Optimum Plasma Source — Substrate distance

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What is the optimum distance to the substrate?

A nitrogen plasma under conditions of direct plasma contact with the substrate—plasma enhanced CVD. In this case high energy species are undergoing collision with the substrate..

This question is frequently asked by Meaglow customers. The short answer is: if you're replacing an existing ICP source with a Meaglow hollow cathode, then using the same distance will be appropriate.

Using the same distance will give you results that will allow you to compare the advantages of your hollow cathode source. The same operating conditions can be used, though there may be changes in the growth per cycle, and improvement in the quality of the material — the extent of which will be material dependent.

The long answer is: the optimum distance is dependent on a number of variables. Plasma gas type, the material being deposited, the metalorganics used, the gas pressure, the power applied to the plasma source and the flow rate from the plasma source, all interact to determine this value.

Some guidelines can be provided. Generally there are two overriding considerations: delivery of a high flux of active species to enhance growth rate, versus the damage that the material being deposited can sustain.

Plasma sources create very active species, the presence of ions is well known but neutral species with high potential energy can also cause damage [1]. The presence and/or manifestation of damage depends very much on the deposition processes and on the material being grown. Plasma damage often manifests itself as etching, though point defect formation can also occur. When etching is the dominant affect, searching for conditions of high growth rate (or high growth per cycle, for atomic layer deposition) can help establish the optimum balance between etching damage versus high flux delivery.

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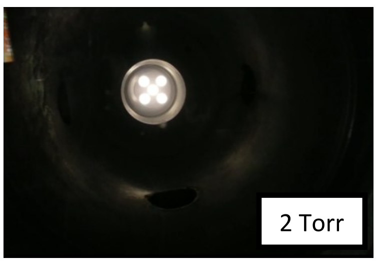
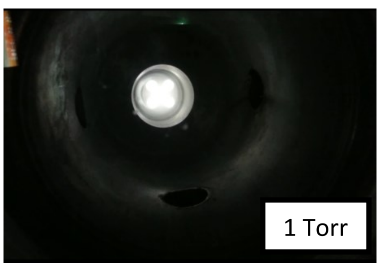
Using pressure and flow for a fixed plasma source-substrate distance.

The images below show the expansion of a plasma beyond the plasma generation region as the gas pressure is dropped from 2 to 0.3 Torr for a 100 Watt oxygen plasma.

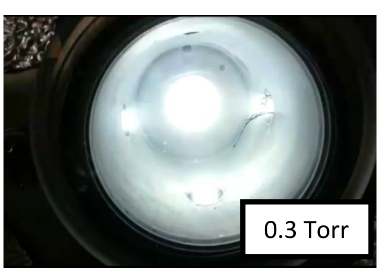


2 Torr



1 Torr

0.5 Torr



0.3 Torr

The plasma source to substrate distance is actually not as important as might be thought, as other variables can be changed to greater effect. In particular the gas pressure and flow rate are important.

Gas pressure and flow rate are important variables because they determine the number of collisions that a plasma species will undergo for a fixed distance between the plasma source and a substrate. Collisions with other gas particles and with containment vessel walls can reduce the energy of damaging plasma species. If enough collisions occur only low potential energy neutral radical species will remain. However, their flux may be reduced by further collisions, resulting in a reduced growth rate. From the previous section, it was noted that etch damage can also reduce growth rate. Therefore, conditions may be sought for the highest growth rate, which should balance conditions of plasma damage versus flux for each material investigated.

To increase the delivery of species to a substrate, when working with a fixed distance between the plasma source and the substrate, and a fixed power level, the following guidelines can be used:

- higher gas flow rate, or velocity = greater flux
- lower pressure = greater flux

The idea here is to minimize the gas collisions that occur between the plasma generation region and the substrate. The images to the side show the effect of lowering pressure for a hollow cathode oxygen plasma operated at 100 Watts of RF power. At 1-2 Torr the plasma is largely confined to the plasma generation region,

