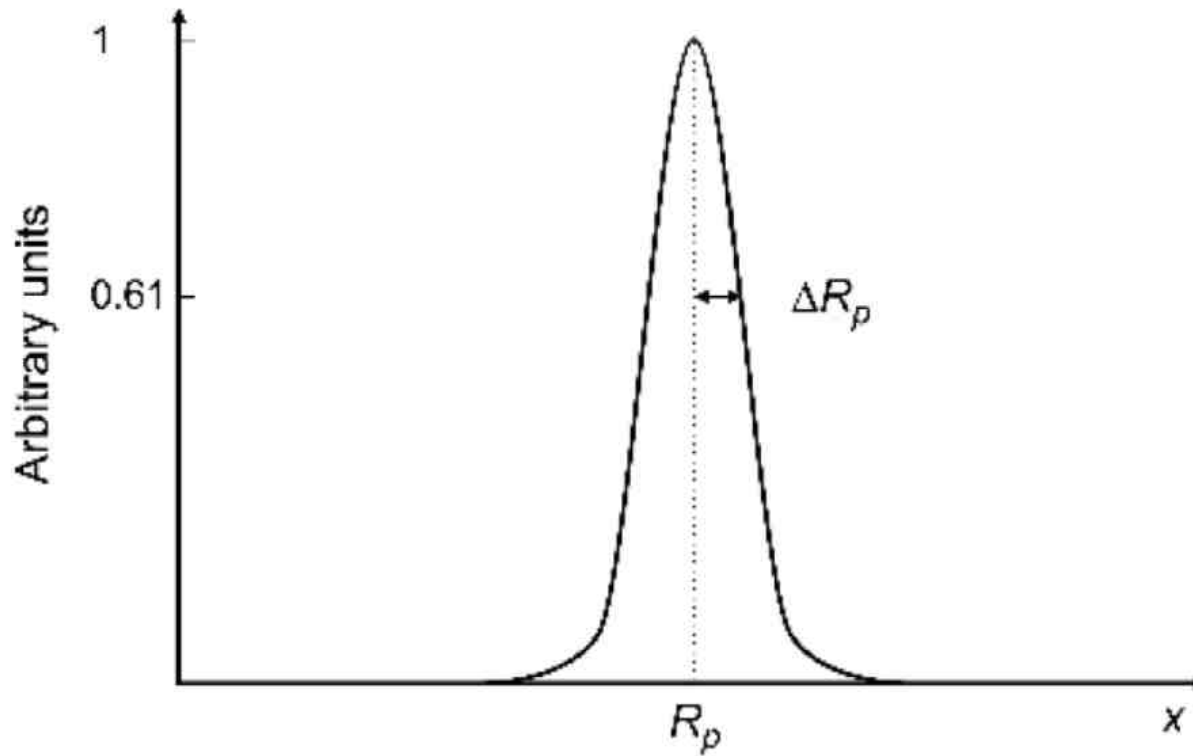
Path of an implanted ion in a lattice

# *Implantation Profile*

- The distribution of the implants is described by a Gaussian curve:

$$N(x) = N_{\max} e^{-\left(\frac{x-R_p}{\Delta R_p \sqrt{2}}\right)^2}$$

- $R_p$  is the position of the center of the distribution,  $\Delta R_p$  is the full width.

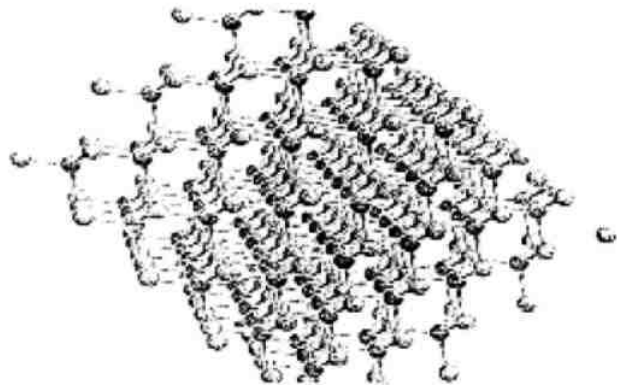
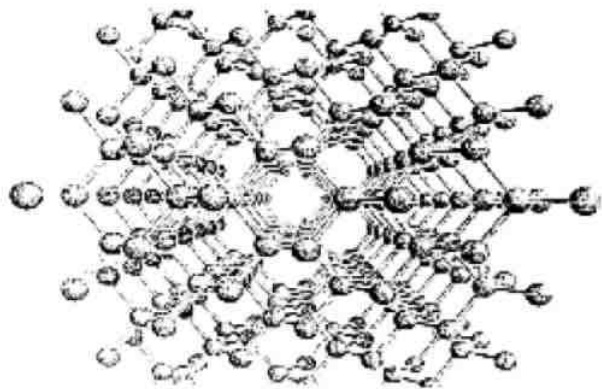


..... Simplified distribution of the implants in the substrate

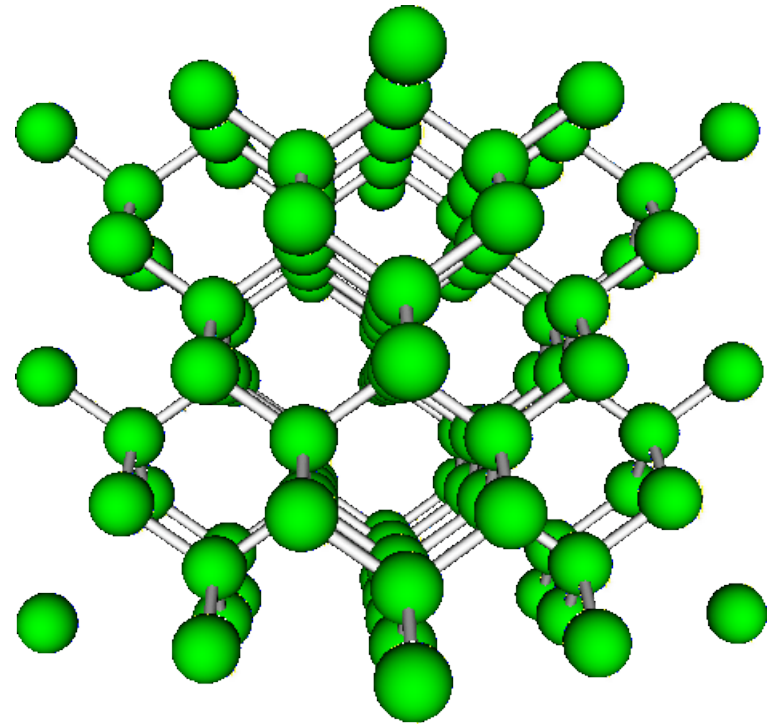
$$\int_0^{\infty} N(x) \, dx = N_I$$

$$N_{\max} \cong 0.4 N_I / \Delta R_p .$$

- If one shoots toward a low indexed crystal orientation, then the ion beam runs without resistance through the lattice channels and reaches substantially large depths (*channeling*).
- Channeling is avoided by tilting the crystal, which is aligned in (110) direction against the ion beam, usually by  $7^\circ$ .

