4.0. Chemical Vapor Deposition

4.1. Introduction

Chemical Vapor Deposition (CVD) is the process of depositing films by reacting chemical vapors to produce a film on a substrate. CVD reactions may be activated by heat (CVD), RF energy (plasma enhanced - PECVD) or by light (photon induced - PHCVD). CVD processes may be used to deposit a wide variety of insulating - dielectric films, poly and single crystal silicon and metal films.

4.2. Basic theory

The CVD process involves one or more gases being introduced into a reactor, most commonly at low pressure. The gases react at the surface of a substrate to form a film on the substrate surface. Figure 4.1 illustrates the steps in a CVD system reaction.

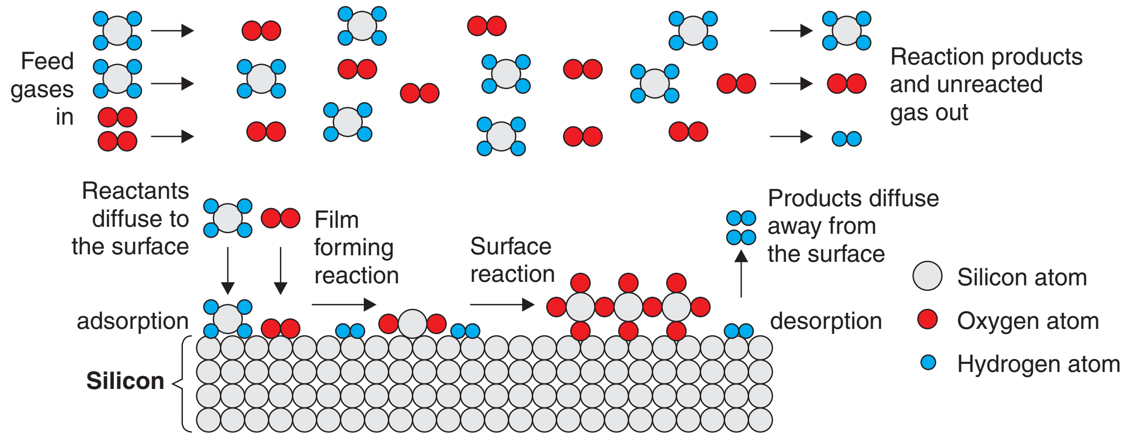
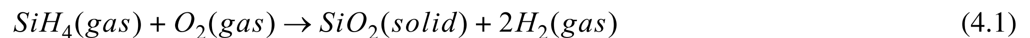


Figure 4.1. CVD deposition of second dioxide from silane.

In figure 4.1, silane (SiH_4) and oxygen (O_2) are introduced into a CVD reactor. The flowing gases form a stagnant boundary layer over the substrate surface that the gases must diffuse through to reach the surface. The gases are adsorbed onto the surface where they react to form silicon dioxide (SiO_2) giving off hydrogen (H_2) that then desorbs from the surface and diffuse away. The reaction is:



$$SiH_4(gas) + O_2(gas) \rightarrow SiO_2(solid) + 2H_2(gas) \quad (4.1)$$

There are many other possible reactions, this reaction is presented as an example. As mentioned in the introduction the process may be activated by heat, RF or photo energy.

CVD reactions may also take place at atmospheric pressure (APCVD) or low pressure (LPCVD).

4.3. Equipment

4.3.1. Horizontal furnace CVD systems

Early CVD systems were horizontal tube furnaces modified to operate under vacuum and with expanded gas control capabilities. Figure 4.2 presents a schematic diagram of such a system. The key elements of the system are:

- A water-cooled door seals the quartz process tube so that a vacuum can be created in the tube. The water cooling keeps the door o-ring seals from breaking down at the relatively high process temperatures required.
- The quartz process tube is surrounded by a three zone heating element.
- 3 zone temperature control with a center master zone to set the furnace temperature and slave end zones. The end zones compensate for heat lost out the ends of the furnace tube and allow for better temperature uniformity up and down the furnace tube. Horizontal furnaces can achieve plus or minus ½ degree centigrade temperature

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uniformity at temperatures up to 1,200 degrees centigrade although CVD processes are typically lower temperature processes.

