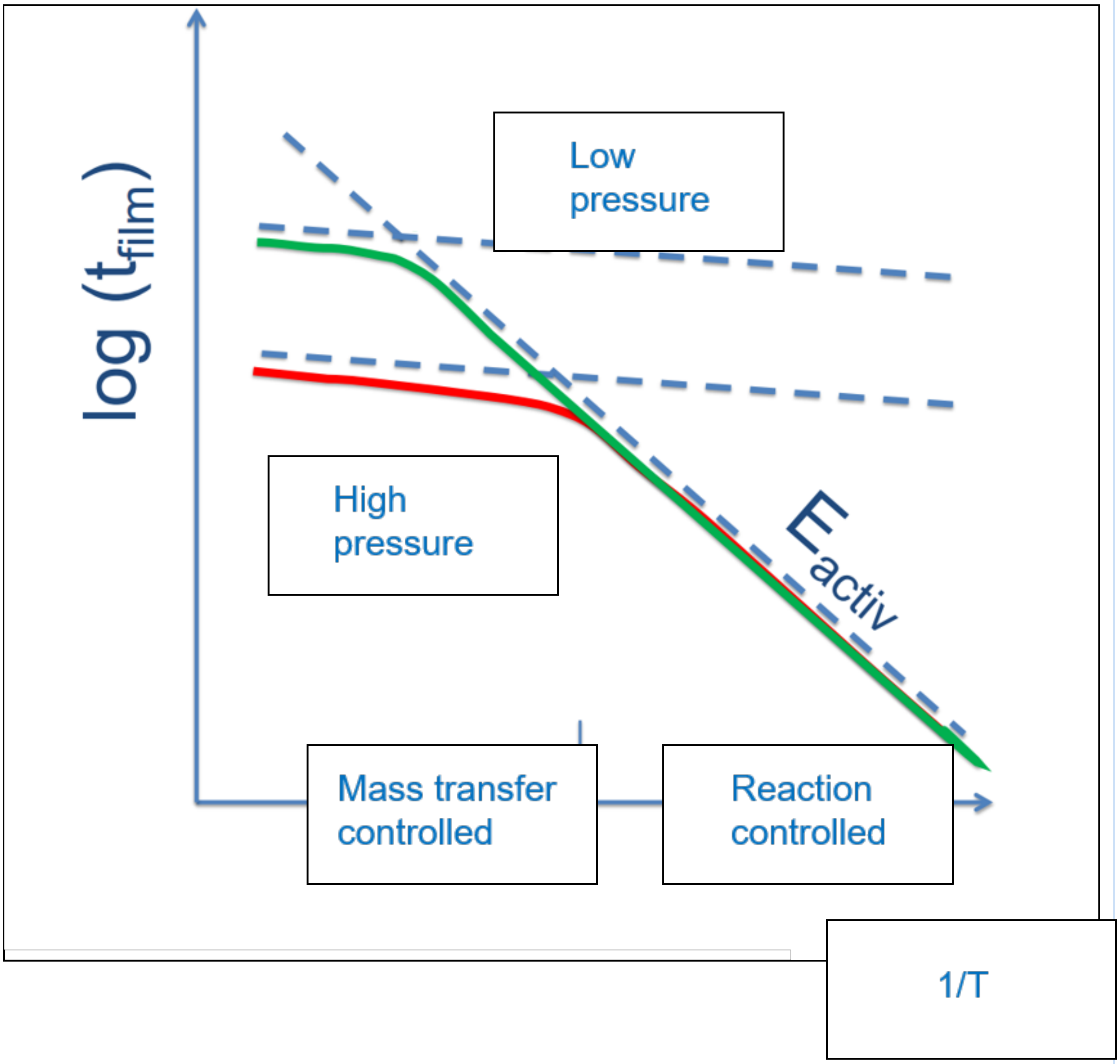
Started on	Sunday, 13 November 2022, 16:38
State	Finished
Completed on	Sunday, 13 November 2022, 19:15
Time taken	2 hours 36 mins
Marks	14.00/24.00
Grade	**5.83** out of 10.00 (**58**%)

Question **1**

Correct

Mark 1.00 out of 1.00

The Arrhenius plot of film growth rate is a convenient way to visualize the influence of temperature on the film formation velocity and the resulting film thickness t_{film} highlighting the different regimes. Please drag and drop the correct term into the image.



Your answer is correct.