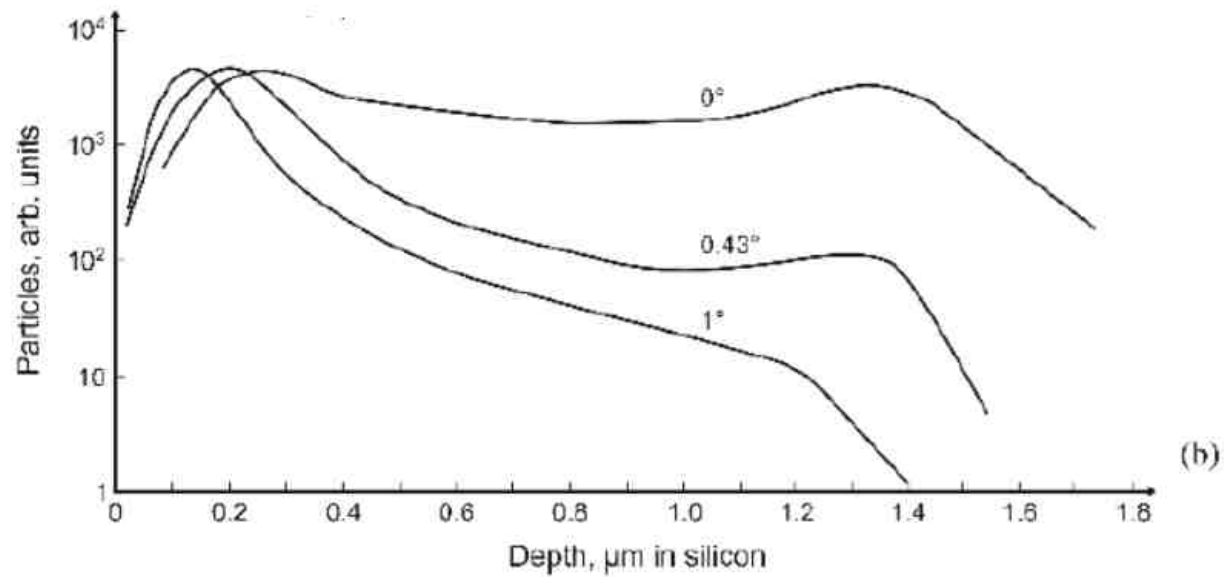
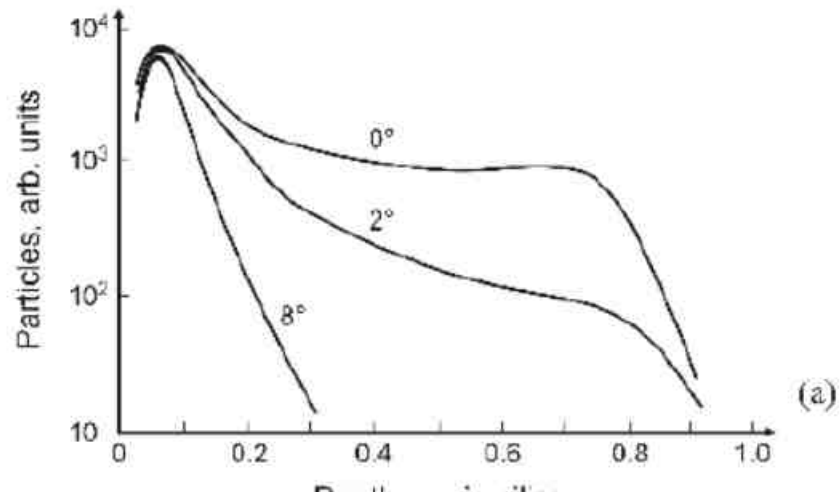


(a)



(b)

(a) Si crystal in (110) direction and (b) misaligned by  $7^\circ$



Dependency of the depth distribution of  $^{32}\text{P}$  after 40 keV (a) and 100 keV (b) implantation. The angles indicate the deviations from the (110) direction [64].

