

Article

Numerical Simulation of Thermal Diffusion Effects on CVD Silicon Carbide Thin-Film Deposition

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Abstract

During the preparation of silicon carbide (SiC) thin films by chemical vapor deposition (CVD), the Soret effect induced by a large temperature gradient influences the deposition rate and uniformity; its sensitivity to process parameters remains unclear. A computational fluid dynamics model coupling detailed gas-phase and surface reaction kinetics was developed and validated for a cold/warm wall vertical CVD reactor. Comparing simulations with and without the thermal diffusion term reveals the dual role—suppressing deposition rate while degrading film uniformity. The thermal diffusion contributions to deposition rate (TDC_GR) and uniformity (TDC_GU) are introduced as quantitative metrics, and simulations evaluated the effects of inlet–substrate temperature difference (ΔT), reactor pressure (p), substrate rotation speed (ω), and carrier gas flow rate (Q) on the Soret effect, clarifying optimal conditions. Results show ΔT dominates. At $\Delta T = 1700$ K, TDC_GR = -56.39% and TDC_GU = 5.29% . Pressure affected TDC_GR negligibly but significantly reduced TDC_GU by enhancing gas-phase mixing; increasing p from 7500 to 12,500 Pa led to a decrease in TDC_GU from 4.19% to 1.93%. Optimal parameters ($\Delta T = 1400$ K, $p = 12,500$ Pa, $\omega = 800$ rpm, $Q = 50$ slm) achieved a deposition rate of $10.71 \mu\text{m/h}$ and non-uniformity of 0.45%. These findings provide theoretical guidance for precise SiC-CVD process control in cold- or hot-wall vertical reactor architectures.

Keywords: silicon carbide (SiC); chemical vapor deposition (CVD); Soret effect; numerical simulation; deposition rate; film uniformity

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1. Introduction

Silicon carbide (SiC), a representative third-generation wide-bandgap semiconductor, exhibits indispensable advantages in high-temperature, high-frequency, and high-power electronic devices owing to its high thermal conductivity, high critical breakdown field, high saturation electron drift velocity, and high chemical stability [1–4]. Consequently, SiC has been widely applied in key technological areas such as new energy vehicles, smart power grids, and aerospace engineering [5–7].

Chemical vapor deposition (CVD) is the primary method for preparing high-quality, low-defect-density SiC thin films [8–12]. Through the decomposition and reaction of gaseous precursors on the substrate surface, CVD enables the controlled growth of materials

at the atomic scale. Recent advances in computational approaches have also enabled atomic-scale insights into SiC growth mechanisms. For instance, molecular dynamics simulations have been employed to investigate the vapor deposition growth of SiC crystals on 4H-SiC substrates, revealing the influence of different crystal orientations and temperatures on the crystalline quality [13]. However, the trade-off between the deposition rate and uniformity remains a core challenge in CVD technology. Although increasing the deposition temperature and precursor concentration within a certain process window effectively enhances the deposition rate, it also exacerbates the non-uniformity of the temperature and velocity fields inside the reactor, degrading film deposition uniformity. This trade-off originates from the highly coupled, complex transport and reaction processes within the CVD reactor, involving multiple physical domains (fluid flow, temperature, concentration, and chemical kinetics) [14–18].

In a typical high-temperature (>1500 °C) SiC-CVD environment, a large temperature gradient (often exceeding 1000 K) exists between the hot substrate and the cooler reactor inlet and walls. This large gradient not only induces natural convection but also gives rise to a non-negligible Soret effect, often referred to as the thermal diffusion effect [19,20]. This effect refers to the phenomenon in which distinct molecules migrate at different velocities under the influence of a temperature gradient, with heavier molecules moving toward the colder regions, thereby establishing a concentration gradient [21]. Consequently, the precursors required for the reaction may be “driven away” from the hot substrate region by the temperature gradient, or intermediate products may become enriched in localized zones, altering the reactant concentration at the substrate surface and affecting both the deposition rate and the film uniformity. Li et al. [22] numerically investigated the Soret effect in graphene CVD and found that whether the effect promotes or hinders methane diffusion depends on the relative molecular weights of the species with respect to the average molecular weight of the gas mixture. Furthermore, the Soret effect significantly altered the distribution of the deposition rate along the gas flow direction.

The deposition rate and uniformity of SiC thin films are generally influenced by the gas flow velocity, operating pressure, substrate rotation speed, and deposition temperature. Seo [23] designed and optimized a funnel-type nozzle structure that effectively controls the gas flow velocity within the reactor and significantly increases the deposition rate. Shinde et al. [24] combined computational fluid dynamics (CFD) with the response surface methodology to optimize the process parameters and achieved favorable optimization results. Deivendran et al. [14] performed three-dimensional modeling and optimization of a vertical hot-wall CVD reactor, revealing the effect of natural convection on thin-film deposition inside the reactor through dimensionless analysis. Zheng et al. [25] employed a combined CFD-DOE approach to optimize the SiC-CVD process parameters and achieved a deposition rate as high as $24.8 \mu\text{m/h}$. However, these prior studies focused heavily on the macroscopic impacts of process parameters on final deposition outcomes, bypassing the underlying role of the thermal diffusion effect.

Although the importance of the thermal diffusion effect has been recognized, systematic studies that quantitatively isolate this effect from other transport phenomena over a wide range of process parameters are lacking [26]. How the thermal diffusion effect interacts with the process parameters, as well as how to reconcile the trade-off between the deposition rate and uniformity, remains to be fully explored.

In this study, systematic CFD simulations of the SiC-CVD process incorporating the thermal diffusion effect are performed. A quantitative evaluation framework based on thermal diffusion contribution (TDC) metrics is established to analyze the individual and coupled effects of ΔT , p , ω , and Q on the thermal diffusion effect and determine the optimal parameters that simultaneously maximize the deposition rate and film uniformity. This work provides theoretical insights into the underlying mechanisms governing the

thermal diffusion effect and provides a framework for the targeted optimization of SiC-CVD processing.

2. Mathematical Model and Numerical Method

2.1. Mathematical Model

Numerical simulations of the mass transport and chemical reactions within the reactor during the SiC-CVD process are performed based on the following assumptions and boundary conditions: (1) The gas is an ideal, incompressible, and viscous fluid with laminar flow; substance transport and surface reaction kinetics jointly determine the deposition behavior. (2) The reactor walls and the substrate are simplified as isothermal. (3) Deposition occurs only on the substrate surface, and the surface reactions are kinetically controlled. (4) Gravity and radiative heat transfer are accounted for. The governing equations are discretized and solved using the finite volume method.

(1) Continuity equation:

$$\nabla \cdot (\rho \vec{u}) = 0 \quad (1)$$

where ρ is the density of the gas mixture, and $\vec{u}$ is the velocity vector.

(2) Momentum conservation equation:

$$\nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot \vec{\tau} + \rho \vec{g} + \vec{F} \quad (2)$$

where p is the static pressure, $\rho \vec{g}$ is the gravitational body force, $\vec{F}$ represents other body forces, and the stress tensor is defined as follows:

$$\vec{\tau} = \mu \left[\left(\nabla \vec{u} + \nabla \vec{u}^T \right) - \frac{2}{3} \nabla \cdot \vec{u} \vec{I} \right] \quad (3)$$

where μ is the dynamic viscosity of the gas mixture, and $\vec{I}$ is the unit tensor.