The Arrhenius plot shows the logarithm of the film thickness vs 1/T. It helps visualize that at moderately low temperatures the film growth is limited by the chemical reaction and the growth rate increases linearly as the temperature is raised (due to the exponential factor). At moderately high temperatures instead, the slope will flatten out as the gas flow will not provide a sufficient concentration of molecules. When the gas pressure is decreased the mean free path of the molecules increases, meaning that gas molecules from further away can be used in the reaction.

Question **2**

Correct

Mark 1.00 out of 1.00

Why is the silicon dioxide thickness t_{ox} in a thermal oxidation process initially proportional to the time and later proportional to the square root of time?

- (•) Initially, the diffusion of oxygen to the SiO_2/Si front is rapid, but later takes longer when the SiO_2 gets thicker ✔
- ( ) Initially, the diffusion of silicon to the SiO_2 surface is negligible, but takes longer when the SiO_2 gets thicker
- ( ) As the process runs, more and more metal contaminants hinder oxygen availability at the substrate surface
- ( ) The diffusion of oxygen to the silicon surface is initially extremely low but recovers after the operation of the CVD reactor
- ( ) The temperature at the substrate surface gets lower when the SiO_2 gets thicker, which decreases the reaction rate

Your answer is correct.

During thermal oxidation, the oxygen reacts with the silicon from the substrate surface. Initially, when the silicon surface is exposed to the reactants (H_2O, H_2), no or very little diffusion is restricting the molecules from reaching the surface and the oxide thickness is proportional to time: $t_{ox}\sim$ time. When a layer of SiO_2 is already present on the surface, oxygen molecules need to diffuse through this layer, which gives an oxide thickness that evolves over time as $t_{ox}\sim\sqrt{\text{time}}$. See "Thermal oxidation processes of silicon and ALD deposition of specific oxides and metals" video from 03:24 to 04:35 for detailed explanations.

The correct answer is:
Initially, the diffusion of oxygen to the SiO_2/Si front is rapid, but later takes longer when the SiO_2 gets thicker

Question **3**

Incorrect

Mark 0.00 out of 1.00

As the pressure in a CVD reactor is reduced well below 1 atmosphere, which of the following statements is correct?

Multiple answers are possible.

- [x] High wafer throughput is not possible ✖
- [x] More fluctuations in the gas pressure favour uniformly deposited films ✖
- [ ] Diffusional gas transport becomes more pronounced
- [ ] Gas phase reactions become less and less dominant

Your answer is incorrect.

Low pressure leads to more homogeneous gas conditions in the reactor and less gas phase reactions. This has as a consequence that the wafers can be stacked vertically, occupying less space than when placed horizontally, thereby enabling higher wafer throughput. See "CVD techniques at different operating pressure, plasma-enhanced CVD and metal-organic CVD" video from 03:48 to 05:25 for detailed explanations.

The correct answers are:
Diffusional gas transport becomes more pronounced,

Gas phase reactions become less and less dominant

Question **4**

Correct

Mark 1.00 out of 1.00

In CVD processes, the growth rate of the thin film is a function of several parameters. One important parameter is the temperature on the substrate where the film forms.

At high substrate temperatures with thermal energy well above the activation energy of the reaction, in which regime is the film growth?	Mass transport-limited regime ✔
At low substrate temperature with thermal energy well below the activation energy of the reaction, in which regime is the film growth?	Reaction-limited regime ✔

Your answer is correct.

At relatively low temperatures the limiting factor for the deposition is the thermal energy needed for the reaction to occur (reaction controlled regime), while at higher temperatures the reaction occurs faster and the deposition is limited by the transport of gas to the substrate (mass transport limited regime).

The correct answer is:
At high substrate temperatures with thermal energy well above the activation energy of the reaction, in which regime is the film growth? → Mass transport-limited regime,

At low substrate temperature with thermal energy well below the activation energy of the reaction, in which regime is the film growth? → Reaction-limited regime

Question **5**

Correct

Mark 1.00 out of 1.00

What is limiting the thickness of SiO_2 layers formed by thermal oxidation of a silicon wafer?

- ○ After a while, all oxygen in the reactor is consumed
- ◉ Oxygen diffuses slowly through previously oxidized silicon ✔
- ○ The reaction is reversible and finds its equilibrium after a while
- ○ The silicon reaction rate at the surface of the substrate is low

Your answer is correct.