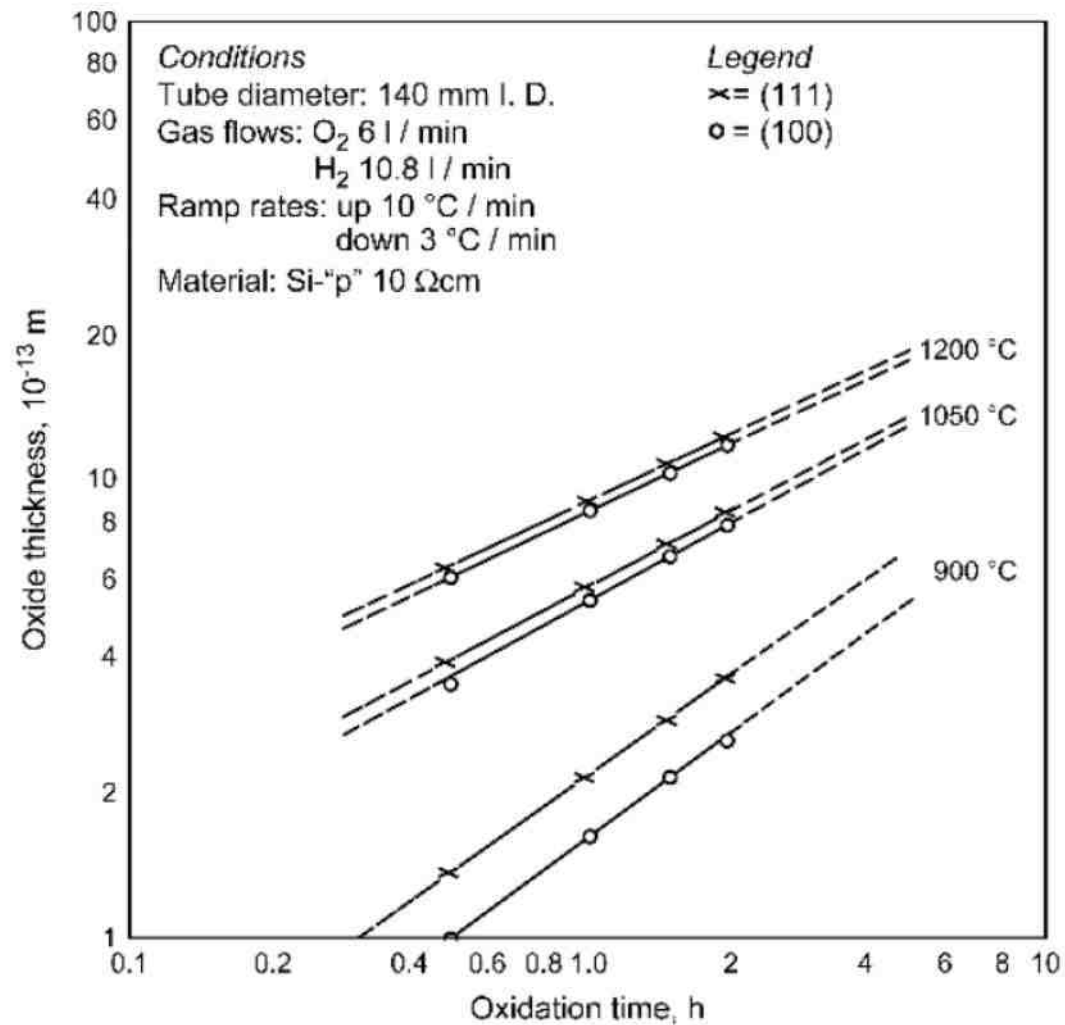
# Formation of Silicon Oxide

- Thin oxide layers are contained in almost all electronic devices.
- SiO<sub>2</sub> can create in different ways
  - Thermal Oxidation
  - CVD : PECVD & TEOS
  - Anodic Oxidation
  - SOI(Silicon on oxide)

# Thermal oxidation.

- Si wafer is cleaned so that any impurity on the surface is removed.
- Then, the wafer is heated to a temperature of about 1100 °C.
- A flow of an oxidizing gas, either pure oxygen (*dry oxidation*) or nitrogen driven through water (*wet oxidation*), is maintained.
- When oxygen penetrates into the substrate, the Si surface reacts with the oxygen and forms silicon dioxide.
- Above process requires highest cleanliness, which is the critical step for the production





Oxide thickness vs. oxidation time (wet oxidation)

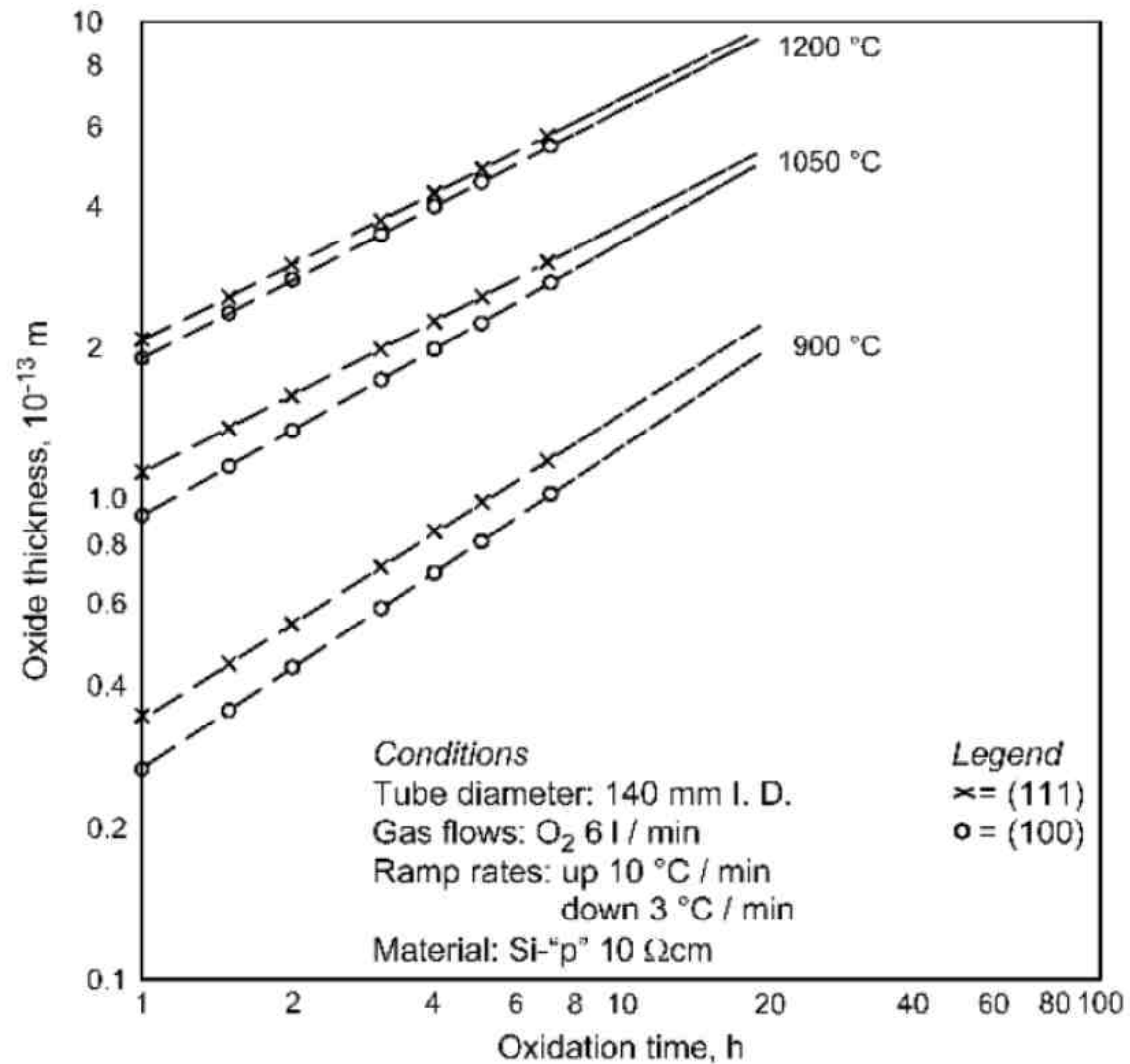
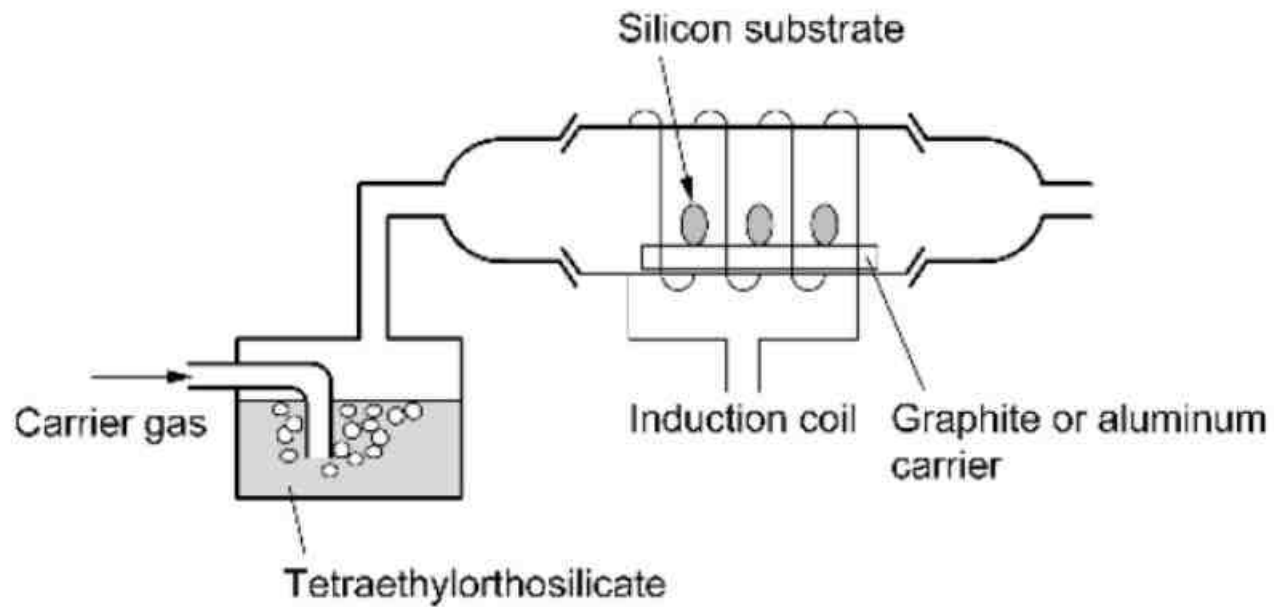


