Nanoelectronics: Devices and Materials
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Lecture - 35
Quantum structures and devices

Hello again. So, we get on with this segment of the course on Nanoelectronics Device Fabrication and characterization.

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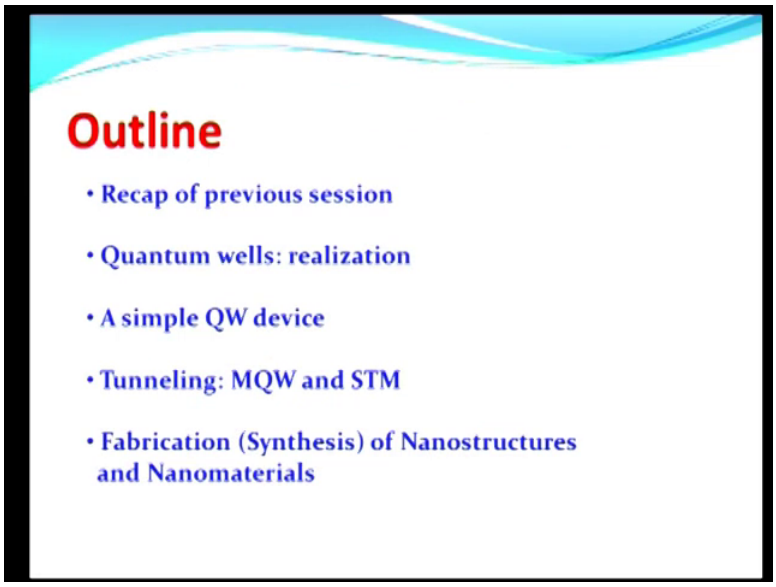

In the previous session we learned about quantum wells and quantization of energy in such confined quantum wells confining wells and how interacting wells, particle motion in interacting wells leads to splitting of energy levels and that can then be taken on to understand the concept of bands of energy, how bands of energy are formed from atomic levels in isolated atoms when these atoms are put together in a condensed fashion into a crystal, and these bands of energies have different widths depending on whether they represent the inner core levels or the outer cover levels.

The inner core levels forming relatively narrow bands of energy in terms of the energy width of these bands whereas, the outer core or the valence electrons form much wider bands. And if I have not mentioned the width of these bands at the outer edge of atoms that is the valence electron bands or bands representing valence electrons then that width is typically a few electron volts.

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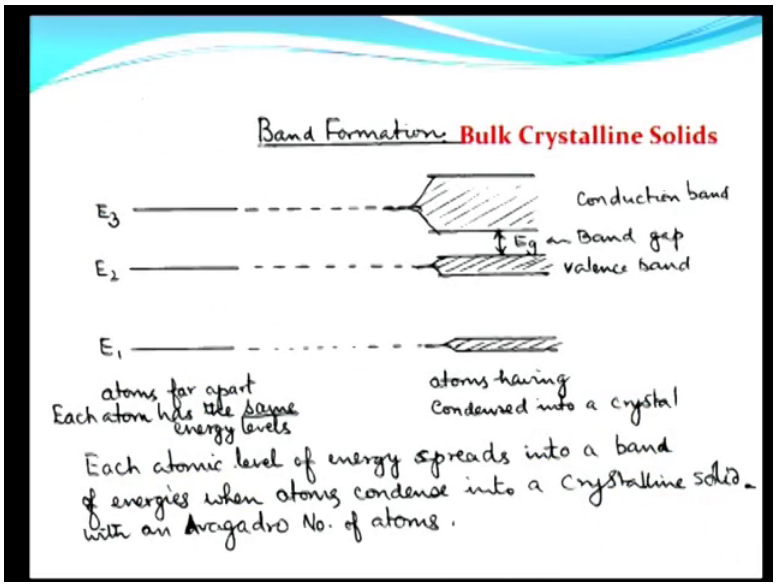

Now, to recap what we have here is a representation of the formation of bands and what I meant was that the width of this band representing the outer electrons the conduction band or even the valence band for the for that matter, is of the order of a few electron volts and in semiconductors. For example, or insulators as opposed to metals there is a gap in energy a so called forbidden energy region, where electrons cannot have their states, this band this difference between the bottom of the conduction band. And the top of the valence band represents the energy band gap which you are very familiar with about 1.1 ev for silicon, 1.43 ev for gallium arsenide for example.

Now, when the same material is assembled into a nano crystal as opposed to a bull so called bulk crystal in a bulk crystal one has typically a number of atoms of the order of the avogadro number, whereas in a nano crystal it is a much smaller number.

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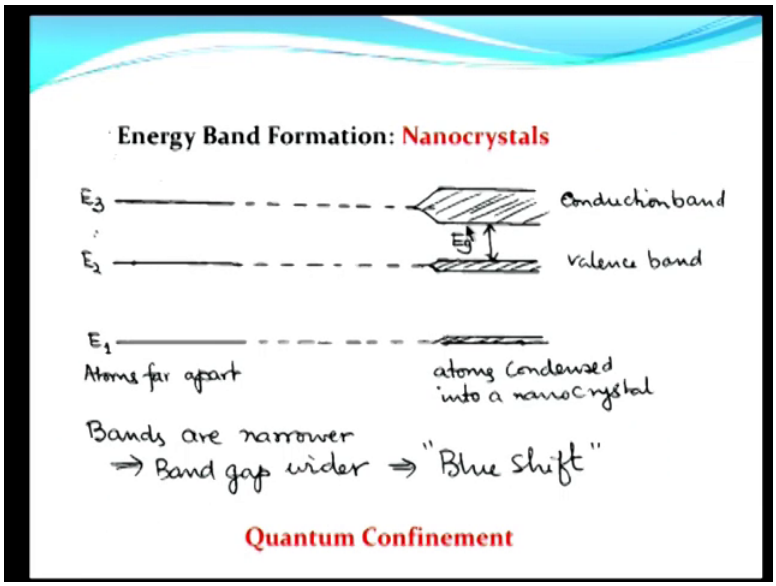

Because a crystal itself measures in nanometers tensor nanometers for example, in which case the number of atom atoms in such a crystal measuring a few tens of nanometers on the edge would be of the order of hundred thousand or so. In that case because there are few are atoms with their potentials with which electrons interact that there is a lesser degree of interaction, as a result of it the spread in the energy corresponding to atomic levels is a little less.

Therefore, these energy bands representing this exactly the same atomic energy levels or narrower in the case of nano crystals than in the case of bulk materials, because both these bands are narrower than the gap between them where such a gap exists is greater and this is the so called Blue shift or the effect of quantum confinement.

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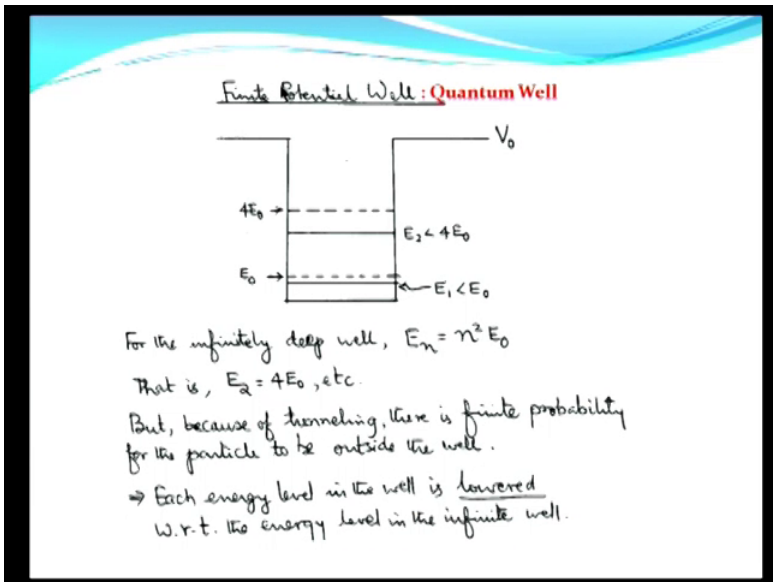

Now let us come back to the concept of the finite potential well, where you have a particle like an electron trapped in a potential well of a finite height V naught and a width let us say l represented by l. And we learned in an earlier session that the energy levels are quantized here also, except that the energy levels corresponding to the same quantum number in the case of an infinitely deep well versus a shallower. Well, this is a finite depth well. So, the energy levels corresponding to the finite depth for the same quantum number is lowered because as I said earlier it is because of the fact that the wave function is so to speak leaking out of this relatively shallow well, as a result of that the energy levels within the well are lowered.

Now can we realize these structures or they simply theoretical constructs that one writes equation is about and solve equations about and so on can we actually realize them.

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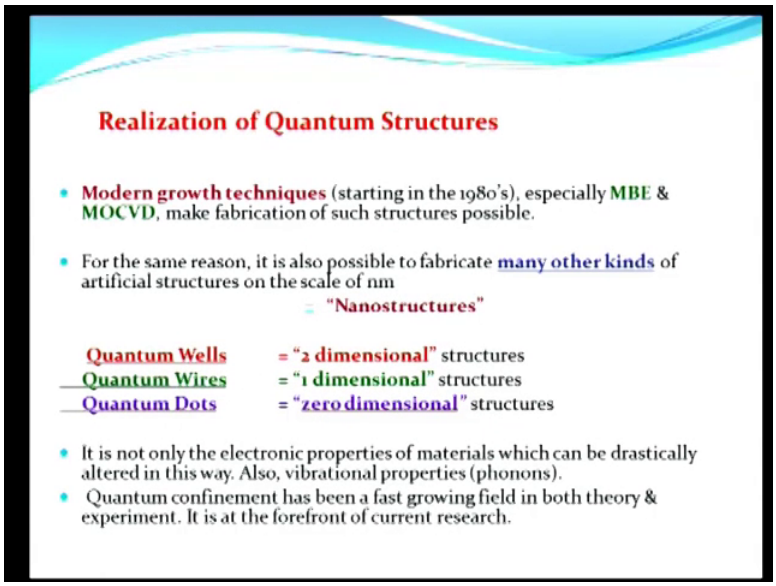

The answer of course, is that they are very much realizable and indeed they are realized more than 30 years ago, growth techniques such as molecular beam epitaxy and MOCVD metal organic chemical vapor deposition these kinds of processes make the realization of such structures which yield quantum wells, where one can observe such finite size effects with a limited number of states available within such a quantum well such structures are realized, because of modern thin film growth techniques such as MBE and MOCVD. Because of the development of these structures development of these techniques which we shall come to again and again in this segment of the course, it is possible to fabricate many other kinds of artificial structures on the nanometer scale so called nano structures quantum wells, that we just will go on to discuss a little bit further quantum wires which are one dimensional structures where there is confinement of motion to just single one single dimension.