During thermal oxidation, oxygen reacts with a silicon wafer from the substrate surface. When a layer of SiO_2 is already present on the surface, oxygen molecules need to diffuse through this layer to reach the unoxidized Si, which results in an oxide thickness that grows less fast than linear with oxidation time, namely $t_{ox} \sim \sqrt{\text{time}}$. See "Atomic layer CVD (ALD) and thermal oxidation of silicon" video from 04:10 to 05:43 for detailed explanations.

The correct answer is:
Oxygen diffuses slowly through previously oxidized silicon

Question **6**

Correct

Mark 1.00 out of 1.00

What is correct in saying about the deposition rate of a thin film in a CVD chamber?

Multiple answers are possible

- [x] If gas pressure is increased at constant temperature, a deposition which is in the reaction controlled regime can never shift to the mass-controlled regime ✗
- [x] Local variations in the gas concentration occur less at lower pressure, in which case more uniform deposition rates can be achieved ✓
- [x] As the activation energy of the reaction decreases, the deposition rate decreases ✗
- [x] When using LPCVD process one can get an appreciable throughput thanks to the possibility of stacking multiple wafers simultaneously in the reactor ✓
- [ ] A lower gas flowrate results in a higher gas concentration near the heated substrate

Your answer is correct.

At atmospheric pressure, local variations in the gas concentration are common and would result in uneven deposition rates across the surface of the substrate. These variations can be reduced by lowering the pressure in the reactor. If the gas pressure is lowered, fewer molecules are available for deposition, but these can be transported from further away, so that the deposition rate increases; also deposition shifts to the reaction-controlled regime. See "Basic principles of CVD and CVD reactors" video from 06:58 to 09:41 for detailed explanations.

The correct answers are:
Local variations in the gas concentration occur less at lower pressure, in which case more uniform deposition rates can be achieved ,

When using LPCVD process one can get an appreciable throughput thanks to the possibility of stacking multiple wafers simultaneously in the reactor

Question **7**

Correct

Mark 1.00 out of 1.00

How is it possible to achieve single atomic layer precision in an Al_2O_3 deposition?

- ( ) By restricting the precursor gases to $Al(CH_3)_3$ only
- (•) By using $Al(CH_3)_3$ and H_2O precursors in a sequential, self-limiting manner ✓
- ( ) Reaction byproducts limit the growth of new layers, which is why the reaction chamber must be purged after the deposition of each new layer
- ( ) Slow reaction rates allow precise control of layer number

Your answer is correct.

ALD involves the use of multiple precursor gases in a sequential, self-limiting manner. A single layer of Al_2O_3 can be deposited in a four-step deposition process (2 precursors, 2 purges). After the first two steps (1st precursor, 1st purge), Al is deposited on the surface but not crosslinked. At the end of the cycle (2nd precursor, 2nd purge), a monolayer of Al_2O_3 is formed. See "Thermal oxidation processes of silicon and ALD deposition of specific oxides and metals" video from 07:49 to 10:00 for detailed explanations.

The correct answer is:
By using $Al(CH_3)_3$ and H_2O precursors in a sequential, self-limiting manner

Question **8**

Correct

Mark 1.00 out of 1.00

Which of the following is a main disadvantage of LPCVD as a thin film deposition method?

- Conformal material deposition across all surfaces of the substrate
- Materials for reactor construction are not readily available
- High wafer throughput is not possible because it is a one wafer at a time process
- The process operates at high temperatures, which can be harmful to substrates ✔

Your answer is correct.

A main advantage of LPCVD is conformal material deposition on substrates with arbitrary texture. This is achieved by the use of a gaseous phase which allows bringing reagents close to every part of the substrate, even when this has important non-planar texture. See "Basic principles of CVD and CVD reactors" video from 0:31 to 2:00 for detailed explanations.

The correct answer is:
The process operates at high temperatures, which can be harmful to substrates

Question **9**

Correct

Mark 1.00 out of 1.00

What can be correctly said about the laminar regime of the boundary layer?

- Inertial forces suddenly set in when the substrate temperature rises
- Inertial forces are much larger than viscous forces
- The mean free path of gas molecules is no longer a relevant parameter for CVD deposition
- The gas flow is more likely to be laminar in a smaller reactor ✔

Your answer is correct.