(3) Energy conservation equation:

Considering heat conduction, thermal radiation, chemical reaction heat sources, and enthalpy transport due to species diffusion:

$$\nabla \cdot (\rho \vec{u} h) = \nabla \cdot (\lambda \nabla T) - \nabla \cdot \vec{q}_{rad} + S_h + \sum_i \nabla \cdot (h_i J_i) \quad (4)$$

where h is the total enthalpy of the gas mixture, λ is the thermal conductivity of the gas mixture, $\vec{q}_{rad}$ is the radiative heat flux (calculated using the discrete ordinates model), S_h is the heat source/sink term due to chemical reactions, h_i is the specific enthalpy of species i , and J_i is the diffusive mass flux of species i .

(4) Species transport equation (including the thermal diffusion term):

$$\nabla \cdot (\rho \vec{u} Y_i) = -\nabla \cdot J_i + R_i \quad (5)$$

where R_i is the net rate of production of species i by gas-phase chemical reactions ($\text{kg} \cdot \text{m}^{-3} \cdot \text{s}^{-1}$).

For the modeling of substance transport in multi-species mixtures, both the mass diffusion coefficient and the thermal diffusion coefficient must be considered. In laminar flow, the process is calculated using Fick's law:

$$J_i = -\rho D_{i,m} \nabla Y_i - D_{T,i} \frac{\nabla T}{T} \quad (6)$$

where the first term represents Fickian diffusion, $D_{i,m}$ is the mass diffusion coefficient of species i in the mixture, the second term represents thermal diffusion (Soret effect), and $D_{T,i}$ is the thermal diffusion coefficient of species i .

$$D_{i,m} = \frac{1 - X_i}{\sum_{j \neq i} (X_j / D_{ij})} \quad (7)$$

where X_i is the mole fraction of species i , and D_{ij} is the binary diffusion coefficient, given by the Chapman–Enskog formula:

$$D_{ij} = 0.0186 \frac{\left[T^3 \left(1 / M_{wi} + 1 / M_{wj} \right) \right]^{0.5}}{p \sigma_{ij}^2 \Omega_D} \quad (8)$$

where X_i is the molar mass of species i (g/mol), P is the absolute pressure (Pa); $\sigma_{ij} = 0.5(\sigma_i + \sigma_j)$ is the average characteristic Lennard–Jones length (Å), and Ω_D is the dimensionless diffusion collision integral for molecular interactions in the system:

$$\Omega_D = \frac{1}{T_D^{0.145}} + \frac{1}{(T_D + 0.5)^2} \quad (9)$$

where $T_D = T / (\epsilon / k_B)_{ij}$, and $(\epsilon / k_B)_{ij} = \sqrt{(\epsilon / k_B)_i (\epsilon / k_B)_j}$ is the average characteristic Lennard–Jones energy parameter.

The thermal diffusion coefficient $D_{T,i}$ is expressed using an empirical species-dependent expression:

$$D_{T,i} = -2.59 \times 10^{-7} T^{0.659} \left(\frac{M_{oi}^{0.511} X_i}{\sum_{k=1}^N M_{oi}^{0.511} X_k} - Y_i \right) \cdot \left(\frac{\sum_{k=1}^N M_{oi}^{0.511} X_k}{\sum_{k=1}^N M_{ok}^{0.489} X_k} \right) \quad (10)$$

(5) Ideal gas equation of state:

$$\rho = \frac{p}{RT \sum_i (Y_i / M_i)} \quad (11)$$

where R is the universal gas constant.

2.2. Chemical Reaction Kinetics Model

For the $\text{SiH}_4 + \text{C}_3\text{H}_8 + \text{H}_2$ (silane–propane–hydrogen) system, this study adopts the model introduced by Meziere et al. [26], which is a reasonably simplified version of previously published gas-phase and surface chemical reaction mechanisms. This chemical reaction model includes 17 gas-phase reactions and 19 surface reactions that influence SiC deposition/etching, as listed in Tables 1 and 2, respectively.

Although the $\text{SiH}_4 + \text{C}_3\text{H}_8 + \text{H}_2$ system has been extensively studied and is well-documented in the literature, we acknowledge that the academic and industrial communities have increasingly shifted towards alternative silicon precursors, such as chlorosilanes (e.g., SiHCl_3 , SiH_2Cl_2) and organosilicon compounds (e.g., hexamethyldisilane, HMDS), for SiC deposition. These precursors are often preferred due to their higher growth rates, improved safety, and better film quality at lower temperatures. However, from a fundamental transport phenomena perspective, the molecular weight, diffusivity, and thermal diffusion behavior of the primary silicon-containing species are the key parameters governing the Soret effect. The underlying model validated here captures these essential

physical and chemical processes, and the quantitative insights—such as the competition between thermal diffusion and convection—are not specific to the precursor chemistry. Therefore, the conclusions drawn from this study regarding the parametric sensitivity of the Soret effect are expected to be qualitatively, and to a large extent semi-quantitatively, transferable to SiC-CVD processes using other silicon precursors. The silane–propane system serves as an ideal benchmark due to its well-established, reduced chemical mechanism, allowing us to isolate and systematically study the thermal diffusion phenomenon without the additional complexity introduced by chlorine chemistry.

Table 1. Gas-phase reactions and kinetic parameters.

	Gas Reaction	$A \text{ (cm}^3\text{/mol)} \text{ s}^{-1}$	n	$E_a/R \text{ (K)}$
R1	$\text{SiH}_4 \rightleftharpoons \text{SiH}_2 + \text{H}_2$	6.671×10^{29}	−4.795	31,946
R2	$\text{Si}_2\text{H}_6 \rightleftharpoons \text{SiH}_2 + \text{H}_2$	3.240×10^{29}	−4.24	29,202
R3	$\text{SiH}_2 \rightleftharpoons \text{Si} + \text{H}_2$	1.060×10^{14}	−0.88	22,657
R4	$2\text{H} + \text{H}_2 \rightleftharpoons 2\text{H}_2$	9.200×10^{16}	−0.6	0
R5	$\text{C}_3\text{H}_8 \rightleftharpoons \text{CH}_3 + \text{C}_2\text{H}_5$	1.698×10^{16}	0	42,715
R6	$\text{CH}_4 + \text{H} \rightleftharpoons \text{CH}_3 + \text{H}_2$	2.200×10^4	3	4406
R7	$\text{C}_2\text{H}_5 + \text{H} \rightleftharpoons 2\text{CH}_3$	1.000×10^{14}	0	0
R8	$2\text{CH}_3 \rightleftharpoons \text{C}_2\text{H}_6$	9.030×10^{16}	−1.18	330
R9	$\text{C}_2\text{H}_4 + \text{H} \rightleftharpoons \text{C}_2\text{H}_5$	2.210×10^{13}	0	1040
R10	$\text{C}_2\text{H}_4 \rightleftharpoons \text{C}_2\text{H}_2 + \text{H}_2$	1.500×10^{15}	0	41,467
R11	$\text{H}_3\text{SiCH}_3 \rightleftharpoons \text{SiH}_2 + \text{H}_2$	2.000×10^{14}	0	36,413
R12	$\text{H}_3\text{SiCH}_3 \rightleftharpoons \text{HSiCH}_3 + \text{H}_2$	1.000×10^{14}	0	32,033
R13	$\text{Si}_2 \rightleftharpoons 2\text{Si}$	1.000×10^{15}	0	37,460
R14	$\text{Si}_2 + \text{CH}_4 \rightleftharpoons \text{Si}_2\text{C} + 2\text{H}_2$	3.011×10^{15}	0	10,000
R15	$\text{SiH}_2 + \text{Si} \rightleftharpoons \text{Si}_2 + \text{H}_2$	1.500×10^{14}	0	0
R16	$\text{CH}_3 + \text{Si} \rightleftharpoons \text{SiCH}_2 + \text{H}$	1.390×10^{12}	0.5	0
R17	$\text{SiCH}_2 + \text{SiH}_2 \rightleftharpoons \text{Si}_2\text{C} + 2\text{H}_2$	1.000×10^{15}	0	0

Table 2. Surface reactions and kinetic parameters.