- Modern horizontal furnaces suspend the wafers on a cantilever that does not touch the furnace sidewalls. Older style furnaces utilized quartz boats that slid along the bottom of the quartz furnace tube. The friction of quartz on quartz generated large numbers of particles. The cantilever systems have 100 to 1,000 times lower particle levels than older sled style systems.
- A roots blower and roughing pump is used to pump down the system and maintain vacuum during processing (see chapter 16 for a discussion of vacuum pumps).
- A pressure controller and throttle valve are used to control the system pressure during processing. The pressure control system allows pressure to be set independently of gas flow. Without a throttle valve the gas flow and pumping package pumping speed would result in a fixed system pressure. The throttle valve can also be used to compensate for changes in the pumping speed of the vacuum pumps as the vacuum pumps age.
- A gas control system with valves and mass flow controllers. The gas control system allows the gases flowing and flow rates to be controlled during processing.
- A central computer is used to control all of the elements of the system - temperature, pressure, gas flow, etc. throughout the process sequence.

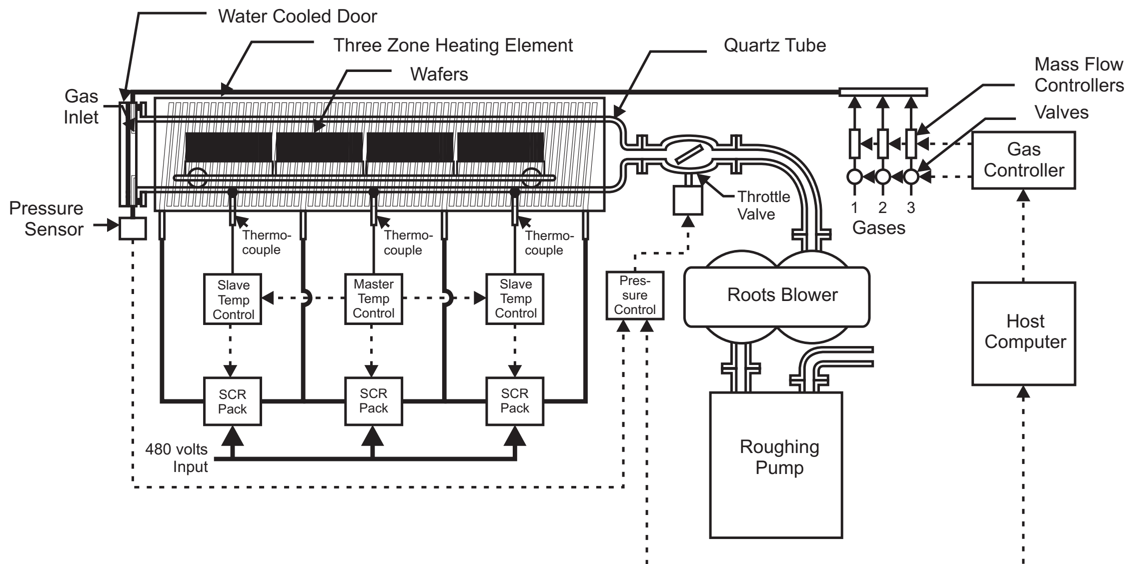

Figure 4.2. Horizontal CVD furnace system.

There are several issues with batch systems. Perhaps the most serious is that the gases are reacting and becoming depleted as the gases flow down the process tube. Without some sort of compensation scheme a thicker film results nearer to the gas inlets than further downstream. Sloping the temperature profile so that the temperature is higher as the gas flows downstream can compensate for gas depletion. Increasing the rate of gas flow can also help to compensate for gas depletion. Sloped temperature profiles can compensate to some extent for film thickness variation, but temperature differences can result in different film properties down the process tube. The hot wall nature of quartz tube batch systems results in significant film deposition on the process tube sidewalls. Over time film buildup on the process sidewalls can begin to flake off resulting in particles problems. A variety of in-situ and ex-situ cleans are used to try to control particle problems.

