Plasma Physics and Applications

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Lecture 60: Laser Produced Plasma and Pulsed Laser Deposited (PLD) Thin Film - II

Good morning. So, I am Dr. Anirban Mitra from Physics Department of IIT Roorkee. So, now we will discuss the step by step all these processes like initially I will discuss about the laser ablations and then the formation of the plasma and the ejection of the plasma from the materials and the expansion of the plasma. So, simply the first process is the absorption of the materials and now the amount of absorption. So, you can say that generally these materials each the transmission that materials if it is the target materials which is of the order of say several generally which we use 5, 6 millimeter it will be the thickness.

So, if the laser light laser light will propagate through this material well propagating through these materials. So, it will decay and it will follow the laws which is called the Beer-Lambert's law and which is as the I naught e to the power minus alpha L. So, here you can see this alpha is the absorption coefficient and L is the length through which light will propagate and I naught is the initial intensity of the light. So, as the light will and R is the reflectivity.

So, the amount of the energy which will be absorbed while propagating through a distance of L capital L. So, the amount of energy which will be absorbed because the it will not around the side the transmissions you can say that there will be no transmissions. So, all energy we assume the all the energy is absorbed within the with most of the energy will be absorbed because within the length of L equal to 1 by alpha which is sometimes also called the skin depth. So, this is the amount of energy which will absorb and then as I have told you that there can be relaxation of the energy through electron phonon interactions and mostly the heating will occur through this and then the heat transfer we can use the heat transfer and equations for melting and then evaporation will takes place. So, here rho is that in the heat conduction equations most of we are familiar here rho is the density and Cp is the specific heat and kappa is the conductivity and T here is the temperature.

So, this is the heat conduction equation. So, one can use it to calculate the temperature rise of the temperature on the surface of the target. Now, these are the different mechanisms. So, initially you can see that initial vapor will form and then there will be in the plasma there will be two region. So, one region will be the transparent where density quite low another region where density will be very high.

So, this is also another important phenomena that the plasma when it will generate and the region where the density is very high it can block the laser beam or it can absorb the laser light and when and it then further increase the temperature of the plasma and then the plasma will expand with very high velocity which is also called the shockwave will be generated and then the plasma will finally it will be deposited onto the substrate. Now, I will discuss in a little bit more detail about the laser plasma interactions and it will laser light will be absorbed by the plasma through a process called the inverse beam style. In this process what will happen the generally then the plasma we know that we have already some basic knowledge about the plasma which is a consist of ions and electrons and also neutrals. Now, the laser light which will generate which is absorbed by the electron while it is colliding with the ions. So, there will be a electron ion collisions or electron ion interactions through the coulomb interactions.

So, in this way what will happen that the laser light which is you can say a oscillating electric field electromagnetic field and it will oscillate the electrons and this energy of this electrons then redistributed into the collisional energy between the electrons and ions. So, inverse beam style long is a process where it will that plasma will absorb the energy from the laser light while it is colliding with the ions. Now, we will consider the linear light plasma which in response to a high frequency electric field of the form e to the power i kx minus omega t. Now, that we consider the ions with a charge state z and it is surrounded by the neutralizing background with the density of Ne x by z. So, Ne is the density of the electrons.

Now, we can use that electron fluid with density Ne and it is has a velocity of e and it is interacting with a relatively generally the ions are the mass of the ions are much larger than the electrons. So, compared to electrons the ions movement of ions will be quite slow. So, one can consider that as if the electrons are moving at the background of the ions. So, in that case when the electrons ion collisions will takes place. So, we can use the equation del del t Ne Ue equal to.

So, that momentum transfers due to that collisions you can say that. So, here Ne Nu Ei is the collision frequency between ions and electrons. Now, we can use the forced equation for the electron fluid and which you can write as del U del t equal to minus E by m E is that electric field which is an E is the small E is the charge of the electron and small m is the mass of the electron and capital E is the electric field which is basically supplied by the laser light. Now, if the since the this electric field is oscillating and we will consider assume that velocities are also oscillating. So, if you just substitute the Ue as the minus omega t kx minus omega t.

