Semiconductor Furnace Injectors

The Hidden Engineering Beyond Gas Delivery

MakeCoTech Engineering Insights | Issue 02: July 2026

MakeCoTech Engineering Insights | Issue 02: July 2026

Engineering for Reliability, Particle Performance, and Manufacturability

Although this article focuses on injectors, the same principles apply to any component exposed to deposition inside a semiconductor furnace.

Injectors are among the most critical components in a semiconductor furnace. They deliver process gases during CVD and ALD processes to the wafer stack, making uniform and repeatable deposition possible.

This article focuses on a less-discussed aspect of injector design: **mechanical reliability, particle performance, manufacturability, and service life**—rather than gas delivery alone.

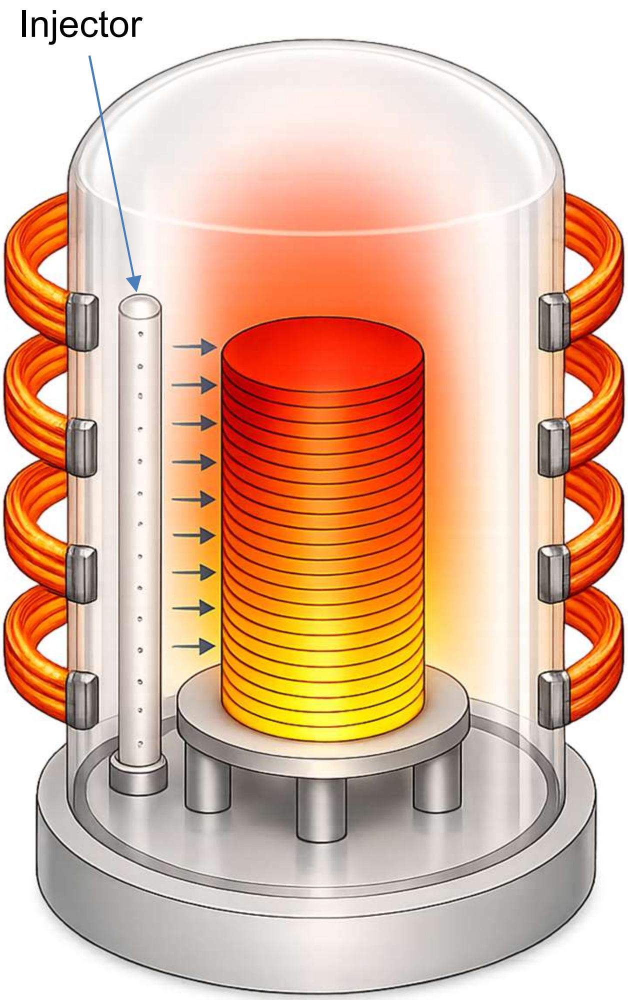
Although injectors are typically consumable components replaced during scheduled preventive maintenance (PM), extending their lifetime is essential to reduce maintenance cost and maximize equipment availability.

A well-designed injector should:

• Provide consistent process gas delivery.
• Minimize particle generation and contamination.
• Withstand deposition-induced and thermal stresses without cracking or distortion.
• Be manufacturable with consistent quality.
• Be optimized for the selected material (quartz, silicon, SiC, or advanced ceramics).
• Be easy to clean and, where applicable, reusable.

The limited space between the wafer stack and the furnace liner makes injector design particularly challenging. A poor design may lead to excessive deflection, particle generation, or premature failure. In the worst case, a broken injector can damage an entire wafer load and result in significant production losses.

Therefore, the injector's geometry, wall thickness, and material selection should be carefully engineered to maximize reliability, minimize contamination, and extend service life.



A Robust Injector Design Should Be:

• Resistant to mechanical failure
• Low particle generation
• Compatible with long PM intervals
• Easy to manufacture
• Cost-effective