Figure 1. Oxide thickness vs. oxidation time (dry oxidation)

- The chemical reaction occurring at the silicon surface during dry oxidation is
- $$\text{Si} + \text{O}_2 \rightarrow \text{SiO}_2 \text{ -----DRY OXIDATION}$$
- And for wet oxidation is
- $$\text{Si} + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2 + 2\text{H}_2 \text{ -----WET OXIDATION}$$
- **Dry oxidation** has a lower growth rate than wet oxidation although the oxide film quality is better than the wet oxide film.
- wet oxidation process has a significantly higher oxidation rate than the dry oxidation. Hence it is used to grow thick oxides

# TEOS

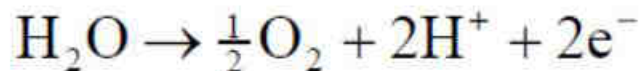
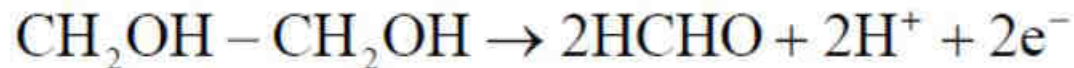
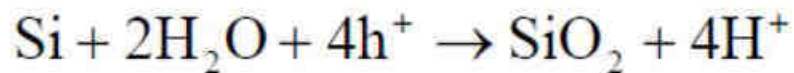
- A feed gas (usually nitrogen) is driven through a container filled with tetraethylorthosilicate (TEOS).
- The enriched nitrogen flows to the wafers where  $\text{SiO}_2$  is deposited on their surfaces.
- The deposition is maintained at a temperature of about 650 to 850 °C.
- deposition temperature (>650 °C) prevents use
- In order to obtain lower deposition temperatures, ozone, is required.
- After adding some few molar per cent of ozone, the optimum deposition temperature is reduced to 400 °C.



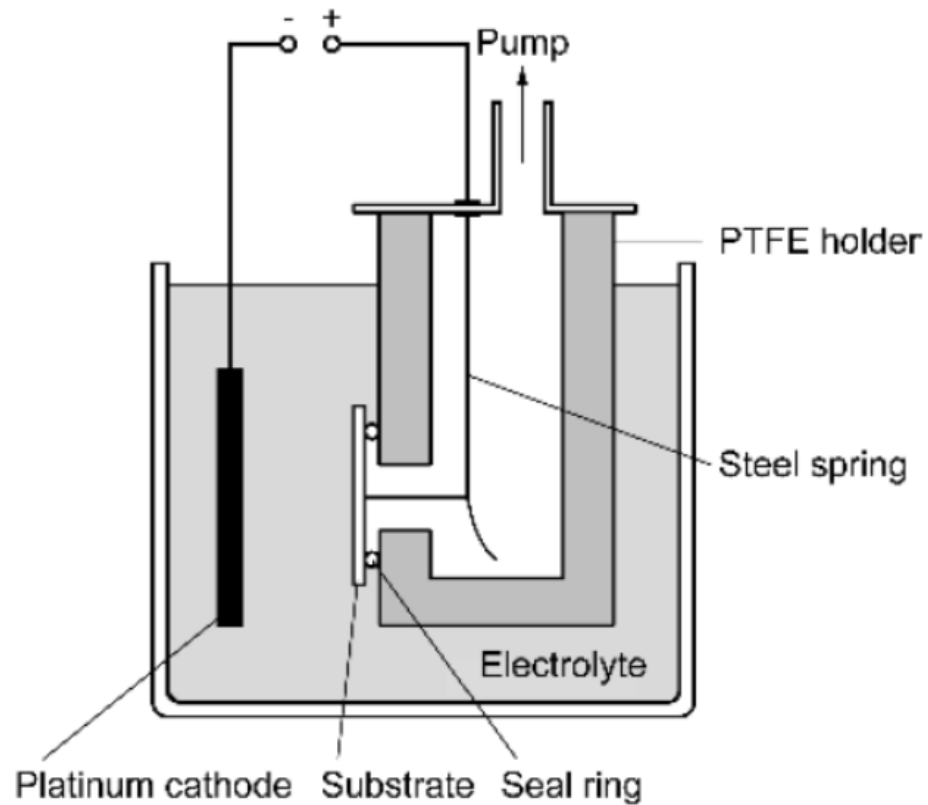
TEOS process

# anodic oxidation

- The wafer is immersed into a 0.04 M solution of KNO<sub>3</sub> in ethylene glycol (CH<sub>2</sub>OH)<sub>2</sub>. with a small addition of water.
- After mounting it to a holder with a vacuum, it is positively charged, while a platinum disk acts as a backplate electrode.