In the case of a 2 dimensional structure there is confinement of motion into 2 dimensions as supposed to 3 and in quantum dots which are 0 dimensional structures there is confinement in all 3 dimensions. As I already mentioned it is not only electronic properties of materials including magnetic properties which are drastically altered because of such confinement because of the small size, but also vibrational properties namely phonons, phonons structures are also altered, because of the very small size structures that these nanostructures represent.

Now quantum confinement as I showed you through the cadmium selenide dots which exhibit dramatic effects of band gap enhancement due to size reduction, this is being studied quite a bit and actually it has important practical applications that we shall return to a bit later.

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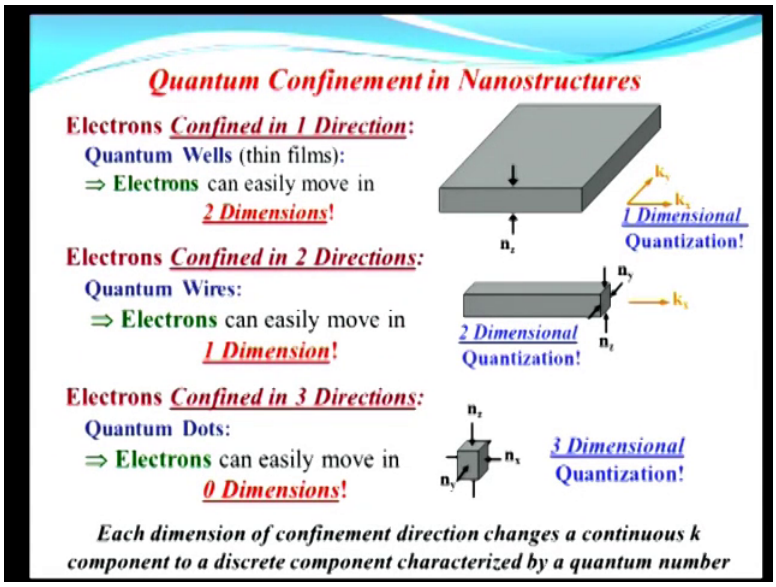

Now quantum confinement; Quantum confinement in nano structures as I said you can have 2 dimensional confinement in terms of these quantum wells and that structure looks something like this, you have a 2 dimensional structure with a narrow separation between these outer walls, to speak. So, these outer walls are pretty large, but separation between these outer walls which represent the potential barrier, this is a narrow dimension narrow length. So, that is where confinement of electrons into the 2 dimensions represented by this cartoon that is where the confinement is that is where the electrons are confined to. Quantum y are represented by this diagram over here were essentially electrons move along this linear dimension given here by kx the wave vector. Electrons confined 3 dimensions is represented by this figure over here where dimensions in all 3 directions x y and z or kx ky and kz are limited.

Now how does one actually practically realize such structures? As I said these are realized by MBE and MOCVD. So, what do these structures look like that can be shown by a diagram like this.

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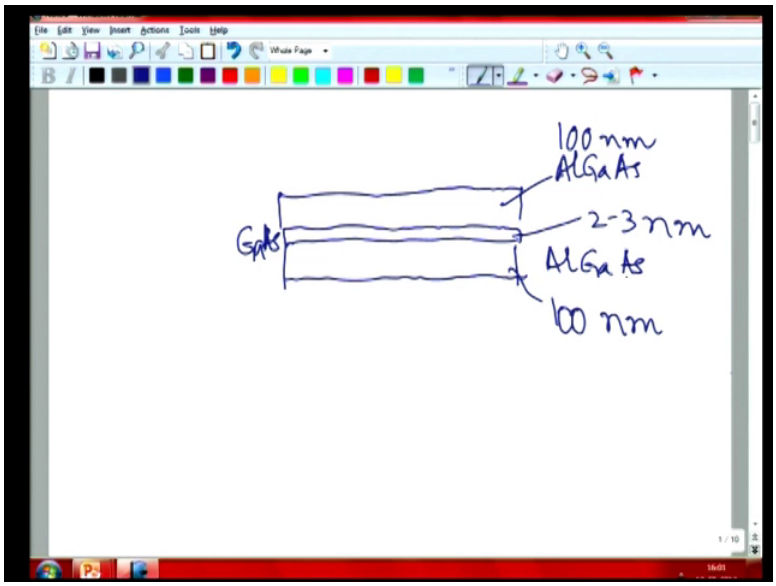

For example, one grows a layer by MBE or MOCVD of a material that is aluminum gallium arsenide and then on top of it one grows a very thin layer of the order of let us say 2 or 3 nanometers of gallium arsenide and on top of it once again one grows a layer of aluminum gallium arsenide again. So, what we have is sandwich structure of a relatively thick layer of aluminum gallium arsenide, let us say you know this could be 100 nanometers or something like that, and a thin layer of gallium arsenide 2 to 3 nanometers and once again an aluminum gallium arsenide layer of the order of 100 nanometers these are just illustrative numbers.

So, this is actually the kind of structure the one talks about in epitaxial nano structures or quantum wells these are called epitaxial structures because they are grown by the process of epitaxy through either MBE or the MOCVD process, now having learned about this way of growth or this way of actual representation. Now just to be sure I want to add that when one grows a layer of aluminum gallium arsenide. And then on top of it a thin layer of gallium arsenide, this becomes possible because the crystal structure of aluminum gallium arsenide and the crystal structure of aluminum of gallium arsenide are such that their lattice constants or very close to each other.

Therefore, epitaxial growth that is the growth of a very high quality layer of gallium arsenide on a very high quality layer of aluminum gallium arsenide, and then this sandwich structure this becomes possible because the lattice constants of aluminum

gallium arsenide and gallium arsenide are very close to each other satisfying the condition of lattice matching.

So, this structure over here that I have shown is the gallium arsenide layer. So, on top of it there will be an aluminum gallium arsenide layer and at the bottom of it also there will be an aluminum gallium arsenide layer, and this layer of gallium arsenide would measure about 2 to 3 nanometers as I just said. So, this is the physical realization the physical representation of the quantum well structure now how does that actually work and why does it work.

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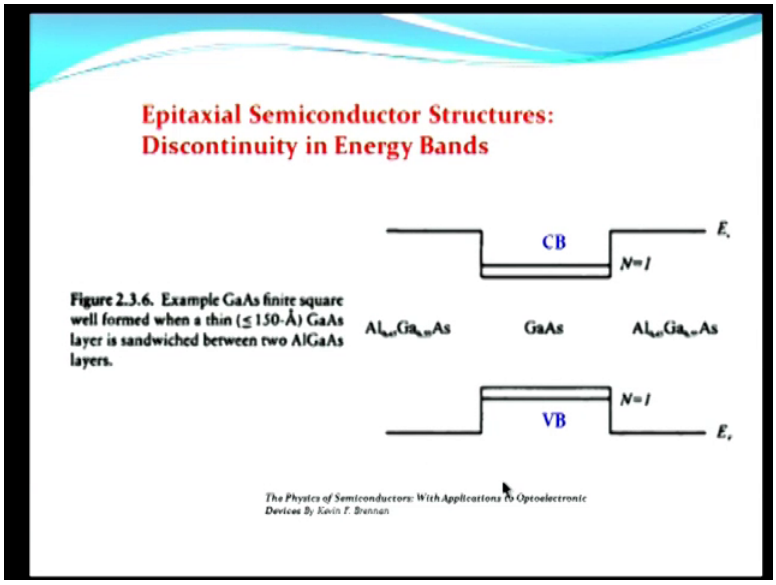

Now what is shown here is the energy band diagram of aluminum gallium arsenide, gallium arsenide and aluminum gallium arsenide, remember that this gallium arsenide is a sandwich between 2 identical layers of aluminum gallium arsenide. It turns out that the band gap of aluminum gallium arsenide is greater than the band gap of gallium arsenide this is the band gap of gallium gallium arsenide and this is the band gap of aluminum gallium arsenide as you can see it is greater.

So, what the top of this diagram represents in the middle is the conduction band of gallium arsenide and at the bottom you have the valence band of gallium arsenide similarly over here you have the conduction band of aluminum gallium arsenide valence band of aluminum gallium arsenide and identically on the left, because the band gap of aluminum gallium arsenide is greater than that of gallium arsenide, what you have shown

is here an abrupt junction an abrupt barrier that a carrier like an electron would see as it tries to go from gallium arsenide to aluminum arsenide.

So, this let us say represents about 1.7 electron volts let us say approximately or maybe around 1.8 or so, gallium arsenide is 1.43. So, this difference in the band gap between gallium arsenide and aluminum arsenide may be taken in first approximation to be equally distributed at the conduction bandage as well as the valence band edge therefore, an electron that is trying to go from gallium arsenide to aluminum gallium arsenide would see a change in the band gap and therefore, a barrier a potential barrier of several tense of a volt, that is depending on the exact composition of gallium aluminum arsenide this barrier that the electron c is may be of the order of 0.3 or 0.4 electron volts.

So, this is how a potential barrier is created in practice in a practical material structure. So, what is therefore, now have is an electron that is trapped in gallium arsenide in a shallow potential well and this is very narrow as I said this 2 to 3 nanometers. So, you have a quantum well structure that mimics what we have shown earlier namely a structure like this, this is mimicked by the physical epitaxial structure where we have gallium arsenide sandys sandwich between 2 layers of aluminum gallium arsenide with a greater band gap.