4.3.2. Barrel type epitaxial reactors

Early epitaxial silicon (single crystal silicon deposited on a substrate that follows the underlying crystal orientation of the substrate) reactors were barrel or pancake type reactors that processed multiple wafers at a time, see figure 4.3 for an example of a barrel reactor.

Key feature of the epitaxial reactor illustrated in figure 4.3 includes:

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- A graphite susceptor is suspended inside a quartz process chamber and holds the wafers on a sloped surface by gravity.
- A set of heat lamps - reflector assemblies surrounds the quartz process chamber and provides rapid heat-up of the wafers.
- Barrel type systems may be used for atmospheric pressure epitaxial deposition or for low-pressure epitaxial deposition when outfitted with a vacuum pump.
- Gas inlets are designed to swirl gas down around the susceptor depositing the films. The gases exit the chamber through an exhaust port at the bottom of the camber.

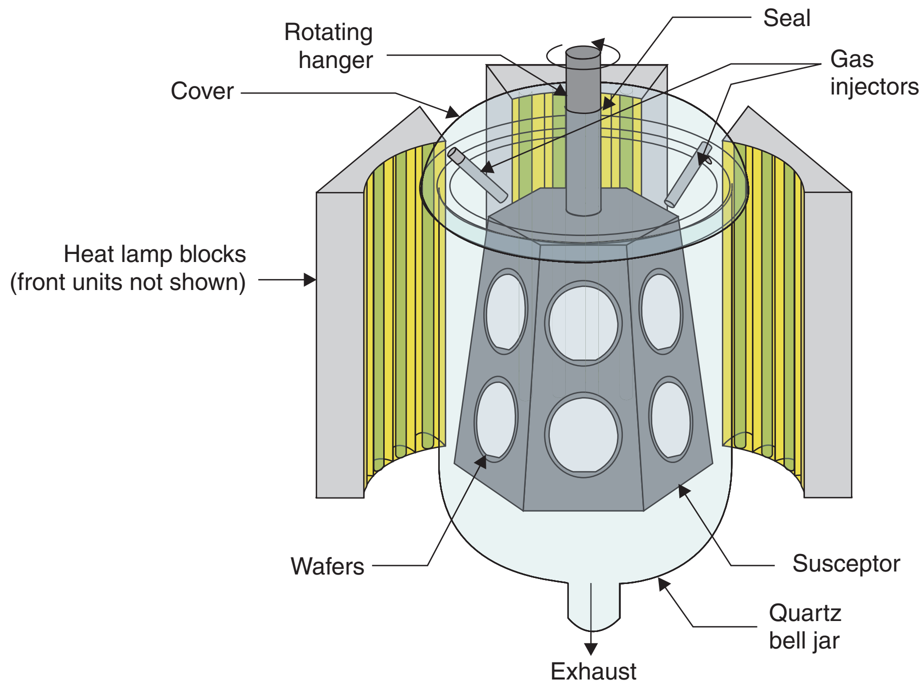

Figure 4.3. Barrel type epitaxial reactor.

4.3.3. Cluster tools

As linewidths shrunk below one micron, requirements for greater uniformity and particle control led to the switch over from batch or multiple wafer at a time CVD systems to single wafer at a time CVD systems and the advent of the cluster tool. In a cluster tool a central robot services load-unload ports and multiple process chambers. Cluster tools allow multiple chambers of the same or different process type to be combined on one common platform and enable complex multiple step processes to be performed in a computer controlled sequence continuously under vacuum. Figure 4.4 illustrates a cluster tool. Key features of the cluster tool illustrated in figure 4.4 include:

- A central robot that transfers wafers from the input and output cassettes to the individual process chambers. The central robot operates under vacuum so that a wafer can be transferred from one process chamber to the next while still under vacuum. The input and output cassettes are also typically under vacuum to minimize transfer times. In the ideal configuration the central cluster tool robot and input and output cassettes are all standards compatible so that process chambers from different vendors can be mixed and matched on the cluster tool for a best of breed approach. In practice only a few process chamber vendors make standards compatible chambers and the largest process chamber manufacture - Applied Materials only supports their own proprietary cluster tools.
- The cluster tool has multiple process positions where a variety of different process modules can be attached. The process modules may be different CVD modules or even different process types. Example of cluster tool approaches might include CVD deposition chambers mixed with etch-back chambers for planarization so that a deposition - etch-back - deposition - etch-back process may be performed. Alternately a deposition module might be mixed with a rapid thermal processing module to allow the deposited film to be annealed. Cluster

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tools are very widely used in state-of-the-art wafer fabs today providing CVD, RTP (see chapter 13), dry etch (see chapter 5) and dry strip (see chapter 6) functions).

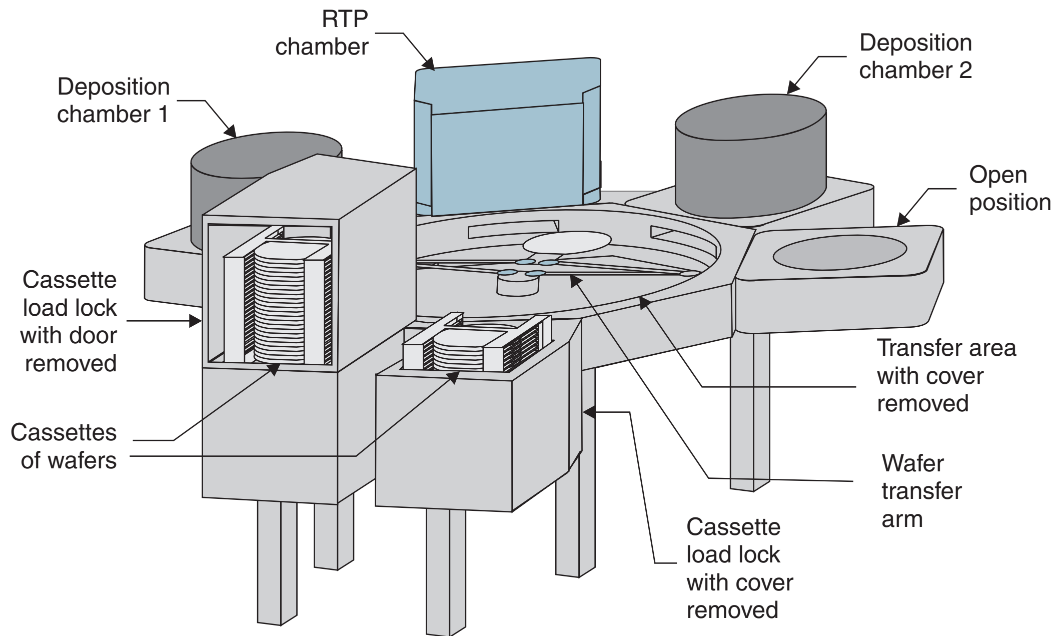

Figure 4.4. Cluster tool.

4.3.4. Single wafer CVD chamber

Figure 4.5 illustrates a single wafer CVD chamber used for submicron processing.