	Surface Reaction	$A \text{ (cm}^3\text{/mol)} \text{ s}^{-1}$	n	$E_a/R \text{ (K)}$
G1	$\text{C}_{\text{vol}} + \text{Si}_{\text{surf}} + \text{H}_2 \rightarrow \text{SiH}_2 + \text{C}_{\text{surf}}$	2.200×10^{18}	0	52,786
G2	$2\text{Si}_{\text{vol}} + 2\text{C}_{\text{surf}} + \text{H}_2 \rightarrow \text{C}_2\text{H}_2 + 2\text{Si}_{\text{surf}}$	2.200×10^{32}	0	52,786
G3	$\text{SiH}_4 + \text{C}_{\text{surf}} \rightarrow \text{SiH}_{2\text{surf}} + \text{H}_2 + \text{C}_{\text{vol}}$	1.592×10^{10}	0.5	9401
G4	$\text{SiH}_{2\text{surf}} \rightarrow \text{H}_2 + \text{Si}_{\text{surf}}$	2.912×10^{14}	0	4527
G5	$\text{SiH}_2 + \text{C}_{\text{surf}} \rightarrow \text{SiH}_{2\text{surf}} + \text{C}_{\text{vol}}$	3.060×10^{11}	0.5	0
G6	$\text{Si} + \text{C}_{\text{surf}} \rightarrow \text{Si}_{\text{surf}} + \text{C}_{\text{vol}}$	3.167×10^{11}	0.5	0
G7	$\text{C}_2\text{H}_2 + \text{Si}_{\text{surf}} \rightarrow 2\text{C}_{\text{surf}} + \text{H}_2 + 2\text{Si}_{\text{vol}}$	3.040×10^{18}	0.5	0
G8	$\text{C}_2\text{H}_4 + 2\text{Si}_{\text{surf}} \rightarrow 2\text{C}_{\text{surf}} + 2\text{H}_2 + 2\text{Si}_{\text{vol}}$	2.342×10^{16}	0.5	0
G9	$\text{CH}_4 + \text{Si}_{\text{surf}} \rightarrow \text{C}_{\text{surf}} + 2\text{H}_2 + \text{Si}_{\text{vol}}$	2.098×10^5	0.5	0
G10	$\text{HSiCH}_3 + \text{C}_{\text{surf}} \rightarrow \text{Si}_{\text{surf}} + \text{H} + \text{CH}_3 + \text{C}_{\text{vol}}$	2.490×10^{11}	0.5	0
G11	$\text{CH}_3 + \text{Si}_{\text{surf}} \rightarrow \text{C}_{\text{surf}} + 1.5\text{H}_2 + \text{Si}_{\text{vol}}$	4.270×10^{11}	0.5	0
G12	$\text{Si}_2 + 2\text{C}_{\text{surf}} \rightarrow 2\text{Si}_{\text{surf}} + 2\text{C}_{\text{vol}}$	1.000×10^{20}	0.5	0
G13	$\text{Si}_2\text{C} + \text{Si}_{\text{surf}} \rightarrow \text{Si}_2 + \text{C}_{\text{surf}} + \text{Si}_{\text{vol}}$	1.000×10^{11}	0.5	0
G14	$\text{SiCH}_2 + \text{C}_{\text{surf}} \rightarrow \text{Si}_{\text{surf}} + \text{CH}_2 + \text{C}_{\text{vol}}$	2.550×10^{11}	0.5	0
G15	$\text{CH}_2 + \text{Si}_{\text{surf}} \rightarrow \text{C}_{\text{surf}} + \text{H}_2 + \text{Si}_{\text{vol}}$	4.419×10^{11}	0.5	0
G16	$\text{H} + \text{Si}_{\text{surf}} \rightarrow \text{SiH}_{\text{surf}}$	2.180×10^{12}	0.5	0
G17	$\text{H} + \text{C}_{\text{surf}} \rightarrow \text{CH}_{\text{surf}}$	2.180×10^{12}	0.5	0
G18	$2\text{SiH}_{\text{surf}} \rightarrow 2\text{Si}_{\text{surf}} + \text{H}_2$	2.250×10^{24}	0	30,000
G19	$2\text{CH}_{\text{surf}} \rightarrow 2\text{C}_{\text{surf}} + \text{H}_2$	2.250×10^{24}	0	30,000

Note: Si_{surf} represents the silicon dangling-bond active sites on the substrate surface; C_{surf} represents the surface carbon active sites; Si_{vol} denotes the surface-layer silicon atoms; C_{vol} denotes the surface-layer carbon atoms; $\text{SiH}_{2\text{surf}}$ represents the SiH_2 groups adsorbed on the surface, among others.

The gas-phase reaction rates follow the Arrhenius law:

$$k = AT^\beta \exp\left(-\frac{E_a}{RT}\right) \quad (12)$$

where A is the pre-exponential factor, E_a is the activation energy, and β is the temperature exponent.

The deposition rate of the SiC thin film (GR , $\mu\text{m}\cdot\text{h}^{-1}$) is calculated by summing the surface deposition fluxes of Si-containing species:

$$GR = \sum_i^N \frac{GR_i}{N} \quad (13)$$

The deposition uniformity (GU) of the thin film is defined as follows:

$$GU = \sum_i^N \frac{|GR_i - GR|}{GR \cdot N} \quad (14)$$

The SiC-CVD process is numerically simulated using the species transport module in FLUENT, which accounts for gas-phase reactions, surface reaction kinetics, and heat and mass transfer phenomena. The simulation involves solving the conservation equations for mass, momentum, energy, and species concentrations. Pressure–velocity coupling is handled using the coupled algorithm. The momentum, species, and energy equations are discretized spatially using the second-order upwind scheme, while pressure interpolation is performed using the standard format. Convergence is established when the residuals for all equations drop below 1×10^{-6} .

2.3. Geometric Model

The vertical CVD reactor used in this study (Figure 1) consists primarily of a cylindrical chamber with a total height of 200 mm, a reaction chamber height of 100 mm, and a reactor diameter of 260 mm. The substrate (6 inches) is placed horizontally on a graphite susceptor. To reduce computational cost by taking advantage of axisymmetry, a two-dimensional axisymmetric model is employed for simplified calculations.

This reactor geometry and wafer size are representative of contemporary SiC epitaxial production systems, where 6-inch and emerging 8-inch wafers are the industry standards for power device fabrication. The axisymmetric nature of the reactor enables efficient 2D modeling while capturing the essential transport phenomena relevant to industrial-scale operation. The optimized process parameters identified in this study are therefore expected to provide practical guidance for process optimization in commercial SiC-CVD reactors of similar configuration.

The reaction gases are uniformly injected from the top and, after reacting over the substrate region, are discharged through the outlet at the bottom. The inlet gas consists of silane (Si source), propane (C source), and hydrogen (carrier gas), with mass flow rates of 120 sccm, 40 sccm, and 70 slm, respectively. Considering that the vertical reactor employs water-cooled walls, all walls are set to an isothermal condition of 300 K. The inlet gas is not preheated and is also maintained at 300 K. The initial substrate temperature is set to 2000 K, which is subsequently varied with ΔT . The outlet pressure is set to the operating pressure. Under such extreme temperature differences, the Grashof (Gr) and Reynolds (Re) numbers are calculated to confirm that the flow remains within the steady laminar regime, thereby validating the assumptions.