So, what is represented here is the first quantized energy level in this quantum well finite height quantum well, where the electron is let us say trapped in the gallium arsenide part of this quantum well structure. So, this is the first level there could be a second level and so on depending on the details of the actual structure the thickness of this and the composition of aluminum gallium arsenide which determines the barrier height. So, this is a typical quantum well structure practically realized in a material system.

Now let us remember that both gallium arsenide and aluminum gallium arsenide of certain compositions both of these are direct band gap semiconductors, I presume that you have learned about direct and indirect band gap semiconductors along the way. And therefore, the fact that these are direct band gap semiconductors is conducive to transitions between states in the conduction band and the valence band; that is recombination of electrons and holes which leads to emission of radiation with significant efficiency. So, these are light emitting devices or alternatively under ideal circumstances these are laser devices or this is the basis of lasing action.

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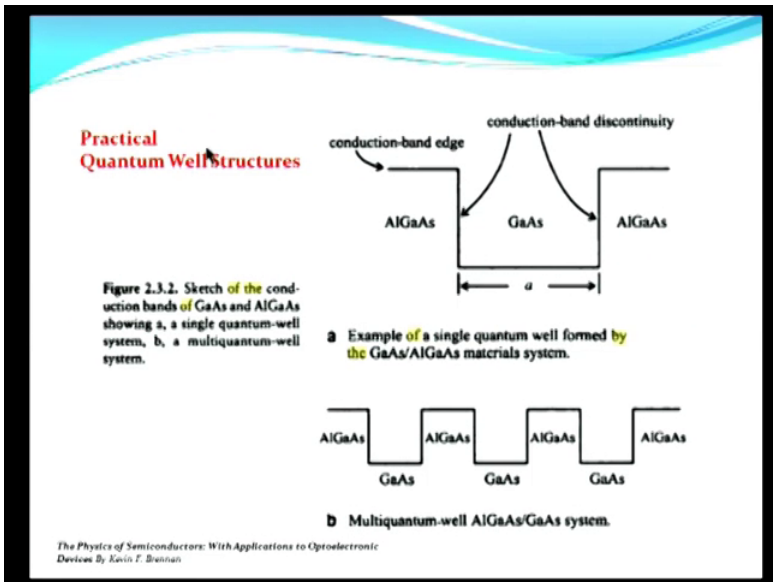

So, this is a practical quantum well structure one can also have so called multiple quantum well structures, that is one has a repetition of aluminum gallium arsenide gallium arsenide and so on. So, this can be repeated because the process of depositing these thin layers especially in MBE can be very highly controlled.

Therefore, one can have these repetitions structures with identical widths for gallium arsenide controlled to within a few angstroms and again a thickness aluminum gallium arsenide that can also be controlled and so forth. And therefore, one can a very precisely defined physical structures repetition structures forming a multiple quantum well.

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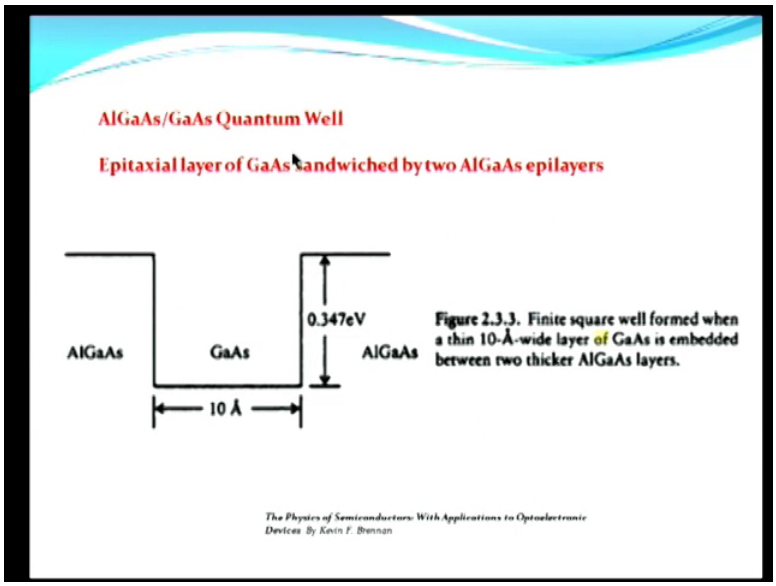

Now for a given composition for a I should say a precise composition this barrier height would be about 0.347 electron volts. And in this test structure shown the width of the gallium arsenide part of it in the sandwich structure is only 10 angstroms or 1 nanometer; so for such a structure where the composition of the aluminum gallium arsenide is such that this barrier height is 0.347 electron volts.

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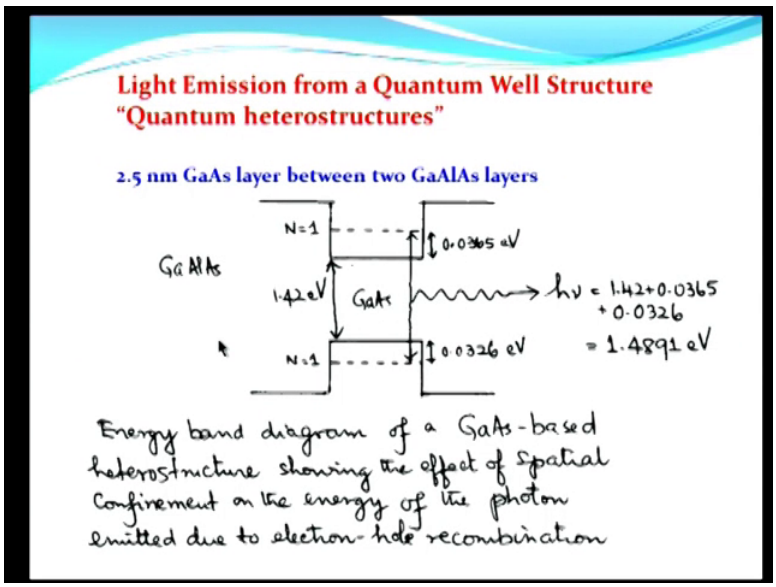

What you can therefore, see in this diagram is a an energy level for quantum number n equal to 1 that is 0.365 electron volts about the bottom of this conduction band, and

similarly a level in the valence band that is 0.326 levels the 3 2 6 electron volts, giving a total separation between n equal to 1 in the conduction band and n equal to 1 in the valence band of 1.42 which is the band gap of gallium arsenide plus these 2 numbers corresponding to the level of energy in these quantum wells corresponding to n equal to 1.

So, that is a total 1.489 electron volts therefore, when there is a transition between these 2 levels these to quantize levels in the gallium arsenide quantum well, radiation corresponding to 1.489 electron volts which is in the infrared is emitted and by designing the structure properly, one can obtain lasing action giving a quantum well laser. I should not forget to say that these are called heterostructures, because you have gallium arsenide of one composition that is a semiconductor one composition which is sandwiched between semiconductors of a different composition therefore, this is a hetero structure. So, these are heterostructure devices heterostructure light emitting devices or lasers. In practical quantum well structures, this is you know a representation of a typical quantum well lasers structure it is more complicated than what is shown here, where we just show one gallium arsenide layer and 2 gallium aluminum arsenide layers.

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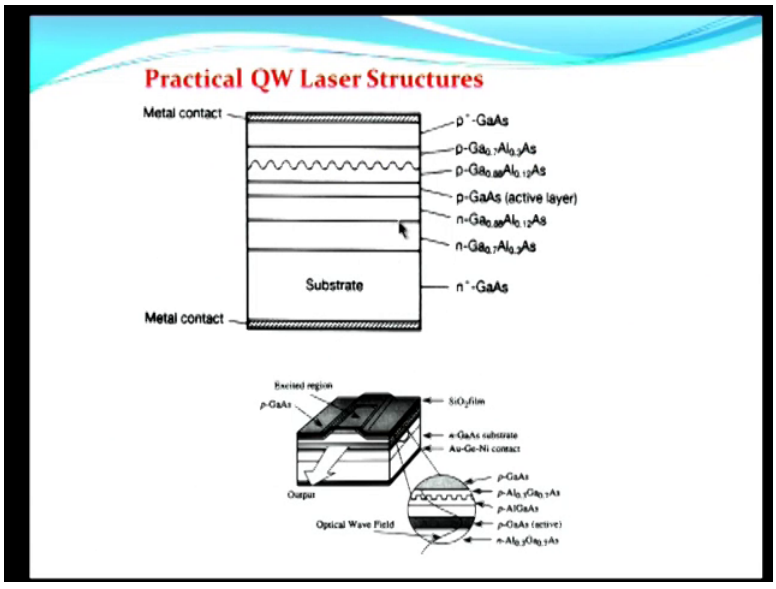

So, in a practical lasing structure the structures of a bit more complicated, but you can see once again that there is a thin gallium arsenide layer in between 2 aluminum gallium arsenide layers these 2 layers and there is there are other structures and so on. We will

not go into those details, but the point is that such a structure is capable of lasing action giving us radiation for example, in the infrared.

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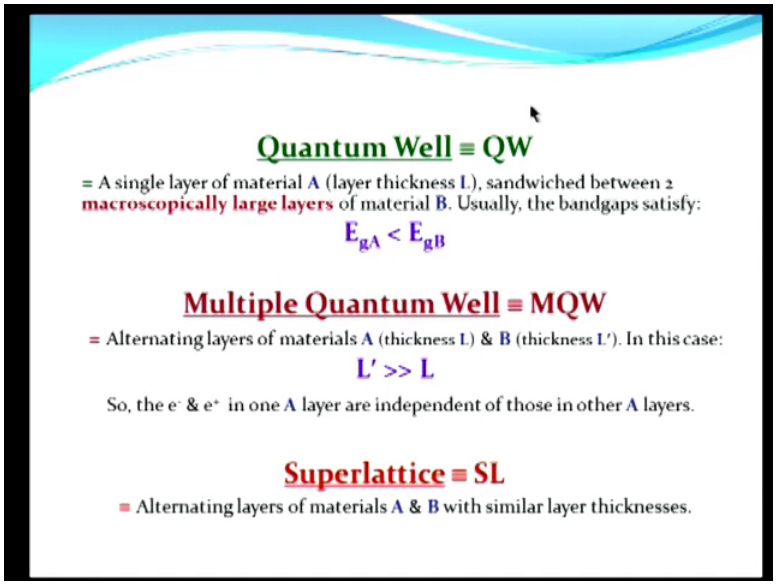

So, this is a single quantum well structure, I already mentioned multiple quantum wells. Now if you have alternating layers of a material a and A material B, A as a thickness of L and B as a thickness of L prime if L prime is much greater than L, then it is a multiple quantum well structure because in such a case the electrons and holes in one a layer is independent of the electrons and holes in the other a layers which are separated by the l be layers.