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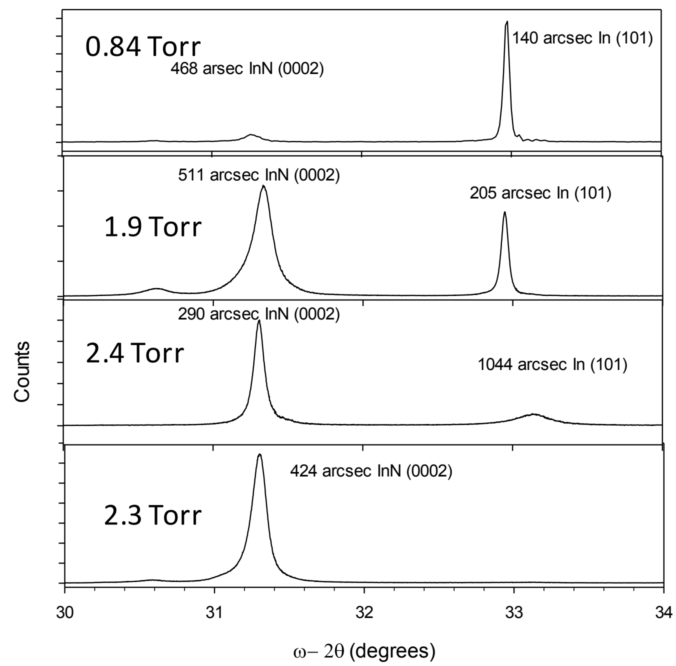
Using pressure and flow for a fixed plasma source-substrate distance (cont.).

though some long lived neutral species may travel further they do not generate light emission in the visible spectrum. Long lived species tend to have a large potential energy gap to the next lowest available energy state. For instance, the lowest excited state of molecular nitrogen has a potential energy of 6.2 eV above the ground state [2]. Photons related to this emission are deep in the UV, and therefore invisible to the eye.

At lower pressures (0.5 to 0.3 Torr) the plasma species that emit light in the visible range are expanding beyond the plasma generation region and at 0.3 Torr, they are basically flooding the chamber.

X-ray diffraction data for InN samples [3] grown with 600 Watt RF plasma power and with a 600 sccm nitrogen flow from the plasma source. The chamber pressure during growth is shown for each example..



Indium Nitride as an example

Our own work with indium nitride (InN) may be used as an indicator. We have found that InN is very susceptible to plasma damage, a journal publication describes this effect [3]. The above diagram provides the relevant data. It can be seen that for a fixed RF power and gas flow rate from the plasma source, for low pressure growth with fewer gas collisions, damaging species were able to reach the substrate and etch away the volatile nitrogen component. This resulted in an indium peak being present regardless of stoichiometry changes introduced by changing the supply of metalorganic.

At the higher pressure of approximately 2.3 to 2.4 Torr, the greater number of gas collisions reduced the flux of more damaging high energy species and InN could be grown without free indium in the film, indicating that loss of the volatile nitrogen component by etching was minimized. Under these conditions the film stoichiometry could be controlled by changing the delivery of the metalorganic.

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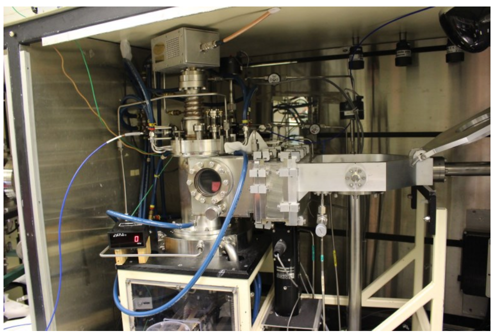
Calculating equivalent flow for different pressures.

MOCVD system converted to hollow cathode plasma operation.



It is evident that where there is no independent pressure control (for instance, using a down stream throttle valve) increased flow affects pressure so that the increase in flux provided by an increase of flow from a plasma source is countered by an increase of the chamber pressure resulting from the higher flow rate.

There are, however, some very simple kinetic gas equations that can be applied to determine, to a first order estimate, whether there is a gain or loss of flux resulting from the interaction of these two factors.