- The quality of the oxide is too low, and the process is time-consuming.



Assembly of the anodic oxidation of silicon

# SOI

- The implantation of oxygen up to the dose and its reaction with silicon to form  $\text{SiO}_2$ .
- SOI has gained in importance because of better radiation resistance and heat distribution compared to conventional technologies

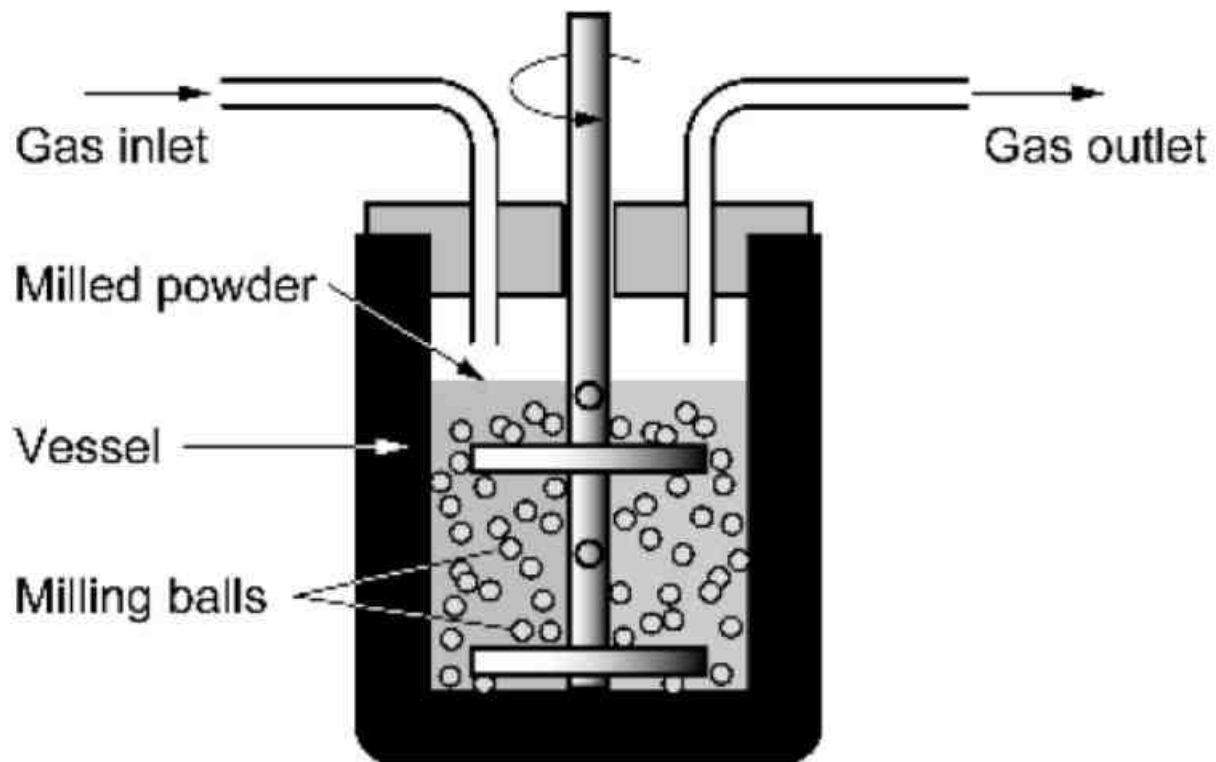


# Nanoparticles

- A nanoparticle is defined as a ball or a ball-like molecule which consists of a few 10 to some 10,000 atoms interconnected by interatomic forces.
- The deposited nanoparticle layers are different from uniform layers, particularly due to the presence of grain(rough) boundaries.

# Grinding with Iron Balls

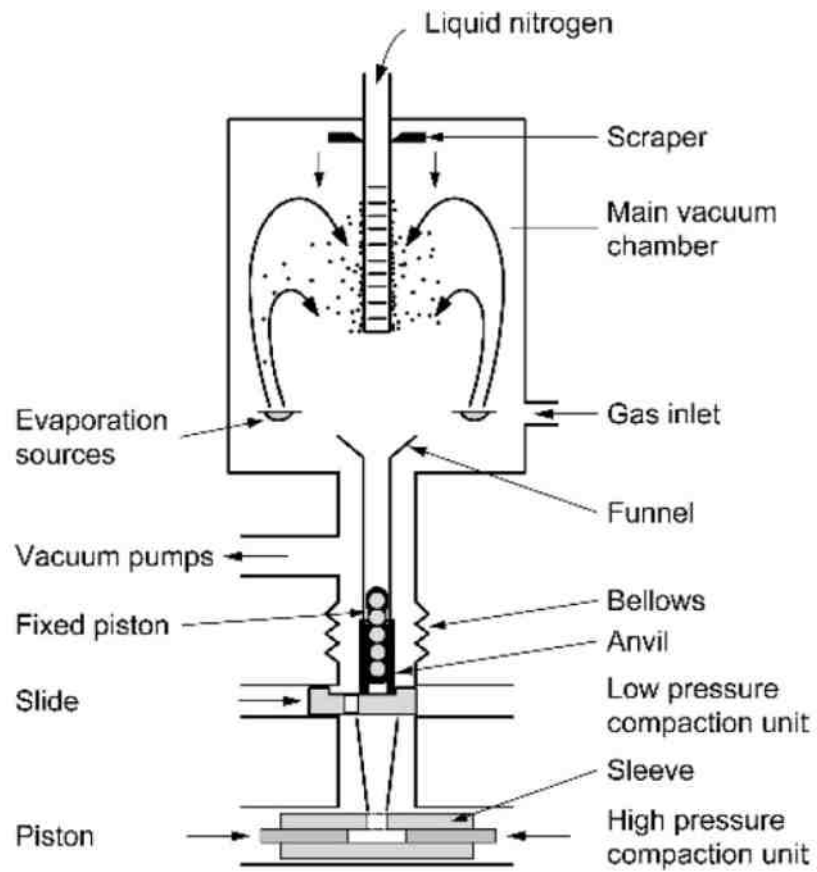
- Container is filled with stainless steel balls of a few millimeters in diameter.
- The material to be crushed is added in the form of a powder of about 50  $\mu\text{m}$  diameter grain size.
- After filling the container with liquid nitrogen, a rotating shaft grinds the material.
- The grinding periods are within the range of minutes to some 100 hours. This process is simple



Ball mill for the fabrication of nanoparticles

# Gas Condensation

- The operation occurs in an evacuated chamber with a pressure of  $10^{-5}$  Pa.
- After mounting the raw material on one or more crucibles, it is evaporated thermally, by an electron gun, or by ion sputtering.
- The evaporated atoms or molecules unite and form particles of different sizes.
- Finally they are captured and collected with a funnel.
- The particle diameter is usually within the range of 5 to 15 nm.