So, this is a multiple quantum well structure; one can also have super lattices which are alternating layers of material A and material B. For example, gallium arsenide and gallium aluminum arsenide with similar layer thicknesses, but we will primarily be interested in this segment in multiple quantum well structures.

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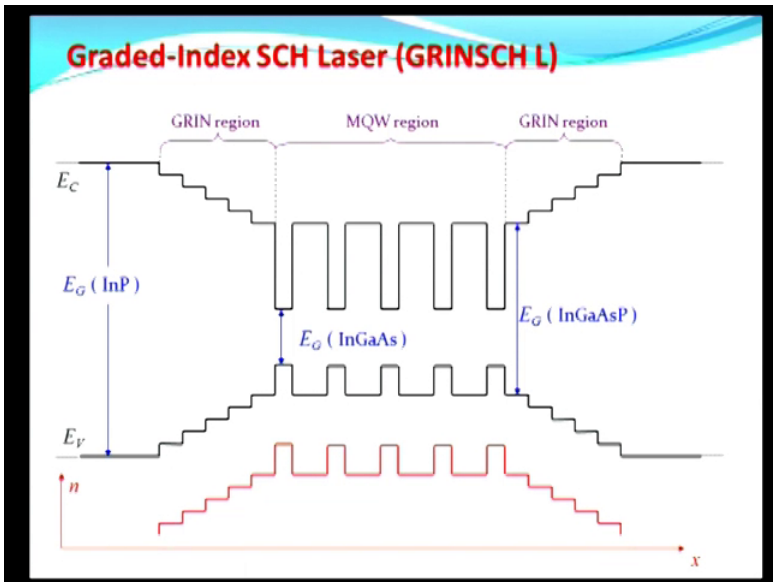

Now, here is an actual structure that has been realized by molecular beam epitaxy where you have indium gallium arsenide with a smaller gang band gap, and in indium gallium arsenide phosphide so called quaternary structure which has a larger band gap. So, this is the quantum multiple quantum well structure, you can see how complicated it is especially given that these layers are angstroms in thickness and they need to have abrupt interfaces, because these vertical lines actually represent sharp potential barriers because of the bandgap differences and this will be sharp only if these layers, change abruptly from one composition to another and that is possible both by MBE and by MOCVD, but especially by MBE.

So, this is actually a realistic structure of a complicated multiple quantum well laser, will not go into the details of this, but this is illustrative of how complex it is and how nanometric structures can be obtained in a very controlled fashion through processes like MBE and MOCVD. So, these are all different regions of the same structure as I said we will not go into the details of the design of this laser structure.

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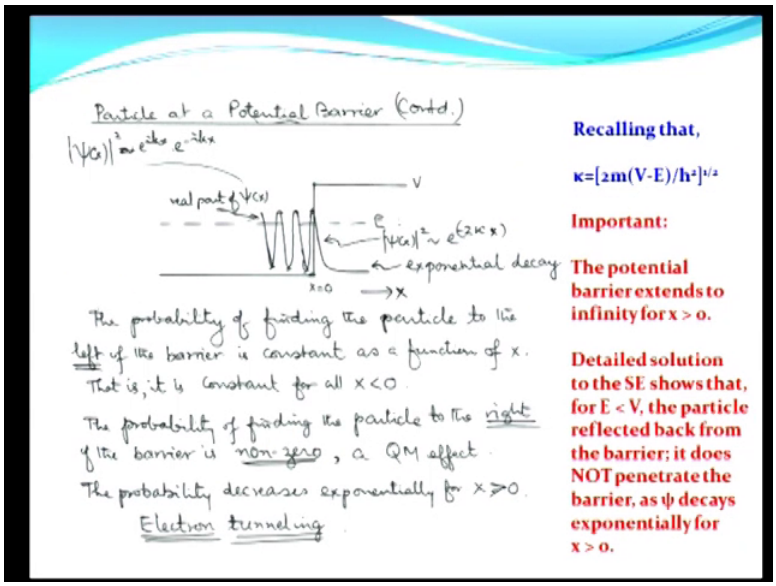

Now one thing that is important here is that.

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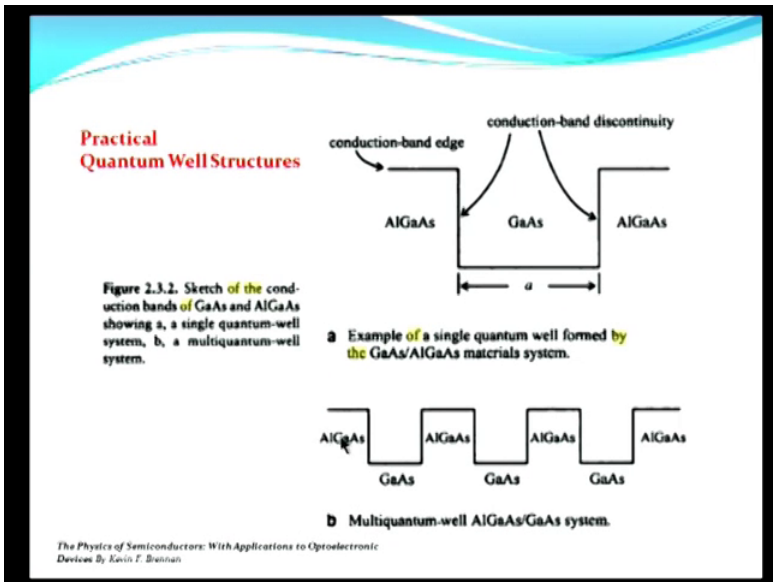

If you have a multiple quantum well structure, let us consider an electron over here it is confined to this region and then you have a barrier, because of the higher band gap of gallium arsenide, but in this structure multiple structure multiple quantum well structure the intention is for the electron not only be 2 be confined here so that it has quantized energy states, but also to transport it from this gallium arsenide layer to the next gallium arsenide layer across this barrier.

So, we will be a talking about an electron this is a quantum particle surmounting a barrier potential barrier to go into a different region. So, this is different from confinement we are talking about how a quantum particle can tunnel from this region into the adjoining gallium arsenide region by overcoming this potential barrier. Remember in an earlier class we dealt with tunneling. So, here we have to deal with tunneling in order that this multiple quantum well structure is utilized for its intended purpose.

Now, recalling what we did earlier when we had an electron with energy e that encounters a potential v which is greater than e, then we saw that this wave function which is really sinusoidal in this left hand region where there is no potential where they 0 potential there is a potential v on the right side. So, this wave function dies off exponentially within a fraction of an angstrom or a very short distance from x equal to 0 where the potential is located potential barrier is located. So, on the other side you have an exponentially decaying function e to the minus 2 k x, 2 kappa x where kappa is given by this factor over here related to V minus E. So, this is the electron tunneling phenomenon.

Now, what is important to remember here is that, this happens when this potential barrier is of an infinite extent; that is the potential is 0 up to x equal to 0 and potential is v for x greater than 0 all the way to infinity. So, you have an infinitely long potential barrier not infinitely high, but an infinitely long potential barrier of a finite height that is when tunneling of this sort takes place and the exponential decay or the wave function takes place on the other side of the barrier.

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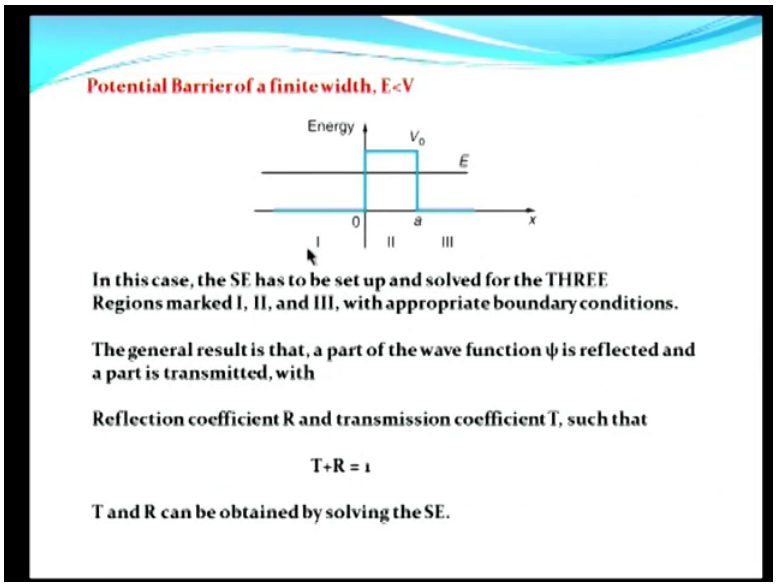

Now, to represent what happens in the case of the multiple quantum well what you have to recognize is that, now you have a consider this as gallium arsenide and this is aluminum gallium arsenide and this is gallium arsenide again in the cartoon that we just showed of the multiple quantum well structure. So, I have an electron coming here and it has to surmount this barrier and go into this region. Now we do not have an infinitely wide potential barrier we have a finitely wide potential barrier. So, the question we ask is what happens if the width of this potential barrier is such that even though the wave function decays exponentially, it does not die down because this width of this potential barrier is not great in fact, this potential barrier is narrow and therefore, even on the other side of the potential barrier there is a finite amplitude for the wave function.