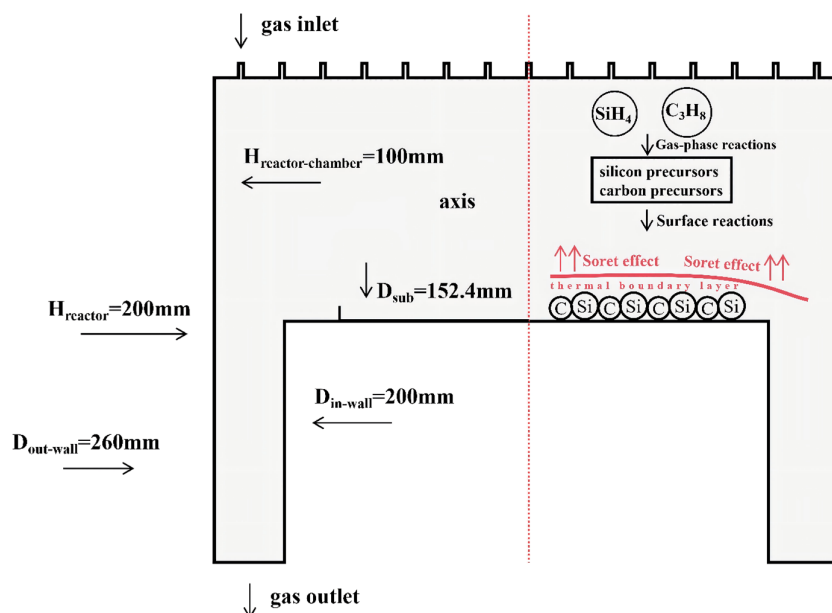


Figure 1. Schematic of the vertical cold/warm wall CVD reactor. The thermal boundary layer above the hot substrate is the region where the Soret effect (thermal diffusion) competes with downward convective transport: heavy precursor molecules (e.g., SiH_4) are driven upward away from the substrate, while light molecules remain largely unaffected, reducing the reactant flux reaching the substrate.

In the vertical CVD reactor configuration employed in this study, both precursor gases (SiH_4 and C_3H_8) are uniformly injected vertically downward from the top gas inlet at a 90° angle to the substrate surface. This injection configuration ensures symmetric gas distribution within the reactor chamber and is consistent with the standard design of vertical showerhead-type CVD reactors.

2.4. Evaluation Metrics for the Thermal Diffusion Effect

To quantitatively evaluate the influence of the thermal diffusion effect, the following two evaluation metrics are defined in this paper:

The thermal diffusion contribution to the deposition rate:

$$TDC_GR = \frac{GR_{on} - GR_{off}}{GR_{off}} \times 100\% \quad (15)$$

where GR_{on} and GR_{off} are the average deposition rates across the substrate with and without considering the thermal diffusion effect, respectively. A negative value indicates that the thermal diffusion effect suppresses the deposition rate, and a larger absolute value of this metric indicates stronger suppression.

The thermal diffusion contribution to the deposition uniformity:

$$TDC_GU = GU_{on} - GU_{off} \quad (16)$$

where GU_{on} and GU_{off} are the average uniformities across the substrate with and without considering the thermal diffusion effect, respectively. A positive value indicates an increase in film non-uniformity when the thermal diffusion effect is considered, meaning that the thermal diffusion effect degrades deposition uniformity.

3. Results and Discussion

3.1. Influence of the Thermal Diffusion Effect Under the Baseline Scenario

The baseline scenario parameters are set as follows: $\Delta T = 1700$ K, $p = 10,000$ Pa, $\omega = 600$ rpm, $Q = 70$ slm. This parameter set was chosen because it corresponds to a well-established baseline scenario adopted in prior SiC-CVD studies. Using this baseline not only allows direct validation of the present model against published data but also provides a consistent reference point against which the individual and combined effects of the process parameters can be systematically isolated and compared. Under this condition, comparative simulations are performed with and without the thermal diffusion term, and Figure 2 shows the resulting temperature and velocity fields. Notably, incorporating the thermal diffusion effect has no significant influence on the temperature or velocity fields. This is because the driving force of the thermal diffusion effect is the temperature gradient; thus, the influence of the thermal diffusion effect is negligible in the region above the thermal boundary layer. Within the thermal boundary layer near the substrate, the pumping effect combined with the high-speed rotation of the substrate increases the fluid velocity, making convection the dominant mode of mass and energy transfer in this region.

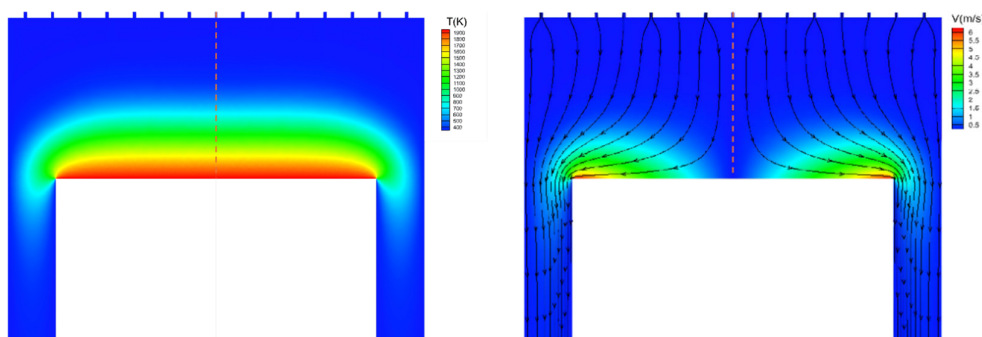


Figure 2. Temperature and velocity fields under the baseline scenario with (left) and without (right) the thermal diffusion effect.

By comparing the molar deposition rates of the carbon and silicon species above the substrate, close agreement is observed (the carbon molar flux is computed to be approximately 1.507776×10^{-6} mol·m⁻²·s⁻¹, while the silicon molar flux is approximately 3.518144×10^{-6} mol·m⁻²·s⁻¹), resulting in a C/Si molar ratio very close to unity. This near-stoichiometric ratio matches the expected composition of SiC, confirming that the numerical model correctly captures the deposition of SiC thin films. The predicted deposition rates under baseline conditions (5.63–12.91 μm/h) are also within the typical range reported in the literature for SiC-CVD processes (5–10 μm/h for standard growth conditions, and up to 24.8 μm/h under optimized conditions).

Nevertheless, the thermal diffusion effect profoundly impacts the deposition results, as seen in Figure 3. When thermal diffusion is considered, the average deposition rate across the substrate surface is 5.63 μm/h, with a film non-uniformity of 6.85%. Here, the degree of slope in the radial deposition rate profile directly reflects the spatial non-uniformity: a steeper slope corresponds to more pronounced non-uniformity. In contrast, when thermal diffusion is neglected, the average deposition rate increases to 12.91 μm/h, and the non-uniformity decreases to 1.55%. Under these baseline scenarios, the calculated TDC_GR is −56.39%, and TDC_GU is 5.29%.

It is noteworthy that the deposition rate profiles are highly uniform within the 0–40 mm radial range, regardless of whether the thermal diffusion effect is considered. This

observation can be attributed to the centrifugal pumping effect generated by the rotating substrate (600 rpm), which effectively suppresses radial non-uniformity in the near-center region.