The Reynolds number is proportional to the horizontal coordinate x along the reactor and thus increases when the reactor size increases. This is why the gas flow in the reactor is more likely to be turbulent in a larger reactor. When the reactor size is getting smaller, the gas flow is more likely to be laminar throughout the chamber. See "Theoretical concepts of gas flow in CVD reactors" video from 06:01 to 07:05 for detailed explanations.

The correct answers are:
The gas flow is more likely to be laminar in a smaller reactor ,

The mean free path of gas molecules is no longer a relevant parameter for CVD deposition

Question **10**

Incorrect

Mark 0.00 out of 1.00

In a LPCVD reactor it is possible to deposit silicon. Polycyrstalline silicon (Poly-Si) is often used in microelectronics as gate in MOSFET's, whereas amorphous silicon (a-Si) is used in solar cells. Assuming otherwise similar conditions, which of the following process parameter is the most important one if the morphology of the deposited silicon film should be polycrystalline instead of amorphous?

- Reactor temperature
- Precursor gases
- Chamber pressure ✖
- Substrate material

Your answer is incorrect.

The critical parameter for the deposition of amorphous/polycrystalline silicon is the temperature. It influences the mobility of the deposited atoms, resulting in structural reorganization and variation of the deposited materials. See "Specific CVD processes for silicon-based materials and diamond" video from 02:34 to 03:42 for detailed explanations.

The correct answer is:
Reactor temperature

Question **11**
Partially correct
Mark 0.50 out of 1.00

The presence of shear stress in the gas flow near a heated substrate is an important phenomenon inside a CVD reactor and it is caused by the [different temperatures] ✖ of the gas flowing [in the boundary layer] ✔

[outside the boundary layer]

[different velocites]

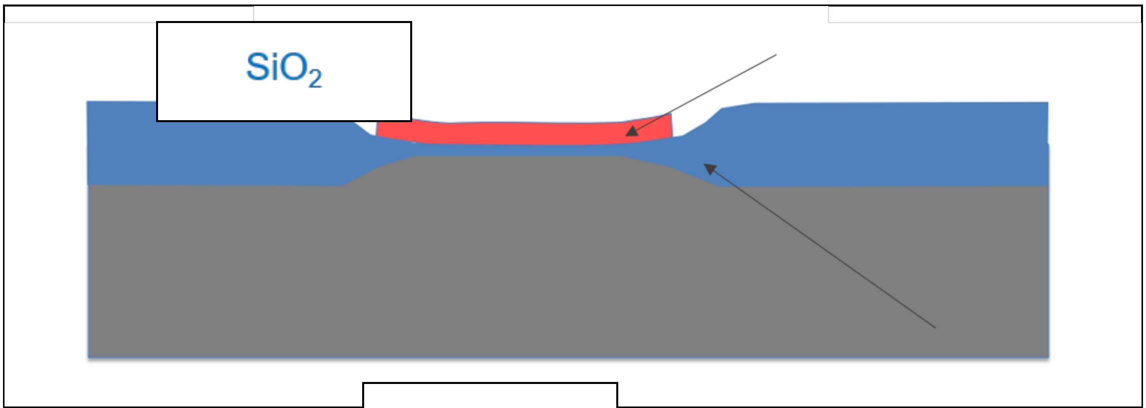
Your answer is partially correct.

You have correctly selected 1.
Shear stress is due to variable gas flow velocities at differing distances from the substrate. Due to the no-slip condition, the speed of a gas at the substrate is zero, but far enough from the substrate, the speed is basically equal that of the applied flowrate. This is causing variable flow speeds in the boundary layer. See "Theoretical concepts of gas flow in CVD reactors" video from 02:28 to 03:50 for detailed explanations.

The correct answer is:
The presence of shear stress in the gas flow near a heated substrate is an important phenomenon inside a CVD reactor and it is caused by the [different velocites] of the gas flowing [in the boundary layer]

Question **12**
Correct
Mark 1.00 out of 1.00

Local oxidation of silicon (LOCOS) is an important process step in the fabrication of a transistor (e.g. FET MOS). The structure shown in the schematic drawing below was fabricated using such a LOCOS process. Drag and drop the items onto the image.



Al_2O_3 Si SiH_4

Your answer is correct.

The drawing illustrates the LOCOS process (local oxidation of silicon) which is a thermal oxidation process where SiO_2 is formed in selected areas on a silicon wafer by using a Si_3N_4 mask.