So, that is what one tries to do in these multiple quantum wells one tries to adjust the width of this potential barrier in such a way that even though the wave function is decaying through the barrier the barrier is narrow enough that at the other end of it you have a finite amplitude for the wave function that has tunneled through this barrier.

Now, detailed calculations which means solution of the time independent Schrodinger equation set up for this physical picture, where you have regions 1 and 2 and 3 the particle is coming through from a region of 0 potential and then there is a potential of height V or V naught and then again it emerges on the other side to a potential 0. So, this is the problem one can set up the Schrodinger equation for this problem time

independent one and solve it with appropriate boundary conditions. And what one finds is that when E of the electron or the quantum particle is less than V for energies of this incident particle less than the barrier height. Then there is a finite probability of reflection of the particle back into this region of this space where it came from and a finite probability of transmission through the barrier because of quantum tunneling.

So, one can therefore calculate the coefficients of reflection and transmission the coefficient of reflection would be R and the coefficient of transmission would be T. And therefore, obviously, T plus R should be equal to unity, and the values of T and R would depend on the width of the potential barrier and the height of the potential barrier apart from the energy of the incident particles, one can calculate these things as I said by solving the Schrodinger equation therefore, one can obtain T and R by solving the Schrodinger equation.

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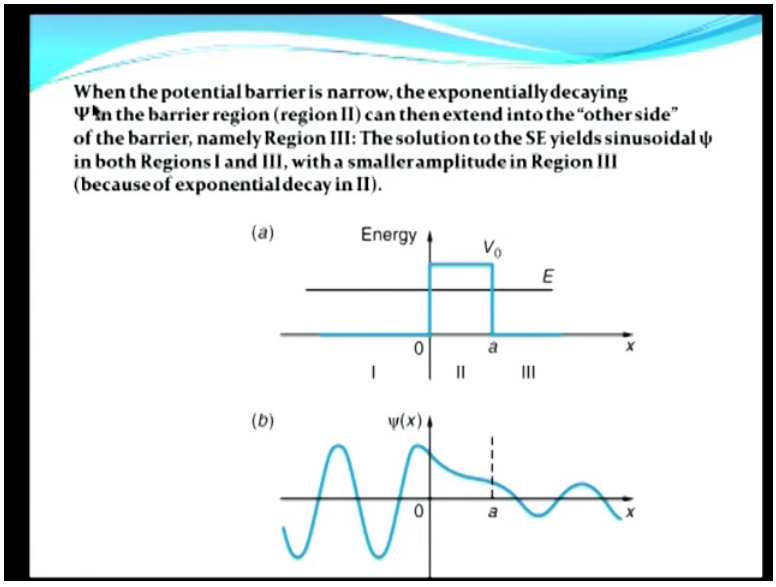

So, to reiterate when the potential barrier is narrow, the exponentially decaying wave function in the berry region that is region number 2 can then extend into the other side of the barrier. So, this is gallium arsenide, aluminum gallium arsenide and gallium arsenide again allumine sorry this is aluminum gallium arsenide gallium arsenide no no I correct myself am sorry I was right to begin with. So, this is gallium arsenide these aluminum gallium arsenide and this is gallium arsenide again, an electron traveling from gallium

arsenide region to the aluminum gallium arsenide region through that region into the other gallium arsenide region.

So, in such a case the solution to the Schrodinger equation yields a sinusoidal function for the electron on the left side and an exponentially decaying function through the barrier, and because it did not die down completely because the barrier is narrow this potential functions of the electron probability amplitude is finite on the other side and it is a sinusoidal function once again. So, this is what happens when you have a finite potential barrier of a finite width.

So, this is what a multiple quantum well represents. So, to get to that picture again. So, think of this as a multiple quantum well. So, you have an electron here, it overcomes the barrier and then it comes into this place and this is also narrow and so on. So, one can have electron motion through this multiple quantum well structure, I should also say that it might as well be holes in this case. So, we are talking about carrier motion through these quantum well structures.

Now, one can use computational methods to calculate the transmissivity or the transmission coefficient as a function of the energy of the incident particle, what we had here remember we had the energy of the incident particle E, the E was less than the barrier height. So, what happens?

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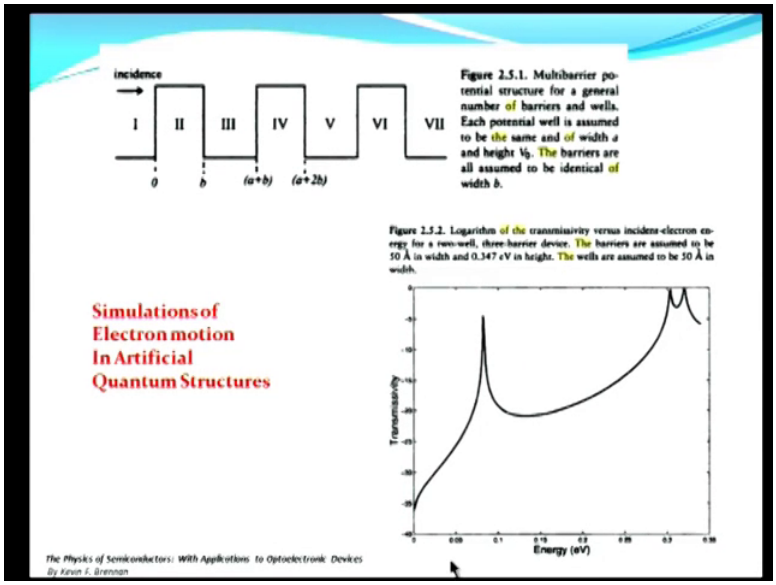

As the energy of the electron incident electron increases, I can see that there are spikes in the transmissivity, this is the part of the peculiarities of quantum mechanics what we have here just to be sure is a 30 angstrom or 3 nanometer well of gallium arsenide that is sandwich between aluminum gallium arsenide on either side.

So, this is the result of computation of what happens when an incident particle with a variable energy along as shown in the x axis is incident on this barrier structure. Similarly one can simulate electron motion in this kind of an artificial quantum structure where you have the transmissivity of the T value computed as a function of the energy of the incident electron or a incident carrier and this transmissivity by the way it is in logarithms over here the y axis in logarithms. So, the logarithm of T is plotted as a function of the value of the incident energy and you can see that there are certain resonances as a function of the incident well value of the energy of the incident particle.

So, one can actually simulate the behavior of a given structure knowing the full details of the composition of the different layer, because that defines the band gap as well as the width of successive layers, because that defines the barrier width. So, knowing these things one can obtain quite precisely the expected behavior of electron motion through such multiple quantum well structures, which will be required for designing specific devices.

Again I want to emphasize that the layers here although deposited on substrates of substantial size that is you have substrates that may measure in centimeters or inches, but the layer thicknesses are in angstroms or nanometers. So, with that kind of precise control one can create these structures and simulate the behavior of electrons through such structures.

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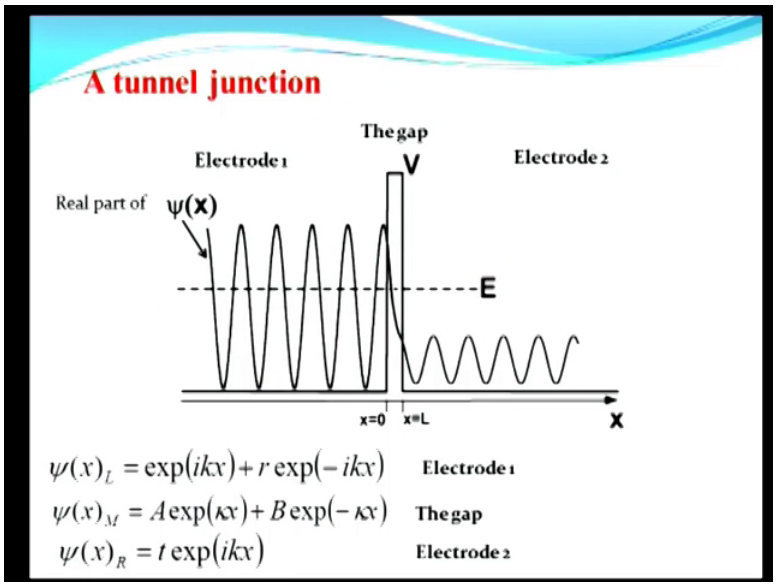

So, what we just showed here might as well be called a tunnel junction. Suppose you now have instead of a structure like gallium arsenide, aluminum arsenide and gallium arsenide, suppose instead you have a metal on the left and an insulator in the middle as the barrier and insulator would have a high band gap and then another metal on the right side.

So, you have electrode 1 electrode 2 and sandwich between them is an insulator very thin layer of insulator typically angstroms in thickness therefore, one can simulate this because what you have here is a free electron because you have an electron you have a metal here similarly a metal here. So, free electron wave function sinusoidal wave function and going through a barrier of height V it could be a insulator layer for example, it could be a an aluminum thin very thin alumina aluminum oxide layer or it could be an air gap.

So, think of this as a very very small air gap air being of course, an insulator. So, you have a metal another metal separated by an air gap and there is a potential that represents this air gap or this insulator over here.

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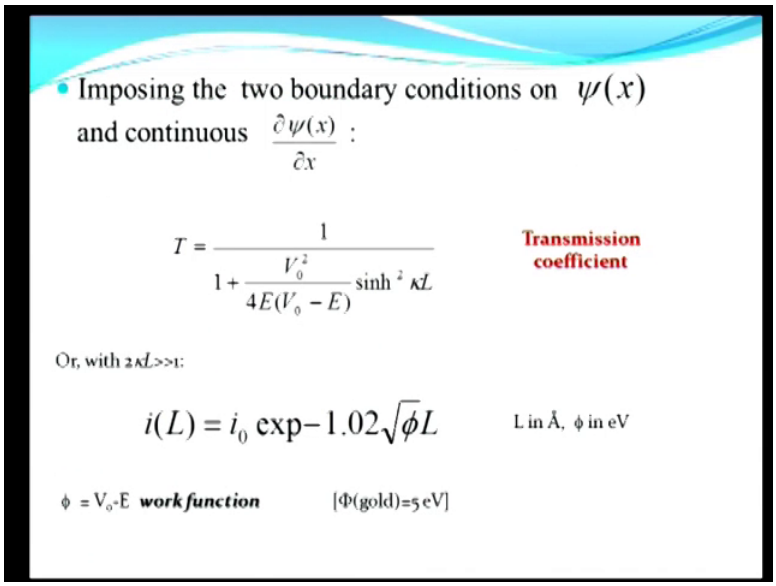

That is precisely the situation with this scanning tunneling microscope.