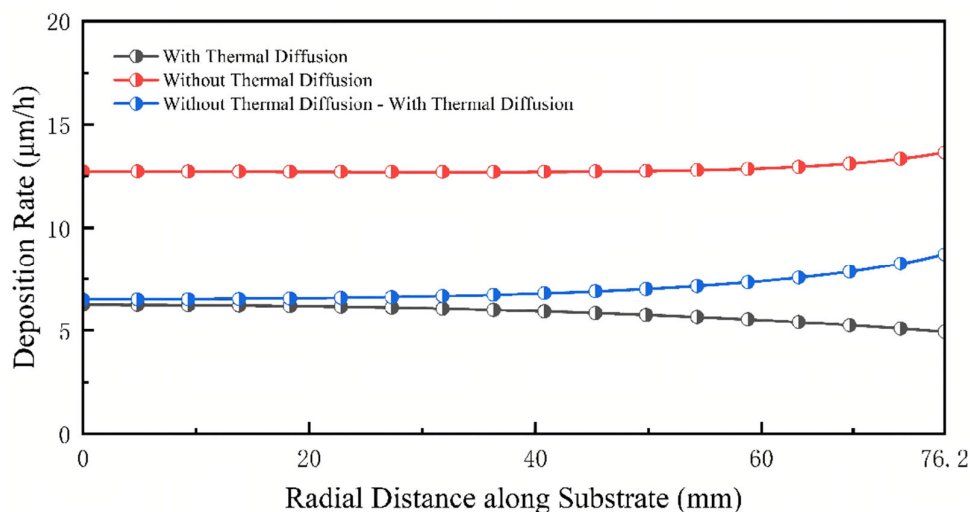


Figure 3. Comparison of deposition rates under the baseline scenario ($\Delta T = 1700$ K, $p = 10,000$ Pa, $\omega = 600$ rpm, $Q = 70$ slm).

As shown in Figure 4, because the steep temperature gradient points toward the substrate, the large-mass precursor molecules experience an upward thermal diffusion flux directed away from the hot substrate, causing them to accumulate above the thermal boundary layer. Consequently, under the effect of thermal diffusion, this upward flux suppresses the net transport of precursors crossing the thermal boundary layer to reach the substrate surface, significantly reducing the deposition rate. Meanwhile, this thermal diffusion barrier intercepts and redistributes precursor molecules that would otherwise be locally oversupplied because of flow field non-uniformities, thereby disrupting the radial flux balance and degrading deposition uniformity to a certain extent. Without the effect of thermal diffusion, the mass fractions of the source gases remain essentially unchanged after entering the reactor, only gradually decreasing near the thermal boundary layer because of gas-phase and surface reactions and dropping to zero at the substrate.

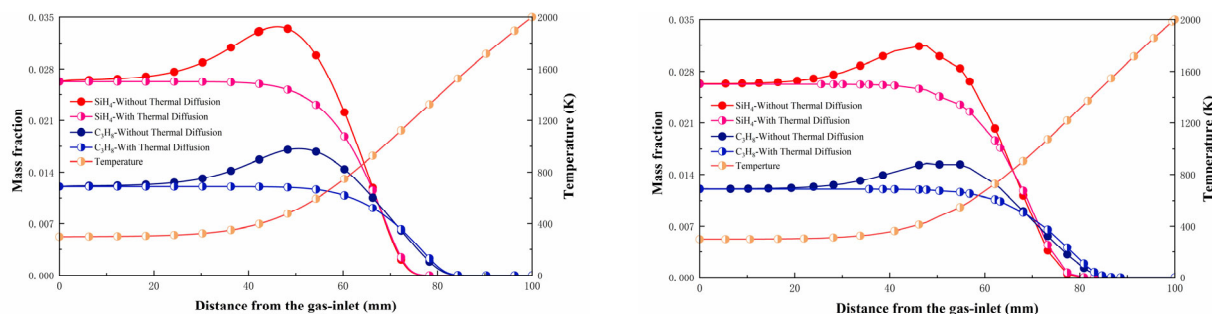


Figure 4. Distribution of source gases at the substrate center (left) and edge (right); precursor gases are injected vertically downward from the top gas inlet at the same angle.

3.2. Effect of Inlet-to-Substrate Temperature Difference (ΔT)

Because ΔT is the direct driving force behind the Soret effect, the increase from 1100 to 1700 K causes the absolute value of TDC_GR to rise, indicating that a larger temperature

gradient induces a stronger flux of precursors away from the substrate, resulting in a more pronounced suppression of the deposition rate. Concurrently, TDC_GU increases sharply from 2.29% to 5.29%, demonstrating that a large temperature difference induces an uneven radial distribution of the thermal diffusion flux, severely degrading the resulting film uniformity (Figure 5).

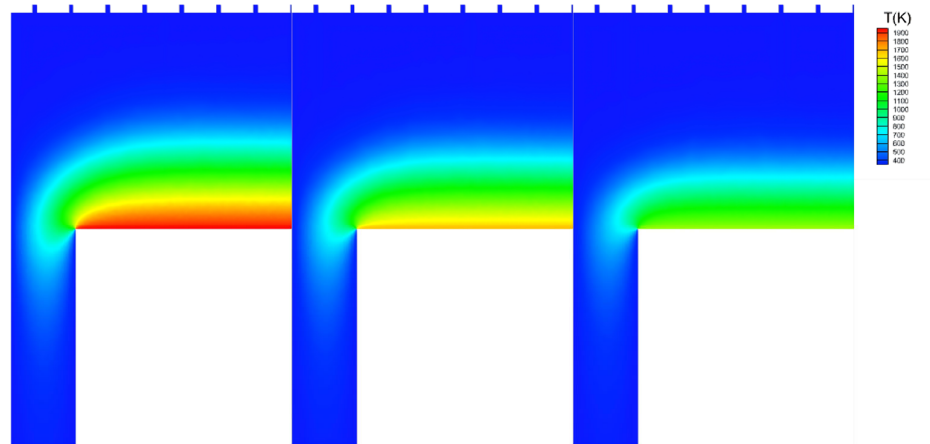


Figure 5. Temperature fields under inlet-to-substrate temperatures of 1700 K (**left**), 1400 K (**center**), and 1100 K (**right**).

Note that GR_{on} is 5.63 $\mu\text{m/h}$ at $\Delta T = 1700$ K, which is lower than that (7.53 $\mu\text{m/h}$) at $\Delta T = 1400$ K (Figure 6). This deviation from a monotonic trend with respect to ΔT is also observed for TDC_{GR}, which can be attributed to the competing H_2 etching reaction occurring at higher temperatures [26]. At $\Delta T = 1400$ K, the substrate temperature is moderate, achieving an optimal balance between the thermal activation of the surface deposition reaction and the H_2 etching reaction. Because the suppression of the precursor supply by the thermal diffusion effect is also relatively moderate at this temperature, the coupling of these multi-physical factors results in the highest net deposition rate.