Question **13**

Incorrect

Mark 0.00 out of 1.00

Consider a CVD reaction with an activation energy of 0.43 eV occurring in a reactor at 655 K. If the temperature is raised to 760 K, how much thicker would be the film for the same deposition time (assuming activation energy, probability of growth and gas concentration stay the same)? Take $8.6 \cdot 10^{-5}$ eV/K for k_B

Answer: 1.067 ✖

$$tfilm = Cgas \times Pgrowth \times exp(-Ea/KbT)$$

One can divide the expression of the thickness at the higher temperature by the one of the thickness at a lower temperature. By assuming that the gas concentration and the probability of growth stay the same, only the fraction of the two exponential factors remains, which can be calculated given the values of the two temperatures, the activation energy and kbT.

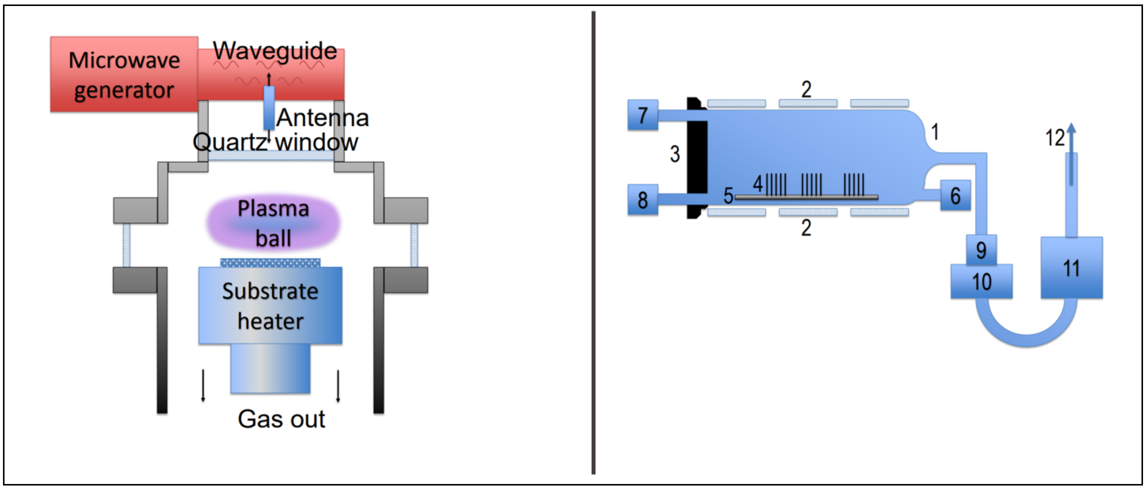
The correct answer is: 2.87

Question **14**

Partially correct

Mark 0.50 out of 1.00

The image below shows the schematic of two different CVD reactors. Drag and drop the items onto the image matching the kind of CVD process among the proposed ones that are compatible with each reactor.



Deposition on polymer substrate

ALD deposited Al_2O_3

Your answer is partially correct.

You have correctly selected 1.

The reactor on the left is a PECVD one meaning can be operated at low temperature and is therefore compatible with deposition on polymer substrates. On the right, there is an LPCVD reactor which can be used for the deposition of poly-Si.

Question **15**

Partially correct

Mark 0.50 out of 1.00

In ALD, how can single atomic layer deposition resolution be achieved?

Multiple answers are possible

- [ ] By using a reaction which stops once the product density is too high

- [x] By using a reaction which has a limited reaction rate due to low precursor concentration ✗
- [x] By introducing two specific gases in a sequential way into the reactor ✓
- [ ] By using a reaction which stops once all reactive sites on the surface are consumed

Your answer is partially correct.

You have correctly selected 1.
A self-limiting reaction is a reaction which stops once all reactive sites on the substrate surface are occupied. In ALCVD, this involves the formation of a monolayer by using a precursor gas, which covers the surface of a substrate and thereby depletes all available reaction sites. By alternating two different precursor gases, each of which is deposited in a self-limiting way, single atomic or molecular layer films can be achieved. See "Atomic layer CVD (ALD) and thermal oxidation of silicon" video from 00:50 to 02:17 for detailed explanations.

The correct answers are:
By using a reaction which stops once all reactive sites on the surface are consumed ,

By introducing two specific gases in a sequential way into the reactor

Question **16**

Incorrect

Mark 0.00 out of 1.00

Which statement is true for the simplified mass transfer equation?
Multiple answers are possible

- [ ] Close to the surface, but not exactly at the surface, the gas density depends linearly on the distance from the surface y
- [ ] It does not consider the advection term present in the general mass transfer equation
- [x] It is based on the assumption that there is no or little diffusion close to the surface ✗
- [x] The annihilation term -n˙ is no longer important for describing deposition phenomena ✗
- [x] It can still correctly describe non-equilibrium phenomena ✗

Your answer is incorrect.