So from the InN example given on the previous page, the original paper [3] suggests that for a pressure of 2300 mTorr, a flow rate of 600 sccm and a source distance of 12.5 cm from the substrate, the low damage conditions necessary for InN film growth were achieved. The delivery area had a 14.6 cm diametre for this flow (the flow rate scales with area).

To a first order approximation we would achieve a similar flux of active species for different conditions by maintaining the same number of gas collisions for the plasma species before they arrive at the substrate. So for a 10 cm distance from source to substrate we would slow the flow rate (for the same pressure) to compensate:

Eg. 600sccmx (10cm/12.5cm) = 480 sccm

Now if we next drop the pressure down to 100 mTorr, from the kinetic theory of gases the gas collision rate is pressure dependent, so to compensate for this we have to lower the flow velocity in proportion to the pressure:

Eg. 480 sccm (100mTorr/2300mTorr) = 20.1 sccm

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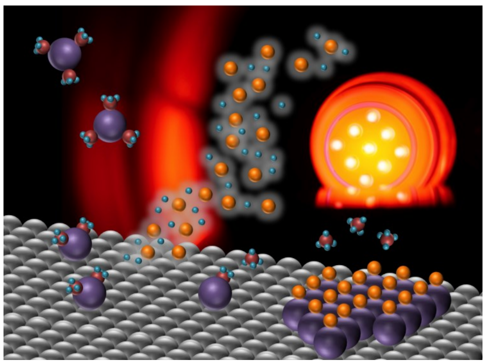
Calculating equivalent flow for different pressures (cont.).

Representation of the plasma enhanced ALD process.



However, flow rate is not the same as flow velocity. Flow rates are given under conditions of STP (standard temperature-pressure). A 20.1 sccm flow rate at a standard atmospheric pressure of 760 Torr has 7600 times the flow velocity at 100 mTorr (for 2300 mTorr the flow velocity is about 330 times higher than for the same flow rate at 760 Torr). So now we have to compensate for this difference in flow velocity related to the flow rate.

20.1 sccm (100mTorr/2300mTorr) = 0.874 sccm.

So, for this approximation (which only takes into account thermallised plasma species) a flow rate of 0.874 sccm at 100 mTorr should provide the equivalent flux of thermalized plasma species seen at 600 sccm for a higher pressure of 2300 mTorr.

For operation at 200 mTorr the equivalent would be 3.5 sccm, and for 300 mTorr 7.89 sccm. Of course, for some processes, having more active species might be advantageous (we find this for GaN) so a higher flow rate might be advantageous in those situations.

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Pressure is more Important.

MEAglow system with independent pressure control.

From the above, and to a first order approximation, it can be seen that substrate to source distance, and deposition area, scale linearly with flow rate in determining the number of collisions that a molecule will undergo between the plasma source and the substrate. Flow rate itself also scales linearly with the number of collisions.

However, pressure scales to the power squared, because of it's influence on flow rate. Therefore the source to substrate distance is less important than the pressure range being used. Indeed a wide range of fixed source to substrate distances can be accommodated through pressure control.

Many ALD systems have no means of independently controlling pressure and flow rate, however having a manual adjustment valve with good gas throughput between the growth chamber and pump can provide this. That extra process control can benefit substantially when there is some ambiguity regarding optimum source to substrate distance.

Alternately, the stronger dependence on pressure in determining molecular collisions can be used to filter more damaging species. A growth series involving pressure increments as the main control variable (despite the flow rate dependence) should provide an optimum growth rate (or growth per cycle) at the balance between film damage and flux supply. Though changes to the metalorganic flux with pressure may also need to be taken into account.

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References:

[1] K. S. A. Butcher, P. P.-T. Chen and J. E. Downes, Appl. Phys. Lett. **100** (2012) 011913.

[2] JN. Newman, Thermochemistry of III-N Semiconductors, Gallium Nitride I, Semiconductors and Semimetals Vol. 50, edited by J. I. Pankove and T. D. Moustakas (Academic Press, 1998), p. 87.

[3] K. S. A. Butcher, D.Alexandrov, P. Terziyska, V. Georgiev, D. Georgieva1 and P. W. Binsted, Phys. Stat. Sol. A **209** (2012) 41.

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