Similarly, if you just substitute that E as. So, you can substitute this in the above equation and you can find out these relations and the finally the plasma current density one can get like this and if we use that formula of Ohms law that is J equal to sigma E. So, then one can find the conductivity sigma here and that which we have calculate. So, sigma is the conductivity of the plasma. So, by using this equation you can find out what will be the conductivity of the plasma.

Now if we use the Faraday's law and the Ampere's law then we can find out the dielectric function of the dielectric constant of the plasma as a function of frequency and where omega pe this is the plasma frequency this is the plasma frequency. Then we can use it in the wave equations and we can use that electron field oscillating electric field it will be a minus ikx minus omega t and if you substitute it in the dielectric constant epsilon then we can get a dispersion relations of laser light while propagating through a specially uniform plasma and this dispersion relation will be which is a very important. So, this is the dispersion relation which will give and now we know that the refracting index if it is it has a two part one is the real refracting index and another part is the complex refracting index and this complex refracting index is responsible for the absorption of light and this kappa that is the absorption coefficient it will be the minus twice of the imaginary part of this propagation constant k omega and if we use this so you can find out that there will be that we can find out the absorption coefficient which will come for the inverse Bemstrahlung process and which will be described where c is the velocity of light and here it will be described by this equation which is important because after generation of the plasma then the laser light it will obstructed or it will blocked by the plasma. So, this densities of plasmas and all other temperature of the plasma so all these things will be very much useful for the deposition further deposition of the laser produce plasma but this absorption process also helpful in further increase the temperature of the plasma so it will further increase the energy of the plasma and then it will move towards that substrate with a very high velocity. So now you can see some photographs of the expansion of the plasma from the substrate to the from the target to the substrate and here you can see that these are the plasma plume so this part this side is the this side is the your target.

So one can see that this is the photograph taken with a ICCD camera which is called the intensified charge coupled detector. So this camera is a very high speed camera it can because plasma which will ejected from the target materials it will be very fast so it is very difficult to capture these images of the plasmas with a very with a ordinary camera so you need a very high speed first camera so which can be useful with a ICCD. And now you can use another either filter or spectrometer so that you can select the different species that is the emission line of different species and so you can fixed either oxygen so here it is different like manganese oxide or lanthanum oxides if you want to deposit so in that case you can you want to study this kind of plasma so you can select the line for the oxygen like 770.54 nanometer with the spectrometer and then you take the image so you can see the how the oxygen this species it is moving from the target so you can see that slowly slowly after different time it is 0.

2 micro second 0.5 0.7 0.23 micro second so this further moving towards the substrate so slowly slowly it is moving. So similarly you can see for manganese also it is slowly expanding towards the substrate so and it can have depending upon the mass of this ions so it can have different velocity so it can have different time of flight to reach the substrate from the target. So now further when this all this species will deposit on the target so what will happen there will be surface diffusion and that surface diffusion will takes place and there will be nucleation also will takes place this is depends upon the temperature of the substrate and as well as the activation energy of the all this materials which will form the thin plume onto the substrate.

So upon reaching the substrate this species which will forming that plasma can fidget absorb or chemi absorb and then the coalitions of the thin plume will takes place via Oswald ripening or may be sintering or cluster migrations. So one has to further sinter or may be the annealing also can do so that it can have this materials can have enough energy to diffuse onto the substrate and it can form a good quality thin plume. Now there are several growth techniques while deposition of thin plume onto the substrate so one is the island type of plume growth so where the high surface tension is result from the it is causing from the atom-atom interactions so compared to the atom and surface interactions. So due to this there will be growth of island type of thin plume. This island type of thin plume are very useful for forming the metal thin plume of island type metal thin plume which are now a days very useful for plasmonic applications or some other optical applications.