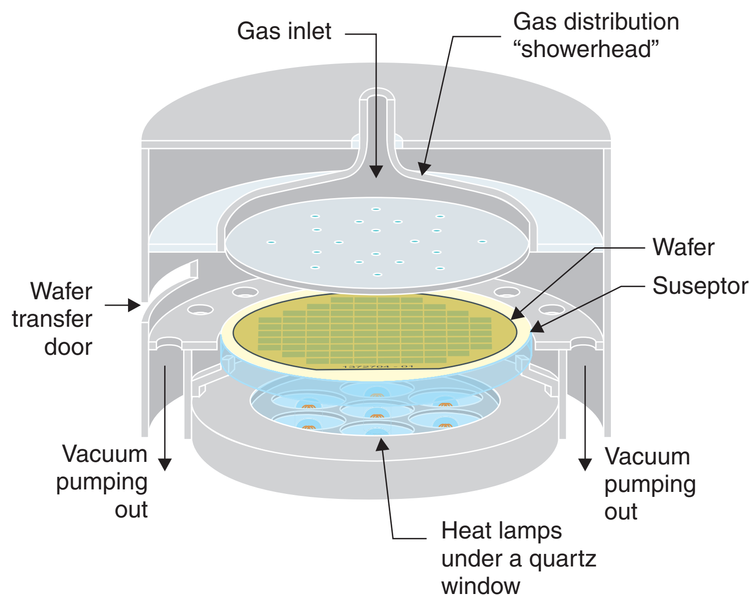

Figure 4.5. Single wafer CVD chamber. Adapted from [1].

Operation of the system illustrated in figure 4.5 is as follows:

- A wafer is inserted onto the susceptor through the wafer transfer door.
- The wafer transfer door closes sealing the vacuum chamber and the chamber is pumped down through the opening arrayed symmetrically around the wafer chuck.

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- The heat lamps under the susceptor turn-on heating up the wafer.
- Gases are introduced through the top of the system and flow down through the “showerhead”. The holes in the showerhead distribute the gas out over the surface of the wafer.
- The gases interact on the heated wafer system depositing the desired film.

The cold chamber walls help to prevent deposition on the walls minimizing particles. The chamber may also undergo an in-situ clean in between deposition steps. CVD systems such as this one are relatively simple, however pure CVD processes require temperatures >450° C Generally limiting CVD to usage prior to metallization.

4.3.5. Single wafer PECVD system

When linewidths were greater than approximately one micron, batch system such as the one illustrated in figure 4.2 were modified with the addition of radio frequency generators (RF) to create PECVD systems (see chapter 5 for a discussion of RF plasmas). PECVD system add plasma activation to CVD system enabling deposition processes with deposition temperatures of 250°C to 400°C making these deposition processes capable of depositing films over metals without exceeding the maximum stable temperatures for the metals.

As linewidths shrunk below one micron the same requirements for film uniformity and particle control that drove CVD system to single wafer processing drove PECVD systems to the same requirements. Figure 4.6 illustrates a CVD system outfitted for PECVD deposition.

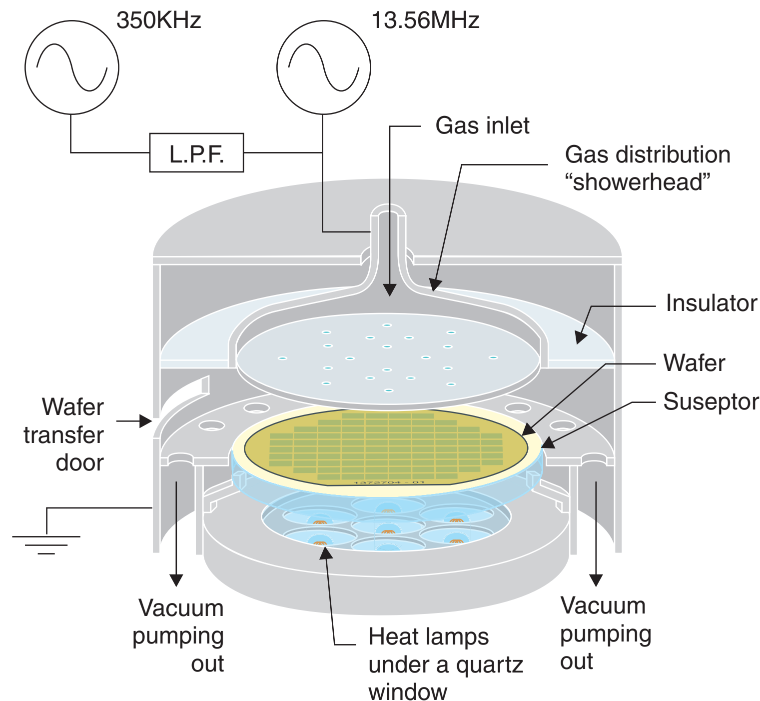

Figure 4.6. Single wafer PECVD system. Adapted from [1].