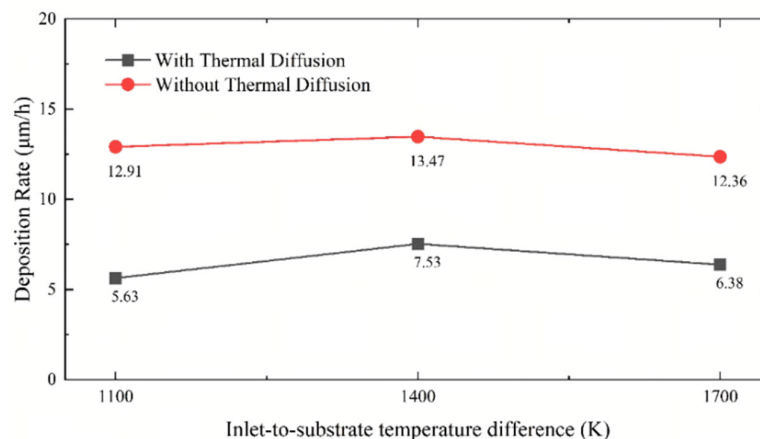


Figure 6. Comparison of deposition rates at different inlet-to-substrate temperatures with and without thermal diffusion.

While keeping all other process parameters unchanged, ΔT was varied at three representative levels (1700, 1400, and 1100 K), which represent the high, medium, and low ends of the typical operating window. This range is sufficient to clearly reveal the non-

monotonic dependence of the deposition rate and the monotonic enhancement of the So-ret effect with increasing temperature difference. The physical mechanisms elucidated below provide a coherent explanation for these observations, and the identification of the optimal ΔT (1400 K) is well-supported by the current data set.

3.3. Effect of Pressure

Table 3 (Rows 4–6) presents the simulation results obtained for pressures of 7500, 10,000, and 12,500 Pa under the constant conditions of $\Delta T = 1400$ K, $\omega = 600$ rpm, and $Q = 70$ slm. As shown in Figure 7, the thermal boundary layer above the substrate does not change significantly as pressure increases.

Table 3. Deposition results under different operating conditions.

Row	ΔT (K)	p (Pa)	ω (rpm)	Q (slm)	GR_On ($\mu\text{m/h}$)	GR_Off ($\mu\text{m/h}$)	TDC_GR (%)	GU_On (%)	GU_Off (%)	TDC_GU (%)
1	1700	10,000	600	70	5.63	12.91	−56.39%	6.85%	1.55%	5.29%
2	1400	10,000	600	70	7.53	13.47	−44.10%	3.56%	0.53%	3.03%
3	1100	10,000	600	70	6.38	12.36	−48.38%	2.41%	0.12%	2.29%
4	1400	7500	600	70	6.22	11.66	−46.66%	5.27%	1.08%	4.19%
5	1400	10,000	600	70	7.53	13.47	−44.10%	3.56%	0.53%	3.03%
6	1400	12,500	600	70	8.56	15.57	−45.02%	2.28%	0.35%	1.93%
7	1400	10,000	400	70	5.37	11.43	−53.02%	4.06%	2.69%	1.37%
8	1400	10,000	600	70	7.53	13.47	−44.10%	3.56%	0.53%	3.03%
9	1400	10,000	800	70	9.13	15.82	−42.29%	1.84%	0.14%	1.70%
10	1400	10,000	600	50	11.54	18.95	−39.10%	3.82%	0.70%	3.12%
11	1400	10,000	600	70	7.53	13.47	−44.10%	3.56%	0.53%	3.03%
12	1400	10,000	600	90	5.53	10.92	−49.36%	2.65%	1.45%	1.20%
13	1400	12,500	800	50	10.71	17.81	−39.87%	0.45%	0.05%	0.40%

Note: Rows 2, 5, 8, and 11 correspond to an identical baseline scenario. These rows are intentionally repeated within each parameter variation group to provide a consistent reference, thereby facilitating direct and convenient comparison of the effects of varying individual process parameters without the need to cross-reference across the table.

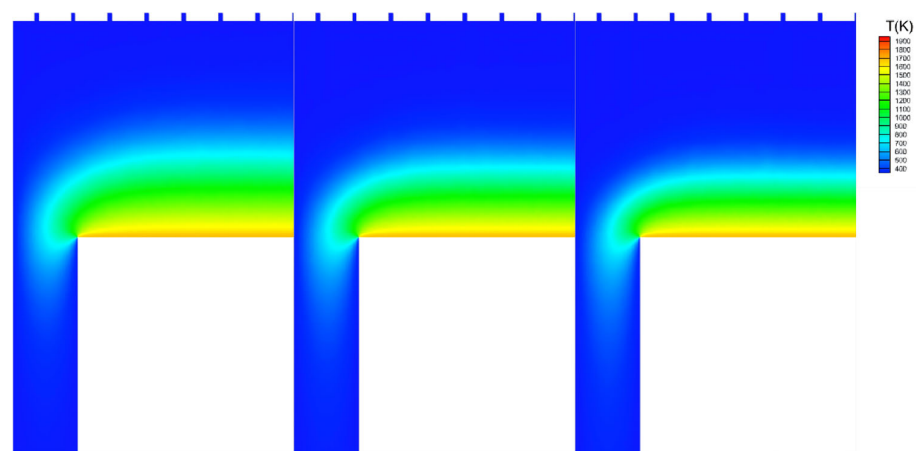


Figure 7. Temperature fields at pressures of 12,500 Pa (left), 10,000 Pa (center), and 7500 Pa (right).

As the pressure increases from 7500 to 12,500 Pa, the absolute value of TDC_GR initially decreases and then slightly increases, but the overall variation remains small (−46.66% $\rightarrow$ −44.10% $\rightarrow$ −45.02%). However, TDC_GU markedly decreases from 4.19% to 1.93% with increasing pressure. These results suggest that although higher pressures do

not significantly weaken the suppression of the deposition rate by the thermal diffusion effect, they promote radial mass transport and mixing by increasing the collision frequency between gas molecules. Hence, increasing the pressure may be effective for mitigating the localized degradation in film uniformity imposed by the Soret effect [20]. Figure 8 shows the change in deposition rates with and without the thermal diffusion effect as the pressure increases; the rates increase monotonically with pressure, as expected. This trend is reasonable because a higher total pressure raises the partial pressures of the reactant gases (SiH_4 and C_3H_8), leading to greater concentrations of the precursor species near the substrate surface. Because the deposition process is surface-kinetics-controlled under the present conditions, the increased reactant availability directly enhances the net deposition rate.

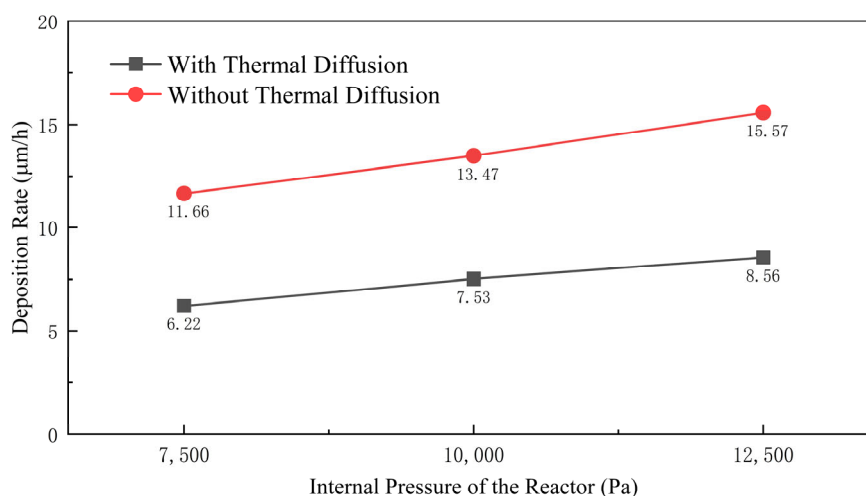


Figure 8. Comparison of deposition rates at different pressures with and without thermal diffusion.