The annihilation term is only non-zero at the surface because theoretically only at the surface gas molecules can be consumed. This leads to the conclusion that close to the surface, the gas concentration depends linearly at a certain distance from the surface y. See "CVD thin film growth model" video from 06:15 to 07:03 for detailed explanations.

The correct answers are:
Close to the surface, but not exactly at the surface, the gas density depends linearly on the distance from the surface y ,

It does not consider the advection term present in the general mass transfer equation

Question **17**

Incorrect

Mark 0.00 out of 1.00

Why are film depositions in LPCVD usually operated in the laminar flow boundary layer regime?

- ( ) Laminar flow allows multiple precursor gases to flow in parallel over the surface, which enables the deposition of mixed material layers
- ( ) Turbulent gas flow leads to a more controlled material deposition
- (•) Turbulent gas flow prevents reactions of the precursor gas with the substrate surface ✗
- ( ) More ordered gas flow leads to more controlled material deposition

Your answer is incorrect.

In LPCVD the pressure is sufficiently low for the system to operate in the laminar flow boundary layer regime which means the gas flows in a more ordered manner compared to the turbulent regime. This leads to a more uniform deposition

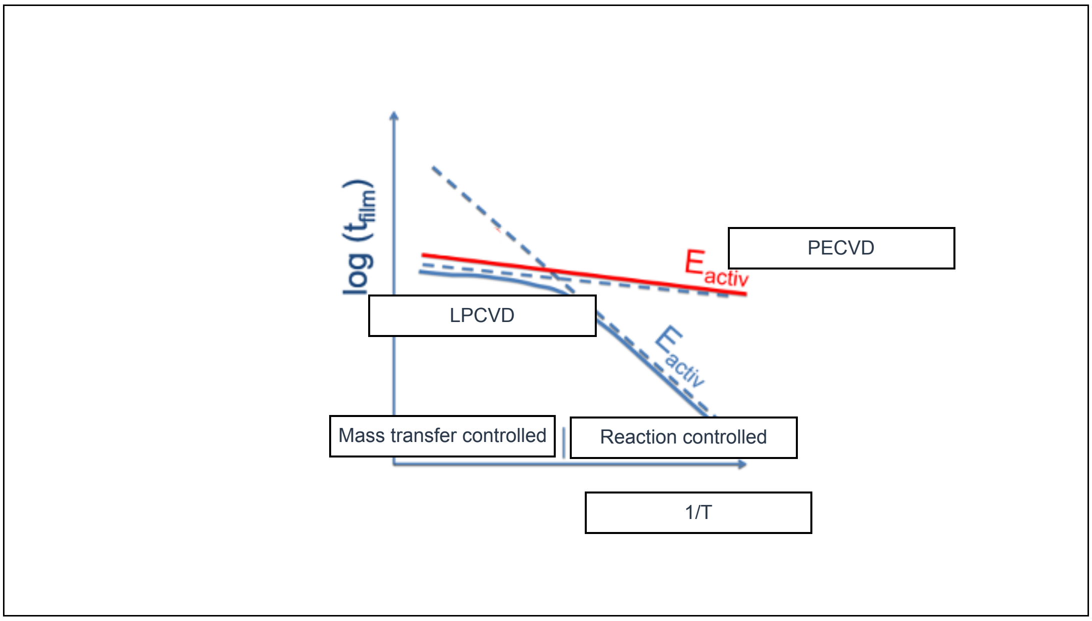
The correct answer is:
More ordered gas flow leads to more controlled material deposition

Question **18**

Correct

Mark 1.00 out of 1.00

The Arrhenius plot of film growth rate is a convenient way to visualize the influence of temperature on the film formation velocity and the resulting film thickness t_{film} highlighting the different regimes. Please drag and drop the correct term into the image.



T

Your answer is correct.