Beyond Gas Delivery: Stress driven failure and particle generation mechanism

Injector Failure Mechanisms and Particle Generation

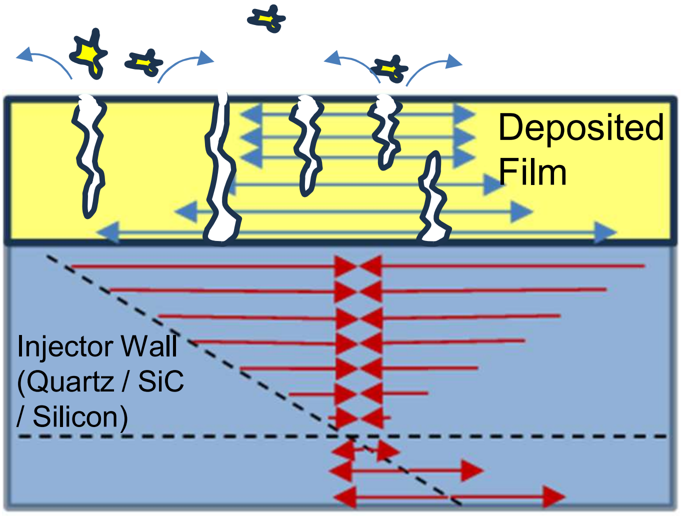
Although the primary function of an injector is to deliver process gases, it is also exposed to the same deposition environment as the wafers. During deposition, thin films grow not only on the wafers but also on the injector surface. Since the injector remains inside the reactor for many process cycles, deposited films continue to accumulate over time, often forming multilayer structures composed of materials different from the injector itself.

Why Can This Become a Problem?

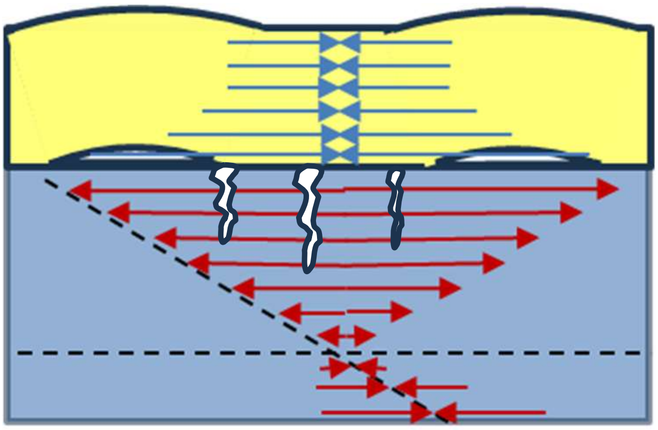
Deposited thin films often develop significant **intrinsic** and **thermal residual stresses**. These stresses depend on the deposition chemistry, process conditions, film thickness, and temperature history. Readers interested in this topic are referred to the extensive published literature on thin-film residual stresses [1-3].
Depending on the process, residual stresses can range from **several hundred MPa to more than 1 GPa**, in either tension or compression. As the deposited film becomes thicker, the elastic strain energy stored within the film increases. Once a critical energy level is reached, cracking of the film or even fracture of the injector substrate may occur.

Intrinsic stress is the internal mechanical stress generated within a thin film during deposition. It is distinct from thermal stress (caused by temperature changes) and depends entirely on atomistic growth mechanisms, such as grain boundary formation, defect annihilation, and lattice mismatch with the substrate.
Residual stress is the total stress locked within a thin film on a substrate. It consists of two main components: **intrinsic stress** (inherent to the deposition process) and **thermal stress** (caused by temperature changes).

Dopants can significantly alter intrinsic stress by modifying the crystal lattice and film microstructure.



Residual Stress Distribution
Film delamination & particle generation



Residual Stress Distribution
Injector wall failure/ layer delamination

- **High tensile residual stress** promotes film cracking, increasing the risk of particle generation.
- **High compressive residual stress** may cause film buckling, delamination, or even cracking of the injector substrate.

Design Constraints for Semiconductor Furnace Injectors

Key Design Considerations for Semiconductor Furnace Injectors

As discussed earlier, the limited space available between the wafer stack and the process tube often prevents the use of large, mechanically robust injectors. As a result, injector cross-sections are frequently non-circular.

The injector geometry is constrained by:

- Available space between the wafer stack and the process tube
- Gas distribution requirements
- Manufacturability
- Material selection
- Injection-hole pattern

Material Selection Matters

Different injector materials offer distinct engineering advantages and limitations.