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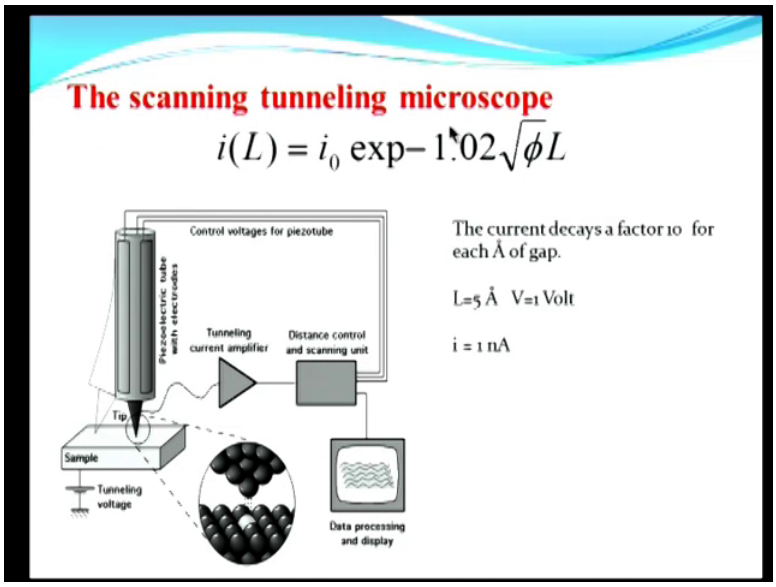

So, what you have here is a very fine tip of a metal and then a metallic sample and what you have is a very minute air gap measuring in angstroms in that case one can show that the current due to tunneling that is electrons tunnel from the tip of the scanning tunneling microscope very fine tip of the scanning tunneling microscope into this metal or vice versa.

And therefore, you have a current due to tunneling which can be used to image the sample that is what you have here is a sample and one applies a potential to this sample this is a metallic sample, and you have a conducting or a metallic tick very fine tip fabricated through lithography. Scanning over this metal sample at a very small distance of the order of a few angstroms or a nanometer or 2 and then electrons tunnel from the metal to the tip and this is then processed to obtain an image of the surface of the metal as this tip scans the surface area of the metal.

So, this scanning tunneling microscope which is actually one could say a starting point of nanotechnology, because this made possible imaging of surfaces on a very fine scale on an angstrom scale. So, in scanning tunneling microscope is actually a device that depends on quantum tunneling, later came the atomic force microscope which operates on a different principle, but which is capable of also scanning across insulating surfaces and therefore, much more versatile than a scanning tunneling microscope. So, these two are really the starting points of modern nanotechnology.

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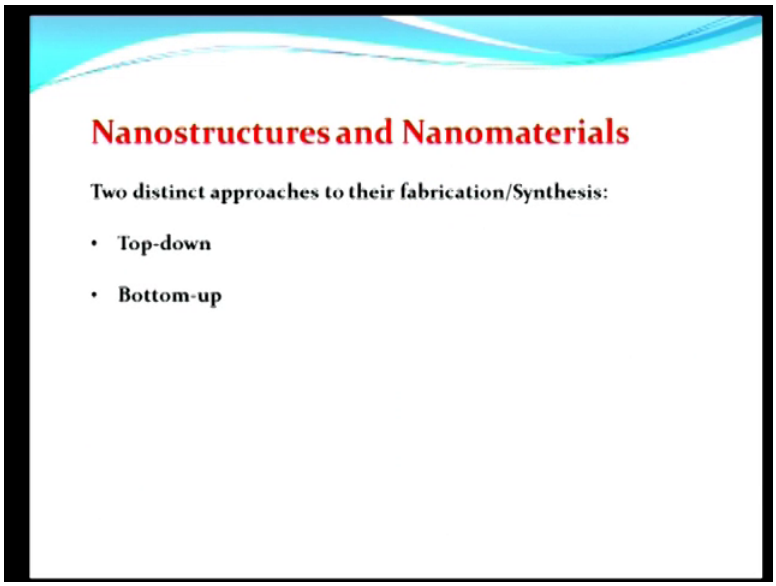

So, having gone through some concepts of quantum mechanics, quantum wells and the realization of some elementary devices that depend on quantum confinement, we can move on to nanostructures and nanomaterials. We will be coming back again and again to illustrative devices, but let us move on to a discussion of nano structures and nano materials, after all that is the central theme of this segment of the course.

As you may have already learned there are 2 distinct approaches to the fabrication of the synthesis of nanomaterials in nanostructure the top down approach and the bottom up approach. The top down approach of course, these phrases are self explanatory the top down approaches starts with large structures relatively large structures and in some way trims them down to very fine dimensions and the bottom of structures at the bottom of approach aims to build very small structures by starting at the atomic or the molecular level.

So, these are the 2 approaches that have been adopted to obtain nanostructures and to synthesize nanomaterials with nano structured feature.

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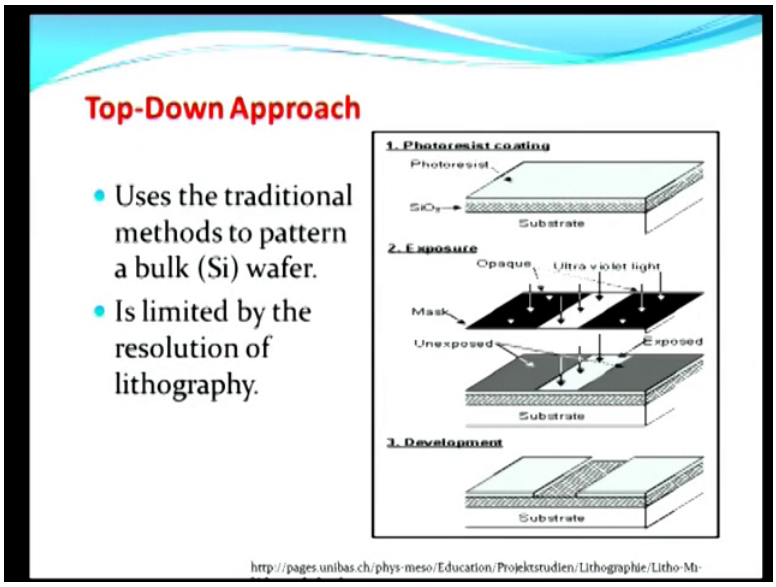

The top down approach uses you know you probably learned about this in the other segments of the course other 2 segments of the course, you probably become familiar with processes like lithography. Pattern transfer where one uses photolithography that is one uses a polymeric photo resist exposed through a very very precisely prepared mask so that wherever this resist is exposed it becomes polymerized, and it becomes soluble later on processable in a development stage of this lithography process.

So, one can transfer the pattern that has been created in a mask on to a wafer. This of course, is the lifeblood of modern integrated circuit technology, it is very very highly developed and of course, very precise, but nevertheless it is limited by the resolution of lithography or the resolution of the lithographic process that one is using.

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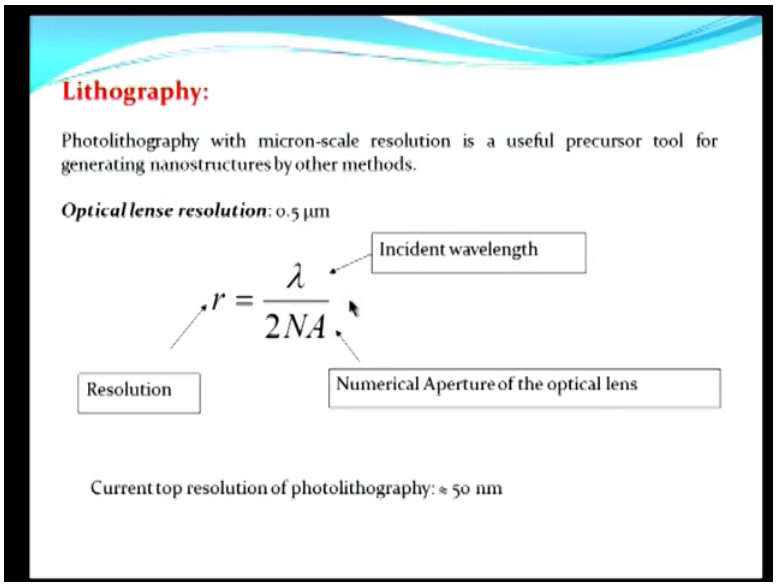

Photolithography which uses light visible light for the most part, but more recently ultraviolet the ultraviolet light of shorter wavelengths, has micron scale resolution and is a useful precursor tool for generating nanostructures by this top down method that reduces large samples to smaller dimensions or imprints smaller dimensions and larger objects.

Now, the resolution of an optical lens which is of the order of 0.5 micrometers or really 500 nanometers is given by r is lambda divided by 2 times the numerical aperture. So, lambda being an enumerator is only limiting factors. So, if lambda is less than the resolution be greater. The current top resolution in photolithography using various kinds of phase contrast and so on is of the order of 50 nanometers.