The Arrhenius plot shows the logarithm of the film thickness vs 1/T. It helps visualize that at moderately low temperatures the film growth is limited by the chemical reaction and the growth rate increases linearly as the temperature is raised (due to the exponential factor). At moderately high temperatures instead, the slope will flatten out as the gas flow will not provide a sufficient concentration of molecules. In the case of PECVD the plasma will raise the molecular energies reducing the effective activation energy for the reaction

Question **19**

Not answered

Marked out of 1.00

Consider a cubic CVD reactor with a side length of 2.5 m. Given a gas mass of 24 g in the reactor, a gas velocity of 2.1 m/s and a dynamic viscosity of $21 \cdot 10^{-5}$ kg/(m·s).

Calculate the Reynolds number.

Answer: ✖

$Re = \rho v L \div \mu$ where ρ is the gas concentration in the chamber, v the gas velocity, L the dimension of the

$Re = \rho v L / \mu$ where ρ is the gas concentration in the chamber, v the gas velocity, L the dimension of the chamber and μ the dynamic viscosity

The correct answer is: 38.40

Question **20**

Incorrect

Mark 0.00 out of 1.00

PECVD is the method of choice when diamond is deposited. Why?

- Other CVD methods are too expensive because a lot of precursor is wasted
- In PECVD, high pressure and high temperature are needed, which supports the diamond carbon allotype over graphite ✖
- Diamond adheres only on pyrex substrates which cannot be used in LPCVD
- Plasma is necessary for the activation of the reagents

Your answer is incorrect.

To deposit diamond by PECVD requires activation of the organic reactants H_2 or CH_4 by plasma to produce reactive sites during growth of the diamond lattice. See "Specific CVD processes for silicon-based materials and diamond" video from 13:09 to 14:17 for detailed explanations.

The correct answer is:
Plasma is necessary for the activation of the reagents

Question **21**

Incorrect

Mark 0.00 out of 1.00

As the pressure in a CVD reactor is reduced well below 1 atmosphere diffusional gas transport becomes [less important] ✖ and gas-phase reactions become [more important] ✖

Your answer is incorrect.

As the pressure is reduced to well below 1 atmosphere gas-phase reactions occur less leading to a more uniform deposition

The correct answer is:
As the pressure in a CVD reactor is reduced well below 1 atmosphere diffusional gas transport becomes [more important] and gas-phase reactions become[less important]

Question **22**

Correct

Mark 1.00 out of 1.00

The plasma used in plasma-enhanced chemical vapour deposition (PECVD) assists in reducing the effective activation energy and thus PECVD can operate at lower reactor temperature.

Select one:
- True ✔
- False

The plasma in a PECVD raises all molecular energies, therefore less heat is needed to activate the process.

The correct answer is 'True'.

Question **23**

If the gas pressure in a CVD reactor is increased at constant temperature, a deposition which is in the

Correct

Mark 1.00 out of 1.00

[mass-transfer controlled] ✔ regime can never shift to the [reaction controlled] ✔ regime

turbulent regime | laminar flow

Your answer is correct.

By lowering the pressure the mean free path of the gas molecules is increased, meaning that there will be gas molecules coming further from the substrate that can be used in the reaction. This causes the deposition at lower pressure to remain in the reaction-controlled regimes for a larger range of temperatures. This means that at a given temperature a process that is in the reaction-controlled regime can shift to the mass transfer controlled regime by increasing the pressure but not viceversa.

The correct answer is:
If the gas pressure in a CVD reactor is increased at constant temperature, a deposition which is in the [mass-transfer controlled] regime can never shift to the [reaction controlled] regime

Question **24**

Partially correct

Mark 0.50 out of 1.00

Which is a main advantage of plasma-enhanced CVD (PECVD)?

Multiple answers are possible

- [x] Deposition on polymer substrates becomes possible ✔
- [ ] Effective activation energy is reduced which enables increased growth rates
- [ ] Thin films can be selectively deposited on the substrates surface
- [x] The deposition is always in the mass-controlled regime ✘
- [x] Wafer throughput increases ✘

Your answer is partially correct.

You have selected too many options.
PECVD lowers the needed activation energy of a reaction because all molecules gain energy due to the plasma. This makes film growth possible at lower temperatures which leads to less restrictions to the used substrate. See "CVD techniques at different operating pressure, plasma-enhanced CVD and metal-organic CVD" video from 7:16 to 8:32 for detailed explanations.

The correct answers are:
Effective activation energy is reduced which enables increased growth rates ,

Deposition on polymer substrates becomes possible

◀ Rehearsal Quiz for Intro. & MEMS

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Rehearsal Quiz for PVD ▶