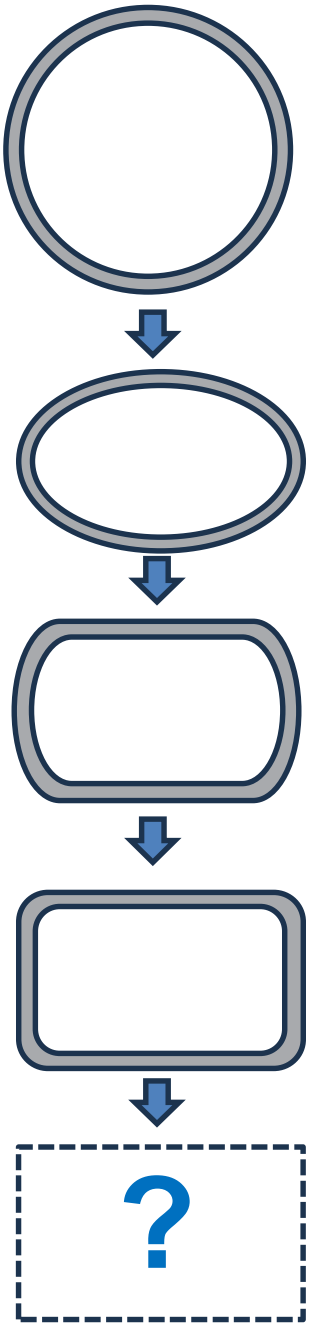
• **Quartz (Fused Silica)** – High purity, low cost, moderate fracture toughness, and often a large CTE mismatch with deposited films.

• **Silicon** – High stiffness, excellent dimensional stability, moderate fracture toughness, and generally a lower CTE mismatch with silicon-based deposited films.

• **Silicon Carbide (SiC)** – High strength, excellent fracture toughness, outstanding thermal resistance, but generally more expensive and difficult to machine.

• **Alumina (Al_2O_3)** – Good chemical resistance, electrical insulation, and high-temperature stability, but lower fracture toughness and thermal conductivity than silicon carbide.

Material selection should balance process chemistry, operating temperature, mechanical reliability, service life, and particle-performance requirements.



Typical form of failure in injectors

Large intrinsic and thermal stresses can initiate cracking and ultimately lead to injector failure. Loading a cold wafer stack into a hot reactor, or cooling during preventive maintenance, can generate significant thermal stresses.

MakeCoTech supports the design and optimization of injectors and other reactor components for Atmospheric, LPCVD, CVD, and ALD processes through advanced thermo-mechanical simulation and engineering consulting.

Engineering Design Guidelines

A robust injector should:

✓ Minimize stress concentrations
✓ Withstand intrinsic and thermal stresses
✓ Avoid sharp corners
✓ Maintain adequate stiffness
✓ Minimize deposited film cracking
✓ Be easy to clean
✓ Be manufacturable
✓ Maximize service life
✓ Minimize particle generation
✓ Allow refurbishment where practical

What Are the Engineering Solutions?

With extensive experience in thermo-mechanical analysis of semiconductor process components, MakeCoTech supports the design and optimization of injectors and other reactor hardware. Our engineering approach combines structural simulation, material selection, manufacturability, and failure analysis to achieve longer preventive maintenance intervals, reduced particle generation, and improved component reliability.

Closing

Whether you are developing a new injector or optimizing an existing design, **MakeCoTech** provides engineering support in thermo-mechanical analysis, particle reduction, structural integrity, and process optimization to improve manufacturing yield.

A reliable injector is defined not only by how well it delivers gas, but also by how long it delivers gas without generating particles or failing.

About the Author

Kianoosh Marandi, PhD, Eng.
Founder & Principal Consultant,
MakeCoTech – Advanced Engineering & Simulation Consulting

Kianoosh has more than 18 years of experience in advanced engineering, finite element analysis, and product development across the semiconductor, automotive, and research industries. His expertise spans semiconductor equipment, finite element analysis, nonlinear material modelling, contact mechanics, thermo-mechanical simulations, and wafer carrier optimization. He helps semiconductor equipment manufacturers solve complex thermo-mechanical and structural engineering challenges.

kianoosh.marandi@makecotech.com
www.linkedin.com/in/kianooshmarandi

Download more Engineering Insights at
www.makecotech.com

References

1- Fitch, J. T. (1989). Intrinsic stress and stress gradients at the SiO2/Si interface in structures prepared by thermal oxidation of Si and subjected to rapid thermal annealing. Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures, 7(4), 775. https://doi.org/10.1116/1.584599
2- Irene, E.A. Residual stress in silicon nitride films. J. Electron. Mater. 5, 287–298 (1976). https://doi.org/10.1007/BF02663273
3- Zhang, X., Chen, K.-S., Ghodssi, R., Ân, A. A. A., & Spearing, S. M. (n.d.). Residual stress and fracture in thick tetraethylorthosilicate (TEOS) and silane-based PECVD oxide films.