System for inert gas condensation of nanocrystalline powder:

# Laser Ablation

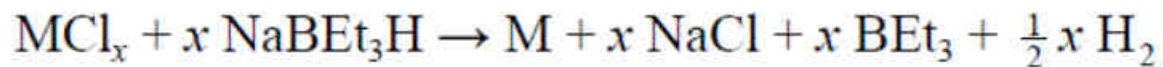
- The raw material is provided as a solid.
- Its dissolution is achieved by a focused laser beam—similar to the cutting of a metal or a semiconductor.
- The advantage of this procedure is a 1:1 transfer of the material composition from the raw material to the particles.

# Thermal and Ultrasonic Decomposition

- As an example of thermal decomposition, the starting material iron pentacarbonyl,  $\text{Fe}(\text{CO})_5$ , is considered.
- It decomposes in a polymeric solution, e.g., polybutadiene, and thus produces iron particles of 7 to 8 nm diameter.
- The material can also be decomposed as immersion in decane by ultrasonic irradiation, resulting in particle sizes roughly between 6 and 240 nm.

# Reduction Methods

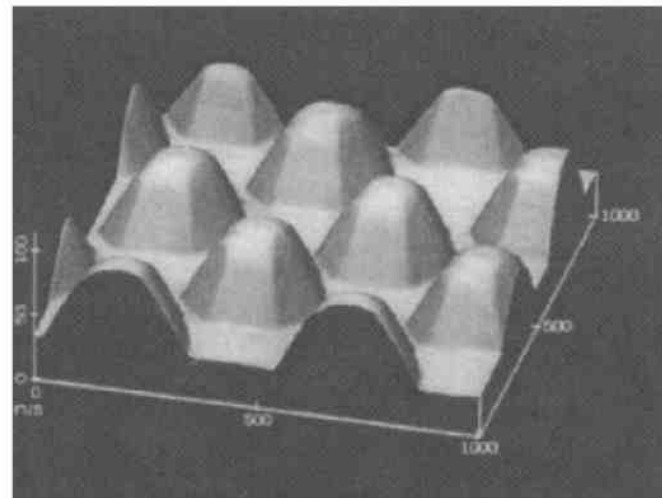
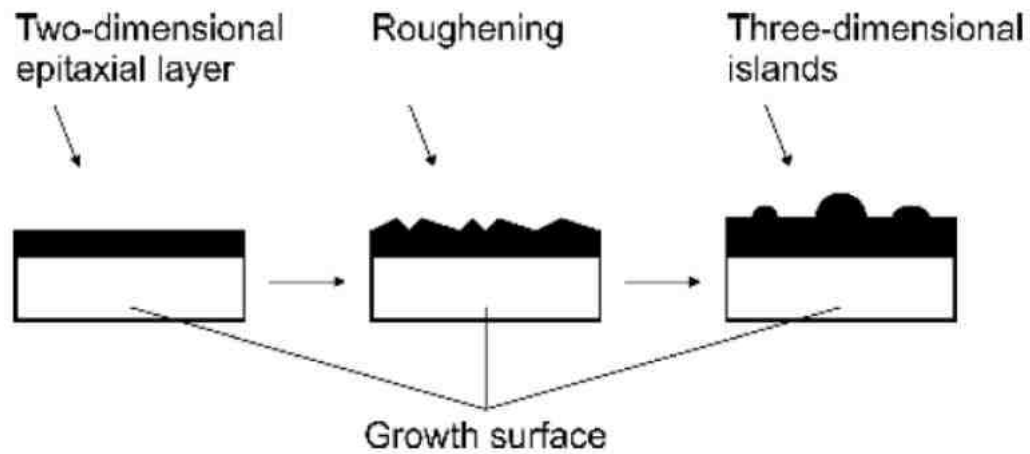
- Some metal compounds (e.g., chlorides) can be reduced to elementary metallic nanopowder by the application of NaBEt<sub>3</sub>H, LiBEt<sub>3</sub>H, and NaBH<sub>4</sub>.
- For example, the reaction equation can be written as (M: metal, Et: ethyl):





# Self-Assembly

- Three-dimensional islands are formed with a rather surprising regularity on a substrate.
- Two extremes can occur: regular layer-on-layer growth and cluster formation.
- The first case is comparable with the picture of butter on bread, and the second one with water drops on butter.
- With sufficient film thickness the film will form three-dimensional islands as shown



Self-assembled  $\text{As}_{0.5}\text{Ga}_{0.5}\text{As}$  islands on  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$

# Low-Pressure, Low-Temperature Plasma

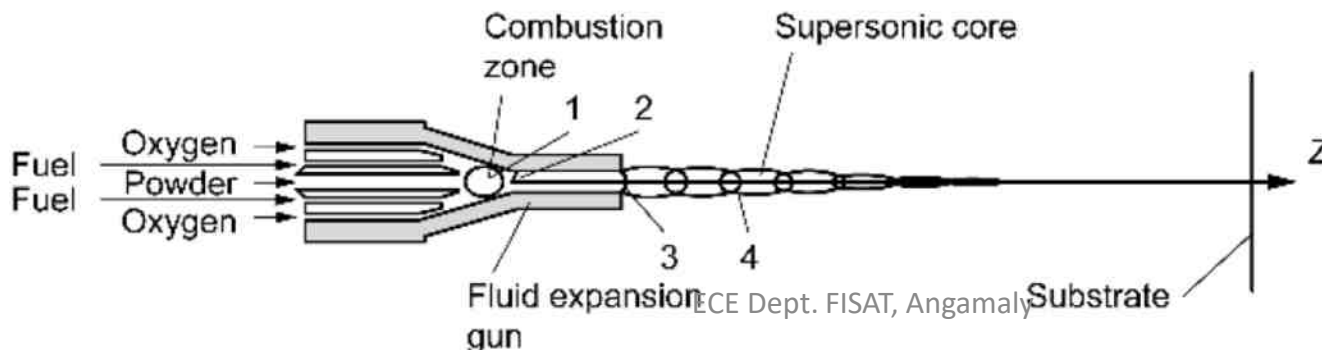
- A conventional capacitively coupled RF plasma device.
- A gas (e.g., silane) is let in at a pressure of 1 to 200 Pa.
- An inert gas is ionized by the applied field. The electrons acquire kinetic energy and, in return, ionize neutral molecules of silane upon impact.
- Dissociation of silane happen after impact with electron of higher energy.
- These ions form the nanoparticles