Table 3 (Rows 4–6) presents the simulation results obtained for pressures of 7500, 10,000, and 12,500 Pa. These three levels cover the practical operational window. The monotonic increase in deposition rate and the significant decrease in TDC_GU with increasing pressure are consistently captured, indicating that higher pressure enhances gas-phase mixing and molecular collisions, which counteracts the radial concentration differences induced by the Soret effect.

3.4. Effect of Substrate Rotation Speed

Table 3 (Rows 7–9) presents the simulation results obtained at substrate rotation speeds of 400, 600, and 800 rpm under the constant conditions of $\Delta T = 1400$ K, $p = 10,000$ Pa, and $Q = 70$ slm. As shown in Figure 9, the thermal boundary layer above the substrate does not change significantly as rotation speed increases.

As the rotation speed increases, the magnitude of growth suppression via TDC_GR decreases from 53.02% to 42.29%. This is primarily because the pumping effect and centrifugal force generated by substrate rotation enhance forced convection, thereby thinning the velocity and thermal boundary layers. Thinner boundary layers shorten the effective distance over which the temperature gradient acts, reducing the total residence time and path length over which precursor molecules are affected by thermal diffusion. Consequently, more precursors can reach the substrate surface and participate in deposition. The deposition rate calculated without the thermal diffusion effect also increases with rotation speed, confirming that substrate rotation primarily influences the convective mass transfer efficiency of precursors through hydrodynamic mechanisms.

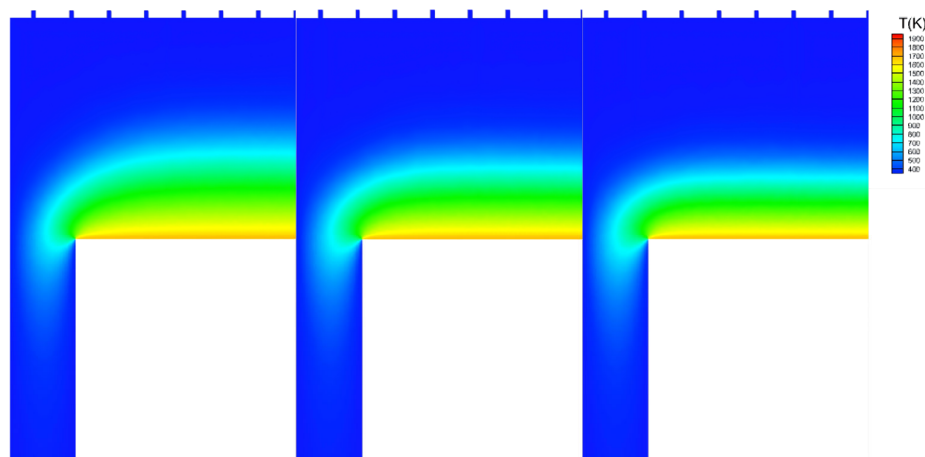


Figure 9. Temperature fields at substrate rotation speeds of 400 rpm (**left**), 600 rpm (**center**), and 800 rpm (**right**).

In contrast, TDC_GU exhibits no significant change with rotation speed, indicating that the rotation speed has a relatively limited capacity to regulate radial uniformity variations caused by the thermal diffusion effect. This is reasonable because the rotation speed predominantly governs the axial transport of chemical species, and its effect on the radial thermal diffusion flux distribution remains less significant than that of pressure. Figure 10 shows that the deposition rates increase with rotation speed, regardless of the thermal diffusion effect. This trend is physically sound because a higher substrate rotation speed intensifies the centrifugal pumping effect, which thins the velocity and thermal boundary layers above the substrate. Consequently, the diffusive transport distance for precursor species is shortened, and the convective supply of reactants to the surface is enhanced.

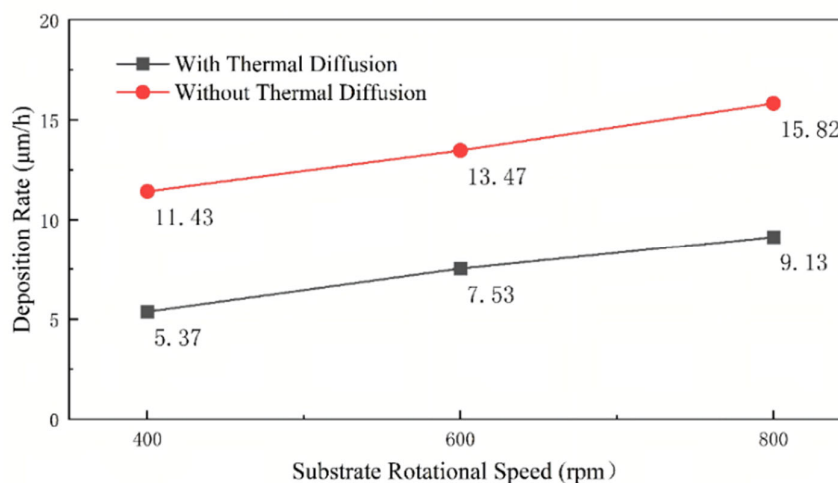


Figure 10. Comparison of deposition rates at different substrate rotation speeds with and without thermal diffusion.

Table 3 (Rows 7–9) presents the simulation results obtained at substrate rotation speeds of 400, 600, and 800 rpm under constant conditions. These three levels cover the practical operational window for vertical CVD reactors. The monotonic increase in deposition rate and the marginal change in uniformity with ω are consistently captured, indicating that the primary role of substrate rotation is to thin the boundary layer and enhance

convective transport. The selected resolution is sufficient to reveal that rotation speed has a limited capacity to regulate radial uniformity variations caused by the Soret effect.

3.5. Effect of Carrier Gas Flow Rate

Table 3 (Rows 10–12) presents the simulation results obtained at H₂ flow rates of 50, 70, and 90 slm under the constant conditions of $\Delta T = 1400$ K, $p = 10,000$ Pa, and $\omega = 600$ rpm. As shown in Figure 11, the thermal boundary layer above the substrate does not change significantly as the gas flow rate increases.

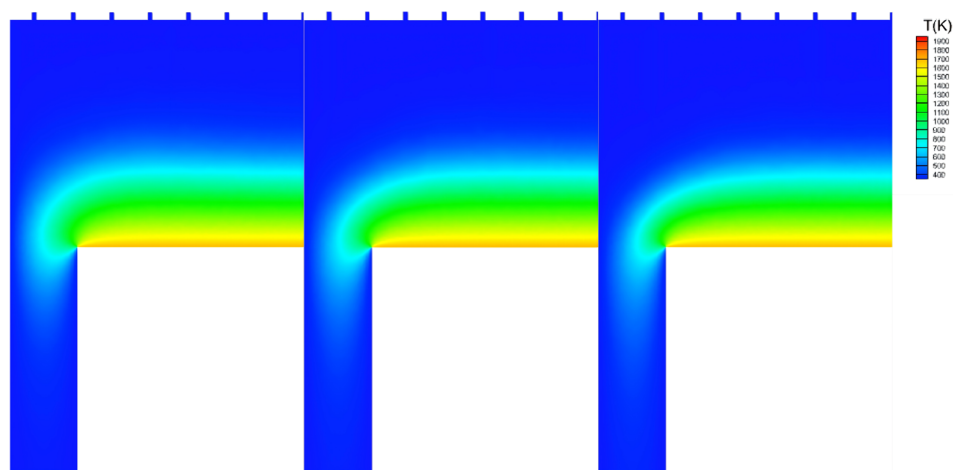


Figure 11. Temperature fields at flow rates of 50 slm (left), 70 slm (center), and 90 slm (right).