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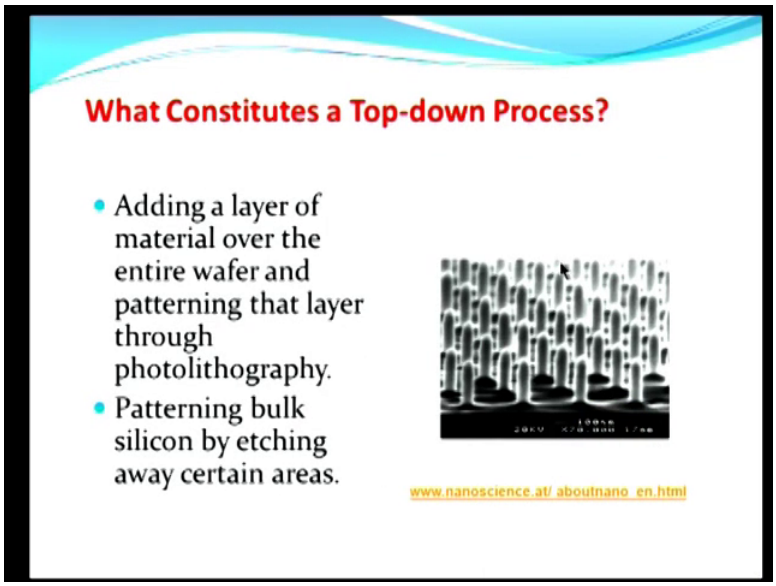

What you have here is the image of a very regular nano structured or a nanostructure created by lithography. The top down process really means that one adds a layer of the material over an entire wafer a silicon wafer for example, and patterns it through photolithography by removing those parts of the wafer or the sample that are not required.

So, when as I said transfer the pattern transverse the pattern to obtain very precisely defined structures, because as I said the ic industry has nearly perfected the lithography process to obtain extremely reproducible very fine structures, there are numerous processes that you are probably familiar with in.

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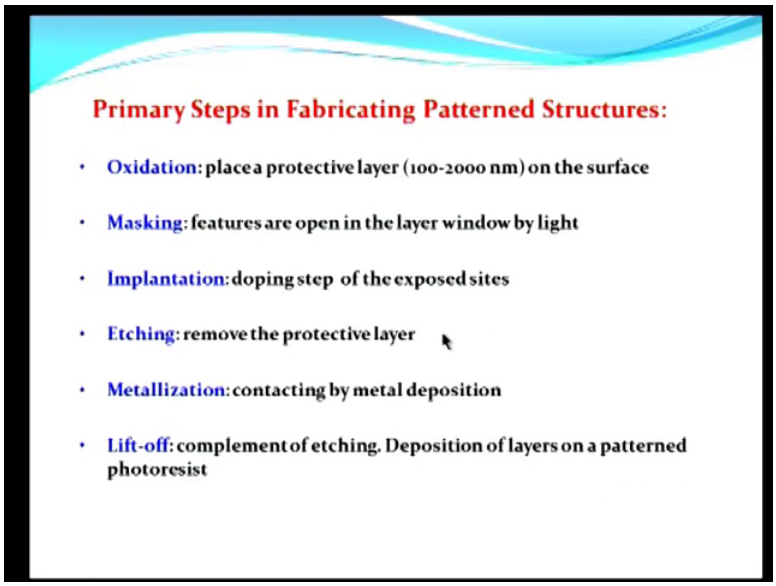

The silicon in the context of silicon technology, oxidation masking implantation for doping etching metallization liftoff and so on these are all different processes that you have probably learned about in the other parts of the course or elsewhere. These are different unit processes that eventually lead us to very well defined structures often periodic structures.

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In the current top down technology for example, lithography is done through argon fluoride excimer laser of wavelength 139, 193 nanometers and you can see that it is a

pretty complicated piece of apparatus. Capable of giving the solutions of the order of 60 band actually low lower than 65 nanometers is also used in the 45 nanometer technology. So calledphase shift masks and very complex optics are used to achieve this sort of a resolution needless to say these are all extremely expensive piece of equipment and processes.

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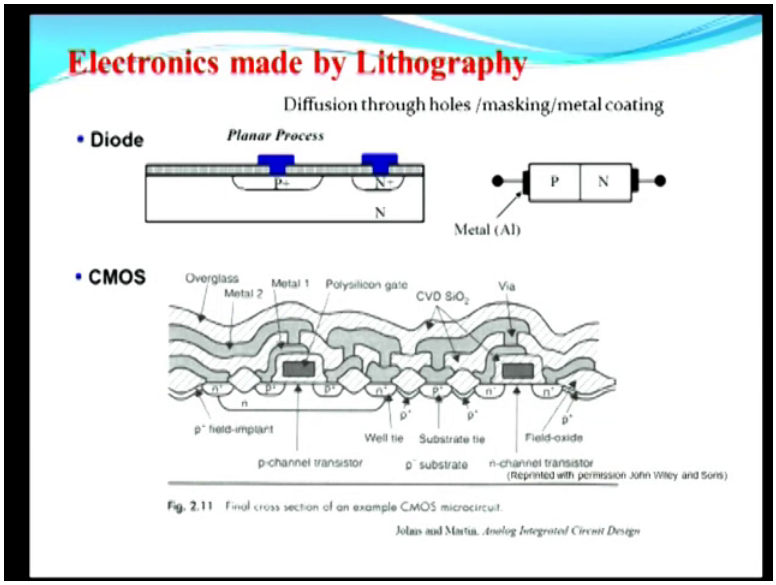

And this is an illustration you know really not the most complicated device, but CMOS device with numerous layers of metallization and so forth extremely fine dimensions this work goes into today's logic circuits CMOS chips with 45 nanometer gate length.

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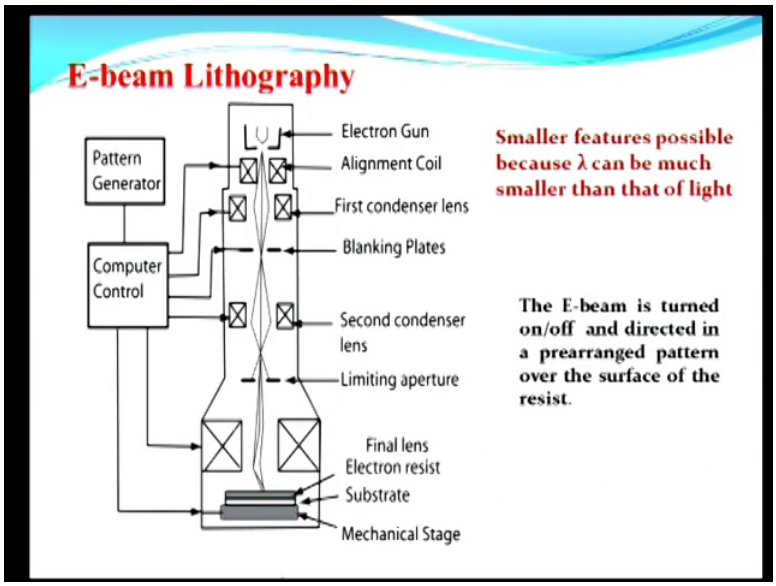

Now we learned a while ago that the resolution is defined by the wavelength directly proportional to the wavelength. So, naturally it is desirable to go to a smaller lambda as possible that is more easily done in the case of electrons than in the case of light. So, electron beam lithography where the wavelength of the electron is inversely proportional to the energy of the electron beam can then be used to obtain smaller features, because lambda can be significant significantly smaller than in the case of electromagnetic radiation light radiation and electron beam lithography is very well developed, but unlike optical lithography this is a serial process. So, one has to literally rest of the electron beam in a prearranged fashion through computer control of course, but it is a serial process because the pattern that one wants to transfer is written on the resist in a serial fashion.

So, it is a slow process and therefore, expensive, but it can provide because of the much smaller lambda possible it can provide much smaller structures than photolithography can.

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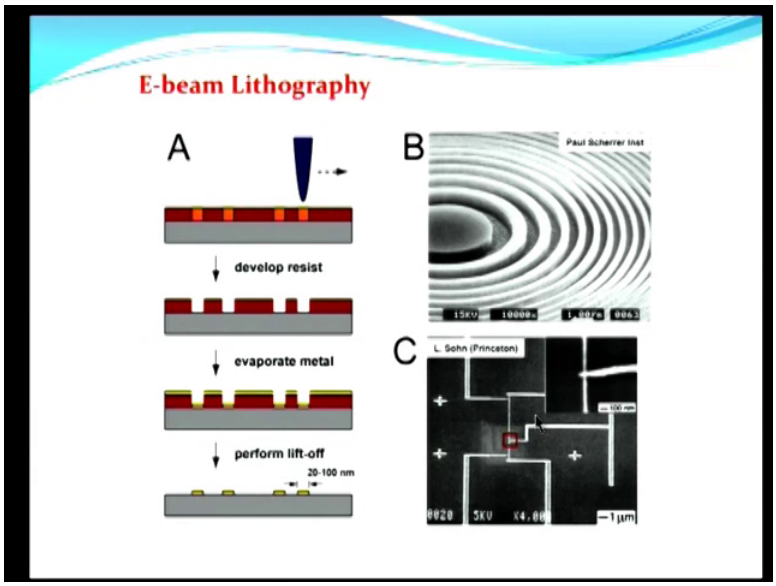

So, these are the exposure is through electron beams, but the rest of the process is similar to what is in load photolithography the typical electron beam resist is p m m a poly methyl methacrylate, and then that exposed wafer is developed and so on and therefore, this is analogous to electron beam in photolithography, but one can obtain much finer structures because of the much smaller wavelength of the electrons and these are illustrated through the writing of very fine lines and so on even though these are not really the narrowest dimensions that one has achieved with electron beam lithography.