### Dissociation products after impact of an electron with silane

Products	Threshold energy, eV
$\text{SiH}_2 + 2\text{H} + \text{e}^-$	8
$\text{SiH}_3 + \text{H} + \text{e}^-$	9
$\text{SiH} + \text{H}_2 + \text{H} + \text{e}^-$	10
$\text{Si} + 2\text{H}_2 + \text{e}^-$	12
$\text{SiH}^* + \text{H}_2 + \text{H} + \text{e}^-$	10.5
$\text{Si}^* + 2\text{H}_2 + \text{e}^-$	11.5
$\text{SiH}_2^+ + \text{H}_2 + 2\text{e}^-$	11.9
$\text{SiH}_3^+ + \text{H} + 2\text{e}^-$	12.3
$\text{Si}^+ + 2\text{H}_2 + 2\text{e}^-$	13.6
$\text{SiH}^+ + \text{H}_2 + \text{H} + 2\text{e}^-$	15.3
$\text{SiH}_3^- + \text{H}$	6.7
$\text{SiH}_2^- + \text{H}_2$	7.7

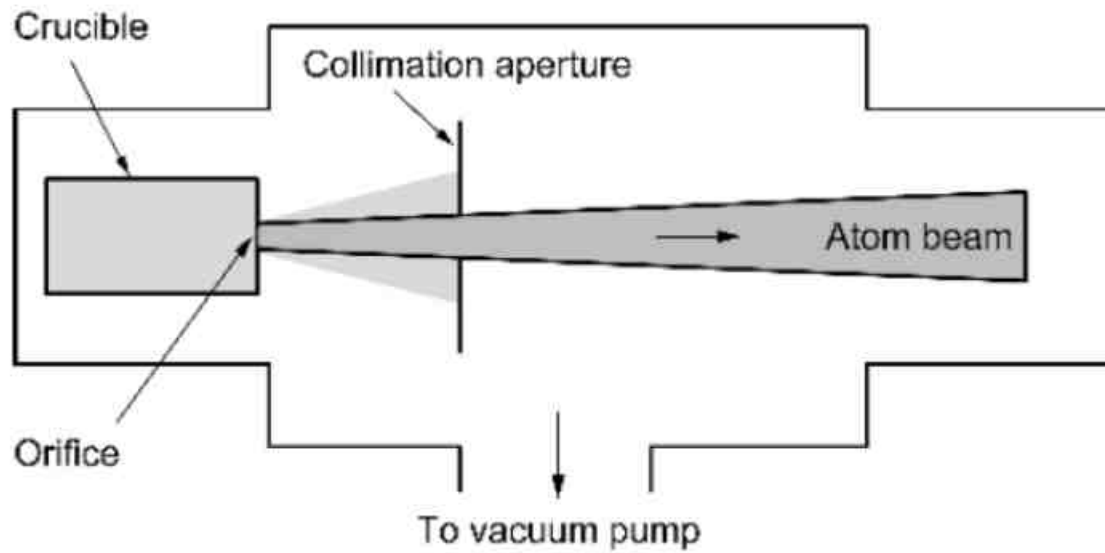
# Thermal High-Speed Spraying of Oxygen

- Thermal spraying is a procedure for Nano crystalline cover layers.
- A burn reaction produces high temperature and high pressure within a spray gun.
- The pressure drives particles of a Nano powder contained in the pistol through a nozzle onto the surface which is to be covered.