So this is a kind of rough thin plume you can say because always depending upon the applications because sometimes people need a very rough plume which is not very smooth good quality plume but it can be useful for many application like sensing applications or some other applications also. So in that case one can grow the island type of thin plume. So there can be another type of thin plume which is where the interaction between atoms and the surface are much more stronger and compared to the atoms themselves. So in that case there will be layer by layer growth which is also similar to like the MB that is the molecular beam epitaxy. So it is a layer by layer growth so sometimes a laser beam epitaxy it is also called the laser beam epitaxy where with the help of laser pass laser deposition one can grow the layer by layer epitaxial thin plume.

So these plumes are very good quality smooth thin plumes. So this can also be these are also called Frank-Wender-Merwe or layer by layer growth. So initially we can have the island growth or layer by layer growth. So there are another type of growth which is called the Stransky-Kansternoff layer plus island. So in this case initially the plume will grow by layer by layer but then the forces between the island and the surface forces between the islands will becomes much more stronger so that the this layer by layer growth will be disturbed and then again islands like thin islands like plume will grow and it will so it will be just a islands on the top of the layer by layer thin plumes.

So this type of thin plumes also can be grown. So these are the three kinds of thin plumes can be grown and one can see that in the volume weber growth you can have island type of growth. So here you can see that all the atoms they are randomly oriented and in this Stransky-Kansternoff growth it will layer an island growth. So initially you can see that there is a layer by layer growth. So this is you can see the layer by layer and on the top this is island and it is totally island and it is completely layer by layer.

So all these type of growth mechanism this one can find while growing the thin plumes. Now we will discuss about the different parameter which initially also discussed. So discussed again that because these are as I have told you that laser wavelength is very important parameter because that which wavelength you will use either you can use mainly we use the UV lens because if you want to deposit the semiconductor or insulator thin plumes which will have a very large band gap or wide band gap. So one has to use the either 248 nanometer, a 244 nano 248 nanometer or 193 nanometer or 308 nanometer so within this range or maybe one can use the NdYa glazers of the wavelength of 355 nanometer or 266 nanometer. Then the pulse length so if you use the nanosecond pulses so their heating effect will be more and in that case initial part of the pulse will utilize for heating the materials and the later part of the pulse will generate the plasmas and then the part that.

So another thing is the pulse energy as I have told you the pulse energy is very important because that energy if it is more then it can rehabilitate the material from the substrate and it is very low so then it will not reach to the substrate. Another important thing is the focus spot, focus spot is also very important for growing because if we have a very small this focus spot is small say then what will happen the plasma will form like this conical shape it will be like this so the material which will be within this region it will be much more uniform which will reaching in this part and other part. So here now if we focus spot so here it is tight focused we can say that it is tight focused now if the focus spot is larger like this so plume will be much more uniform so you can get a uniform plume over a larger area. So this is wider focus spot so large area but in this case when you focus because pore site is much larger so you have to fix the energy also accordingly you have to choose. So this is also important thing sometimes how we will generate the plasma plume with the lens so which either it will be focused or defocused or which focal length you will use because on the focal length also if you have a very short focal length so then your Rayleigh parameter so Rayleigh parameter means within that the beam will be not uniform beam will be focused within and it is not uniform it will be within a small length it will vary but if you have a larger longer focal length so it will that Rayleigh length is quite longer that is mean that means that within this length that spot size of the laser beam will not very much changes.

So these are the then how much distance also because it will beam should be almost like parallel so when you will because we know that laser if laser light which will use if it is a fundamental so then it will be that distribution of the energy will be like a Gaussian so or the spot size will be like a Gaussian the intensity pattern will be Gaussian so when it propagate that beam it will diffract and so the distance which will use from the target to from that target to the laser output of the laser beam so that will be quite long enough so that the beam will be almost like a collimated type of beam. So these are also so from there you can find out the how much the beam will be diverge from the laser and then when it will focus by the lens and what will be the focus spot size so those things one can calculate and we can one can do some theoretical calculations prior to deposition of the thin flames. Then another problem another thing is the gaseous environment that also I have told you that if you use a inert gases like helium or argon then generally it is used to slow down the species so that a uniform good quality films can be takes place but it also depend upon the which material you are using the sometimes that background gas that is oxygen which will use if the masses of this oxygens are larger then the collisions which will takes place will be different when the if the masses of this species is lighter than the oxygen. Depending upon all these masses the collisions will takes place and then the how much amount of material will reach to the substrate it will depend. So gaseous environment it is plays a also a very crucial role for the pulse laser deposition of thin flame.