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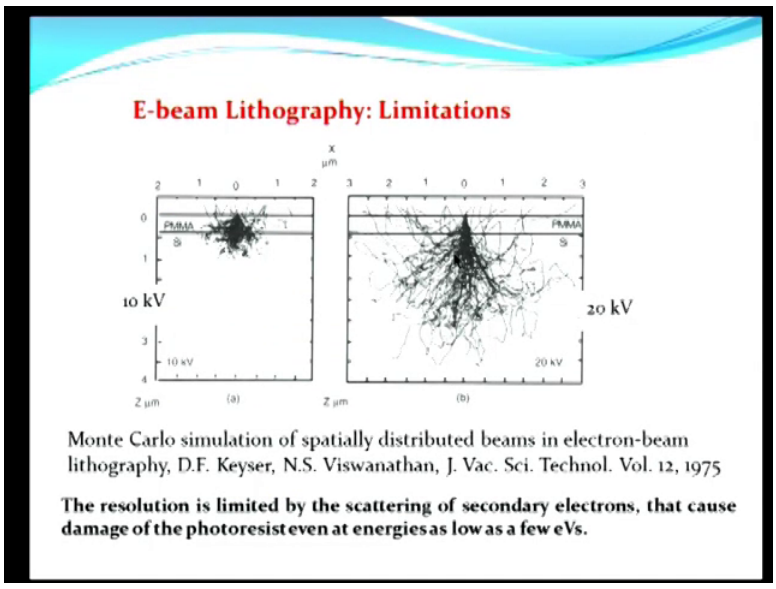

One of the problems is the electron beam lithography is that, even though it provides higher resolution the resolution is actually limited because of scattering of second secondary electrons that is you have you have the resist through which the electron beam goes that is the resistance exposed to electron beams, because of this scattering of secondary electrons that is generated the this damages the photoresist even at energy is as low as a few eVs.

So, because of that what these are really or Monte Carlo simulations of the trajectory of electrons through a resist. So, what this is showing is the spreading of the electrons through the resist which is the ultimate determiner determinant of the resolution of the e beam process e beam lithography process.

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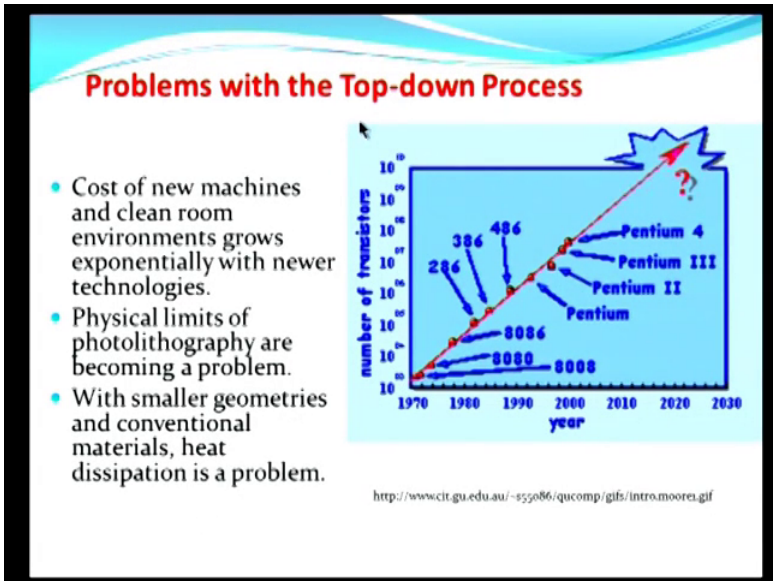

Now the top down process has been very well developed in the context of semiconductor technology as you know, but of course, there are problems serious problems with that even adopting the top down process to nanotechnology, and that is the cost of the new machines and the clean room environments that they have to operate in grows exponentially with the newer technologies.

I have just shown you the picture of the very complicated organ fluoride e b m litha in xml laser lithography equipment the physical limits of photolithography are becoming a problem because of the limited resolution that is possible through photolithography, and in structures device structures which you are not really concerned with there are these

dissipation problems and so on, but the top down process is really a an expensive approach to nanostructures.

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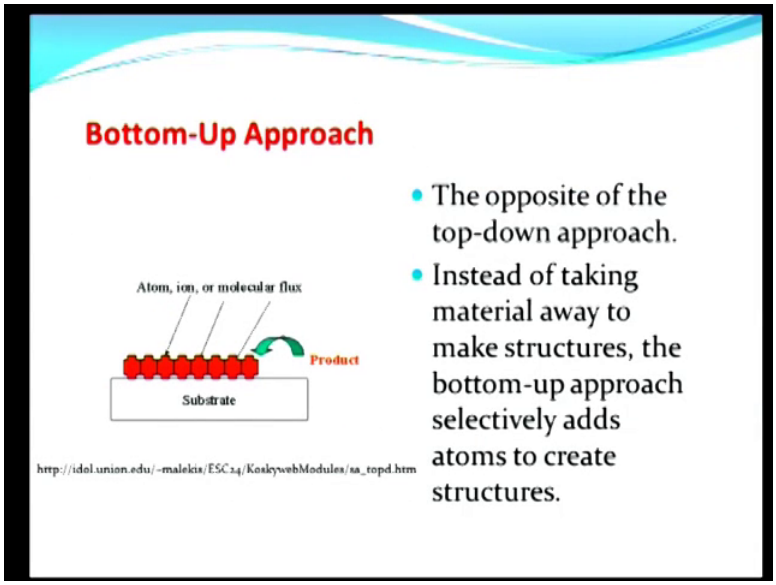

In the bottom of approach on the other hand which is the opposite of the top down approach instead of taking material away from structures the bottom up approach selectively adds atoms and molecules to create structures. Therefore, it is possible notionally at least to have extremely small structures by controlling this process of addition of atoms and molecules to create structures of very fine dimensions in presumably a very controlled way.

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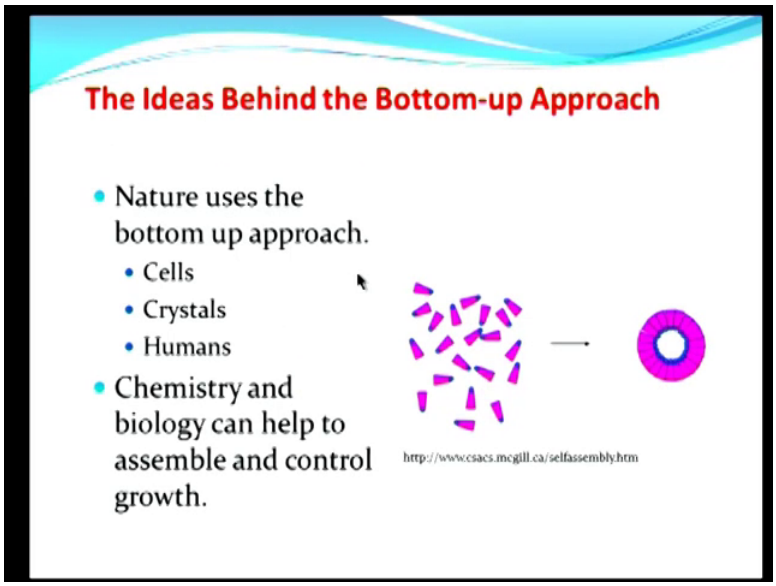

The ideas for a bottom up approach really come from nature, after all cells are assembled that way crystals are assembled that way because to growth even in the lab for example, from a solution occurs out of accumulation steady accumulation of nuclei of crystals into larger entities. All biological processes really are bottom up approach approaches chemical processes chemical synthesis is necessarily a bottom up approach.

Therefore, as shown in this cartoon one can think of ways of assembling into order structures from elements that are nano scopic in dimension. And we assemble them from their high entropy disordered condition as shown in the left of this cartoon into an ordered structure. So, this is the bottom up approach.

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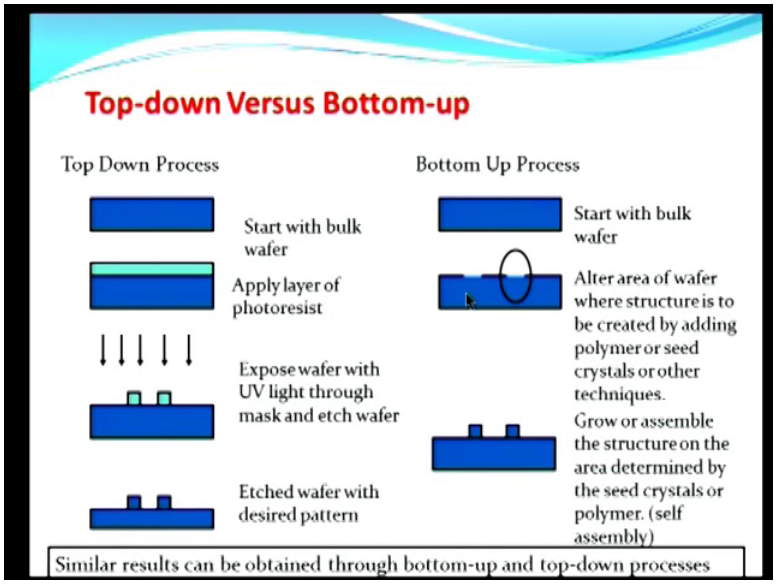

So, let us compare the **2** approaches one in as I have shown you just now is done through lithography and some sort of subtraction of material, at some stage you build up a lot of material add a lot of material and you take a large portion of it out to create small structures whereas, in the bottom of process one would again start with a wafer as in the left hand side. And you know suppose you want to add something to a particular area of this substrate, and then we may be in a position to see this area where we want to build a small structure.

And therefore, build that small structure only in that selected area. So, that unlike in the left hand process is the top down approach, where the largest part of the applied material largest part of the material in each you want to make a structure the largest part of it is subtracted here such a process of subtraction and therefore, essentially a wasteful expenditure of precious material is avoided.

Therefore a bottom up approach if that is well controlled seems to be much more suitable for nanostructures, because one would have to build from atoms to nanostructures. Think of it this way you have atoms which measure in angstroms and you go on that is one tenth of a nanometer and you go on to build a structure that may be 100 nanometers in dimension therefore, you are going up in size by about a factor of 100 2 orders of magnitude, whereas here you create a large structure of centimeters in size and wash more most of it away to get your nanometric structure. So, clearly this is much more wasteful and if one were to control the bottom up approach, it would certainly be the more desirable way to build nanostructures in a systematic fashion.

So, what we have learned in this segment of the course in this particular session is about quantum wells, multiple quantum wells and simple device structures order those how the phenomenon of quantum confinement as well as quantum tunneling lead to the operational devices. And after having gone through that we have begun to discuss two approaches to nanomaterials and nanostructures namely the top down and the bottom of approach we have just compared them. And then we move on now to discussion of specific nanostructures.

Thank you.