The major difference between the CVD system illustrated in figure 4.5 and the PECVD system illustrated in figure 4.6 is the addition of the R.F. generators for plasma generation. The use of two generators allows the plasma density and ion energy to be independently adjusted, the high frequency 13.56MHz generator primarily determines plasma density and the low frequency 350KHz generator primarily determines the ion energy.

The disadvantage of PECVD systems is low film density and a tendency of PECVD films to “cusp” at sharp corners pinching off deposition into high aspect ratio features leaving gaps in the film.

4.3.6. High density plasma (HDP) systems

HDP systems utilize high density plasma sources such as Inductively Coupled Plasmas to increase plasma density and also provide tunable ion bombardment. The addition of wafer biasing with ion bombardment cause the

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"cusps' normally seen during PECVD to be etched off by the ions and results in better gap fill, more planarization and a denser film.

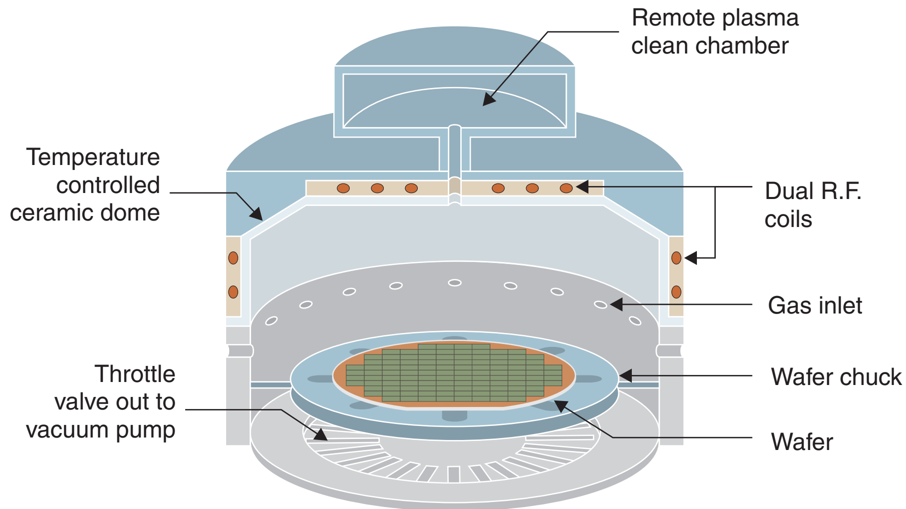

Figure 4.7. HDP deposition system. Adapted from [2].

The HDP system illustrated in figure 4.7 includes the following features:

- A remote plasma clean chamber used for chamber cleans between deposition runs.
- Dual inductively coupled R.F. coils that achieve high plasma densities with tunable bias.
- Distributed gas inlets and high flow symmetric pumping to insure uniform gas distributions.

4.4. Recipes

Table 4.1 summarizes some CVD applications, the deposited film and the typical system used for the deposition step. Table 4.2 summarizes some CVD recipes.

Table 4.1. Dielectric deposition applications summary.