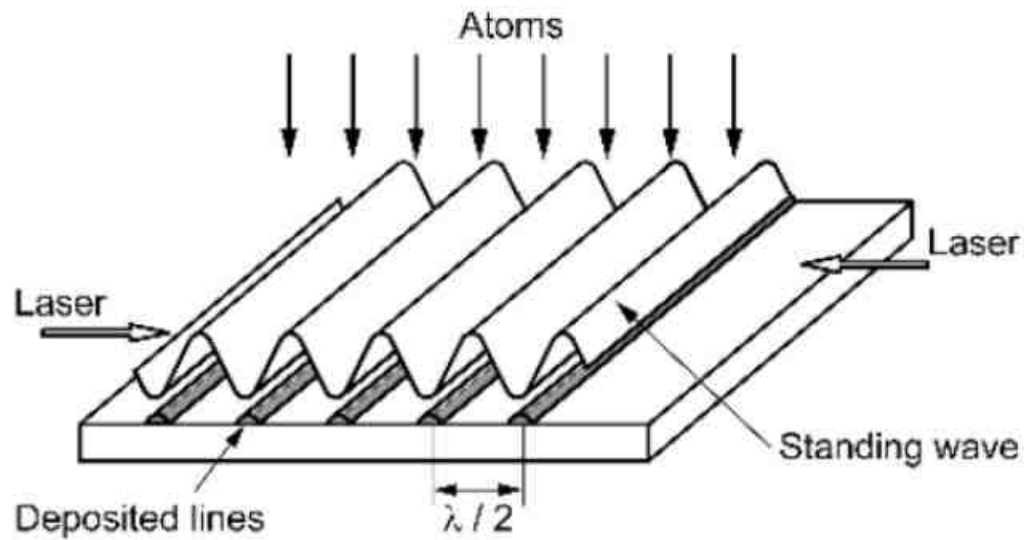


# Atom Optics

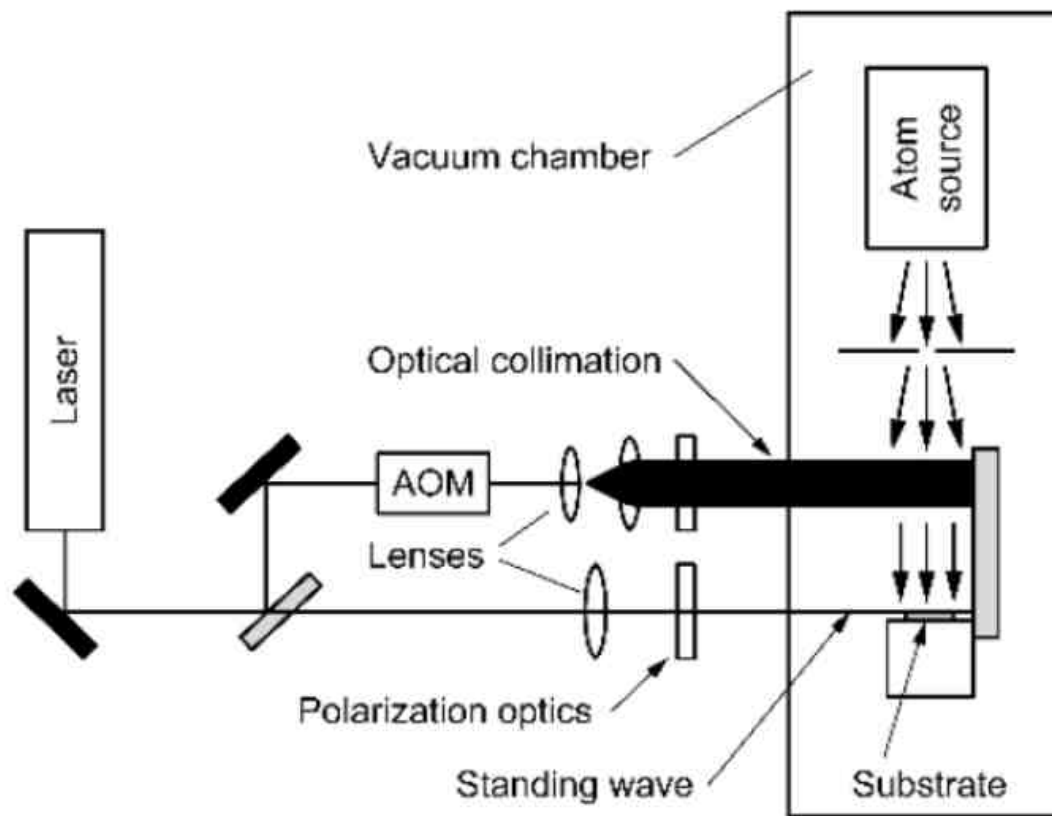
- An atom beam which is produced by heating up a material in a crucible is assumed.
- The beam is bundled by one or more apertures and steered onto the substrate
- The beam is subjected to the dipole forces of a standing wave which is produced by a laser beam.
- The atoms will deviate to the nodes of the standing wave where they are subjected to the smallest forces.
- A lattice pattern reflecting the wavelength of the laser is produced.
- A second standing wave may be used perpendicularly to the first and to the direction of the beam for a two-dimensional pattern of deposited atoms



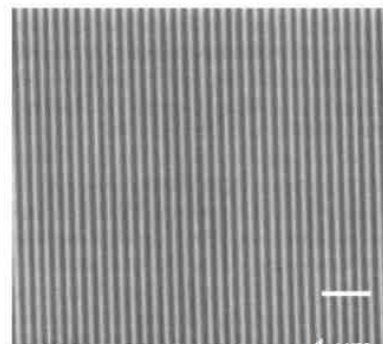
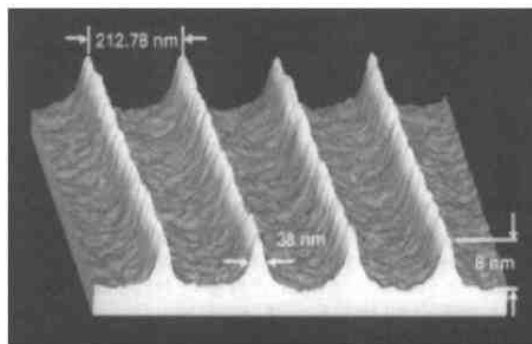
Manufacture of an atom beam



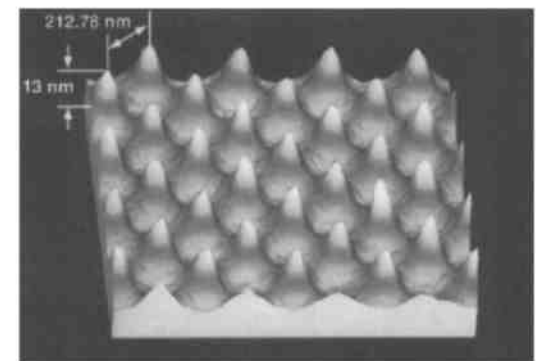
Lens arrangement with a standing wave



Assembly for atom focusing in a standing wave



AFM images of a one-dimensional lattice with 212 nm pitch and 38 nm line width formed by laser-focused atom deposition of chromium

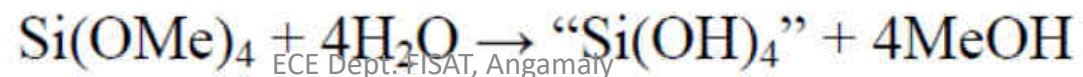


AFM images of a two-dimensional lattice formed by laser-focused Cr deposition



# Sol Gels

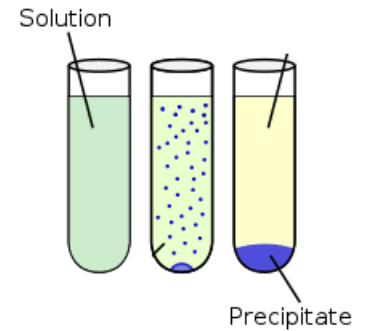
- A sol (hydrosol) is a colloidal dispersion in liquid.
- A gel is a jelly-like substance formed by coagulation of a sol into a gel.
- The best known example of a sol gel process is probably the production of SiO<sub>2</sub>.
- A catalyst (acid or base) is added to a solution of tetramethoxysilane (TMOS), water, and methanol. This leads to the formation of Si–OH groups:



- Further dehydration reduces the “ $\text{Si(OH)}_4$ ” to  $\text{SiO}_2$  gel.
- During the reaction, the gel reaches a viscosity so low that it can be applied onto a centrifuge and distributed over the wafer.
- Then  $\text{SiO}_2$  layers are produced by annealing over  $800^\circ\text{C}$ .

# Precipitation of Quantum Dots

- Quantum dots are three-dimensional semiconductor materials and falls in the category of nanopartilces.
- **Precipitation** is the creation of a solid from a solution.
- When the reaction occurs in a liquid solution, the solid formed is called the 'precipitate'.
- The chemical that causes the solid to form is called the 'precipitant'.
- Precipitation is still used in the manufacturing GaAs, and Si nanocrystallites in silica glasses.
- The contaminants are added to the melt, and after a further annealing step from 600 to 1400 °C, they form precipitates of controllable size.



- Quantum dots can also be manufactured by means of electron beam lithography.
- The material which is to be converted into quantum dots is deposited on a substrate like GaAs via MBE.
- 
- The size of the electron beam spot determines the smallest possible size of the quantum dot.
- Therefore, if the wafer is etched, islands of this size remain. They are further reduced by etching so that quantum dots of a few 10 nm can be produced.