Then the target substrate distance also because one has to optimize this target substrate distance because if the distance is too large so then too long so then what will happen that material will not finally reach to the substrate but this distance is very small so then what will happen this plasma plume can de-ablet the material. Now finally I will come to that advantages and disadvantages of the pulse laser deposition technique. Though pulse laser deposition technique is a very versatile and it is very much useful for deposition but it has certain advantages as well as the disadvantages. Most advantages is the stoichiometry that is the flexibility for fabrications of the target material so it will maintain the stoichiometry of the target that is the composition of the target will be maintained while depositing the thin plume that is the stoichiometry of the thin plume will be same as the stoichiometry of the target. So that is the main advantage of the laser produced plasma.

Another thing is the cost if you want to use the normal MBE so it will almost the cost will be almost 10 times than the laser produced MBE so the cost is also compared to that other technique cost is low and another advantage is the different any kind of material whether it is insulator, it is semiconductor, it is conductor or it is metal so any kind of material one can deposit with this. While as some kind of sputtering and other technique like in the thermal evaporation if the evaporating temperature is very high then it may not be possible to deposit many oxide materials. Another thing is like sputtering in some cases you need a conducting target other but here you can deposit insulator conducting or any kind of target so all these things are very useful another thing is that deposition time is also relatively low and it can deposit both the inert and the reactive both in the presence of reactive and the inert gases. But despite the certain advantages there are main disadvantages, advantage of partial laser deposition is the large area uniform thin film because large area thin film is still is challenging but there are certain method like studying that substrate or some combinatorial partial laser deposition techniques so those are also people are using so maybe in near future it can be useful for industrial purposes. And then sometimes the particulates of micron size particle sometimes presence in the thin films which is detrimental to the quality of the thin films.

And now another thing is that problem which I have told you that light elements like oxygen or lithium have different expansion velocities and angular distribution in a plasma flow compared to the heavy elements so that will also vary the composition of the target and so a background gases is required to like inert gases to make a very good uniform and that with uniform composition and uniform thickness thin films. So in summary we can say that this partial laser deposition is a very useful and very simple things for deposition of any kind of materials and after deposition of thin films of course you have to do the characterization and other things those are mainly the problems with the condensed matter species. So then one can do the characterization of this thin films like that one can do the X-ray diffraction for crystalline structure for analyzing the crystalline structure of the thin film then one can do that electrical conductivity measurement like with the 4-probe method or IV characteristics and then one can do some optical characterization also by using UV visible photo photo UV visible spectrophotometer or one can use the ellipsometer also for studying the real and imaginary refracting index of the thin films. So depending and also one can study the magnetic properties with the help of squid or some whole technique and some other techniques also. So there are several techniques for characterization and also one can use the Raman spectroscopy photo luminescence spectroscopy so they are the different spectroscopy for studying the optical properties of thin films.

So depending upon the application so one can use the different techniques for characterization of the thin films but the as I have already shown you that knowledge of plasma is also very useful for depositing a very good quality thin film. So in situ monitoring of the plasma while depositing the thin film with the help of laser is also very important because as I have told you that the lighter elements like the oxygen or lithium they may have different velocities than the heavier elements and then the temperature of the plasma then the density of the plasma so all these parameters of the plasma which will determine the actual the quality of the thin film. So prior to the deposition of thin film and it may vary from different targets from target to target it will vary so if one can use this knowledge of these parameters all these parameters of this plasma parameters like electron and ion temperature plasma and then the velocity of electrons and ions so density of electron ion so all these parameters are useful so knowledge will be useful for deposition of the thin film. So with this I will just complete so thank you very much. Thank you.