Application	Film	Requirements	System
Shallow Trench Isolation polish stop layer.	Si_3N_4	High density film to resist oxidation during trench corner rounding oxidation step.	CVD
Shallow Trench Isolation trench fill.	SiO_2	High density film with good gap filling properties.	HDP
Gate polysilicon anti-reflective coating.	Si_3N_4	Optical properties.	CVD
Sidewall spacers.	Si_3N_4	Etch rate difference relative to SiO_2	CVD
Intermetal Dielectric layer 0 etch stop.	Si_3N_4	High density film with good barrier properties and etch rate difference relative to SiO_2.	HDP
Intermetal Dielectric layer 0.	Doped SiO_2	Thick film without cracking. Typically phosphorus doped or borophosphorous doped SiO_2.	PECVD
Intermetal Dielectric layer 1+ with aluminum lines.	SiO_2	Good gap fill.	HDP
Intermetal Dielectric film 1+ with damascene copper.	FSG or SiOC	Low-k films such as fluorine doped oxide or carbon doped oxide. Can be deposited with HDP or PECVD. PECVD is preferred due to lower complexity although many FSG films were deposited in HDP system already installed in fabs from previous generation products.	HDP or PECVD.

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Table 4.1. Dielectric deposition applications summary.

Application	Film	Requirements	System
Intermetal Dielectric film 1+ etch stop layer.	Si_3N_4 or SiC	Etch rate difference relative to FSG or SiOC. Lowest k value possible also desired.	PECVD
Passivation	Si_3N_4	Good barrier properties	PECVD

Table 4.2. Common CVD deposition reactants.

Film	Reactants	System	Composition	Step coverage	Temperature (^oC)
Al	TIBA, DIBAH, DMAH	LPCVD	---	Conformal	<250
Cu	$Cu(hfac)_2 + H_2$ or $Cu^1(hfac)L$	LPCVD	---	Conformal	350-450
Si	SiH_4	APCVD	Crystalline	---	950-1,050
	$SiCl_2H_2$	APCVD	Crystalline	---	1,050-1,150
	$SiHCl_3$	APCVD	Crystalline	---	1,100-1,200
	$SiCl_4$	APCVD	Crystalline	---	1,150-1,250
	SiH_4	LPCVD	Crystalline	---	550-700
	SiH_4	LPCVD	Polycrystalline	Conformal	580-650
Si_3N_4	---	PHCVD	---	---	50-250
	$SiH_4 + NH_3$	PECVD	$Si_xN_yH_z$	Non Conformal?-	250-350
	$SiH_4 + NH_3 + N_2O$	PECVD	$Si_xO_yN_z$	Non Conformal?	250-350
	$SiCl_2H_2 + NH_3$	LPCVD	$Si_3N_4(H)$	Conformal	700-800
SiO_2	SiH_4+N_2O	PHCVD	SiO_2	---	50-200
	$SiH_4 + O_2$ or $SiH_4 + N_2O$	PECVD	$SiO_{1.9}(H)$	Non Conformal	250
	TEOS + O_2	PECVD	SiO_x	Conformal	400
	TEOS + O_2	APCVD	SiO_2(-OH)	Isotropic flow	400
	$SiH_4 + O_2$	LPCVD	SiO_2(H)	Non conformal	450
	TEOS + O_2	LPCVD	SiO_2(-OH)	Conformal	700
	$SiCl_2H_2 + N_2O$	LPCVD	SiO_2(Cl)	Conformal	900
	O_2 or H_2O	Thermal	SiO_2	Conformal	700-1,200
TiN	$TiCl_2 + NH_3$ or $TiCl_3 + H_2/N_2$ or TDMAT + NH_3	LPCVD	---	Conformal	400-700, or >700
W	$WF_6 + SiH_4$ or $WF_6 + H_2$	LPCVD	---	Conformal	400-500

4.5. References

[1] Peter W. Lee, Shinsuke Mizuno, Amrita Verna, Huyen Tran and NBang Nguyen, *"Dielectric Constant Stability of Fluorine-Doped Plasma Enhanced Chemical Vapor Deposited SiO_2 Thin Films,"* J. Electrochem. Soc., p. 2015, Vol. 143, No. 6 (1996).

[2] *"Update,"* Applied Materials, Vol. 1, Issue 1 (2002)

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