Increasing the carrier gas flow rate simultaneously reduces the residence time and the partial pressures of the precursors in the reactor. Together, these two mechanisms drive a continuous decrease in the deposition rate, as shown in Figure 12. The absolute value of TDC_{GR} reaches 39.10% at 50 slm, 44.10% at 70 slm, and 49.36% at 90 slm. Under low flow rate conditions, the prolonged residence time and elevated precursor partial pressures make convective transport more effective than thermal transport, increasing the fraction of precursors reaching the substrate and decreasing the absolute value of TDC_{GR}. Conversely, under high flow rate conditions, precursor molecules flow more rapidly, and under a constant thermal diffusion intensity, the proportion of precursors reaching the substrate further decreases, leading to a corresponding increase in the absolute value of TDC_{GR} (growth suppression).

Meanwhile, TDC_{GU} decreases from 3.12% to 1.20% as the flow rate increases. This improvement occurs because high flow rates shorten the gas residence time above the substrate, attenuating the cumulative development of radial concentration differences caused by the thermal diffusion effect, resulting in a macroscopically uniform concentration distribution across the boundary layer.

Table 3 (Rows 10–12) presents the simulation results obtained at H₂ flow rates of 50, 70, and 90 slm. These three levels cover the practical operational window. The monotonic decrease in deposition rate and the reduction in TDC_{GU} with increasing flow rate are consistently captured, indicating that higher flow rates shorten residence time and reduce precursor partial pressures, while also attenuating the cumulative development of radial concentration differences caused by the Soret effect.

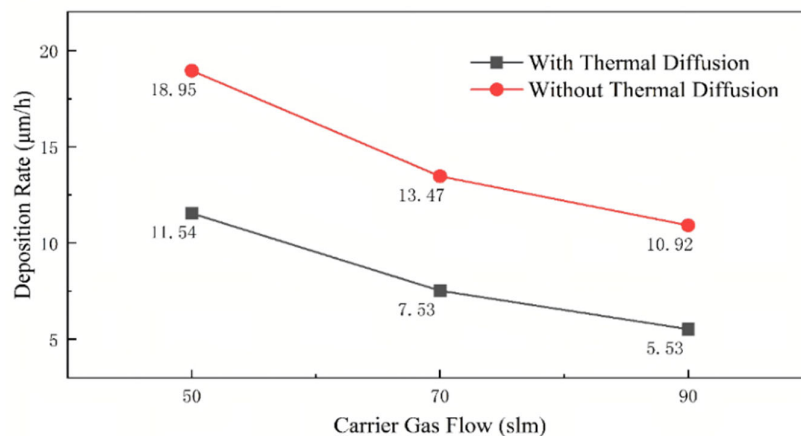


Figure 12. Comparison of deposition rates at different carrier gas flow rates with and without thermal diffusion.

3.6. Process Parameter Optimization

Based on the comprehensive analysis of the individual and interactive effects of each parameter, ΔT is established as the dominant factor influencing the thermal diffusion effect. Recent simulation studies on 6-inch 4H-SiC homoepitaxial growth have similarly demonstrated the importance of optimizing gas flow and temperature field distributions to achieve uniform doping and thickness across large-area wafers [27]. Pressure mainly suppresses the radial non-uniformity induced by the thermal diffusion effect by enhancing gas-phase mixing. Substrate rotation speed improves precursor transport efficiency by thinning the boundary layer. The carrier gas flow rate affects both deposition rate and uniformity by altering the residence time and partial pressure of precursors. Balancing the inherent trade-off between deposition rate and film uniformity, an optimal process parameter combination was identified within the investigated range: $\Delta T = 1400$ K, $p = 12,500$ Pa, $\omega = 800$ rpm, $Q = 50$ slm (Row 13 in Table 3). The optimization rationale for this combination is described as follows: a moderate ΔT (1400 K) regulates the baseline intensity of the thermal diffusion effect, avoiding severe deposition rate loss caused by an excessively large temperature difference; a higher pressure (12,500 Pa) enhances gas-phase mixing, effectively reducing TDC_GU; a higher rotation speed (800 rpm) enhances convection, thins the boundary layer, and improves precursor transport efficiency; and a lower flow rate (50 slm) increases the precursor residence time and partial pressure, compensating for the flux loss caused by the thermal diffusion effect.

Under this optimized condition, the actual deposition rate (with the thermal diffusion effect considered) reaches $10.71 \mu\text{m/h}$ (Figure 13), with a non-uniformity of 0.45%. When the thermal diffusion effect is artificially neglected, the deposition rate is $17.81 \mu\text{m/h}$ (Figure 13), with a non-uniformity of 0.05%. Thus, TDC_GR is -39.87% , and TDC_GU is only 0.40%. Compared with the baseline scenario (TDC_GR = -56.39% , TDC_GU = 5.29%), the optimized combination still delivers high deposition uniformity while maintaining a relatively high deposition rate.

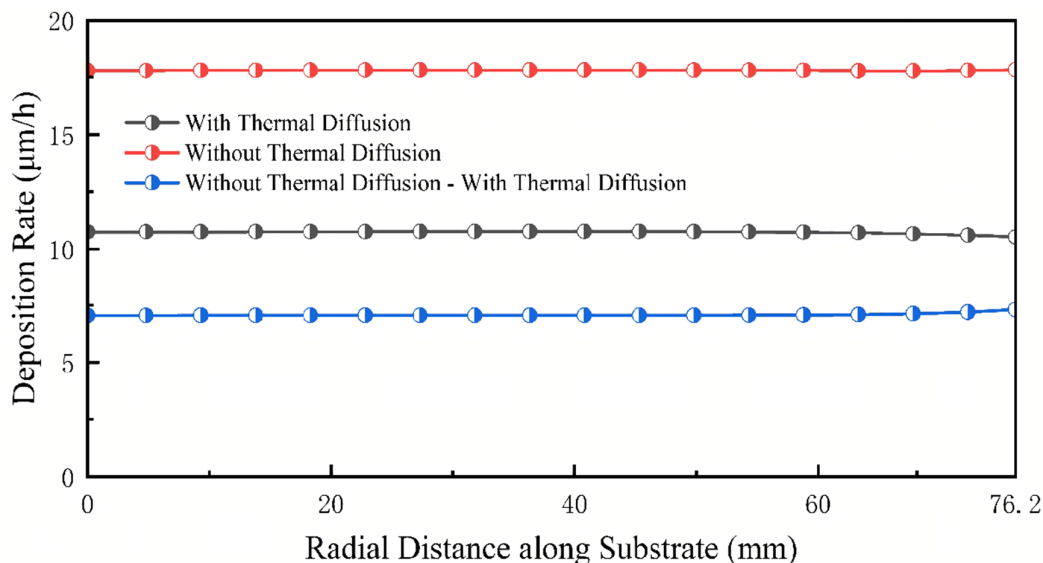


Figure 13. Comparison of deposition rates under the optimal parameter combination.

4. Conclusions

In this study, a CFD model coupled with detailed chemical reaction kinetics was established. Combined with a design of experiments under various operating conditions, the influencing mechanism and regulatory pathway of the thermal diffusion effect on the deposition rate and uniformity of SiC thin films during the SiC-CVD process were systematically investigated. The main conclusions are summarized as follows:

- (1) Under the baseline scenario, the Soret effect reduces the deposition rate by 56.39% and raises non-uniformity from 1.55% to 6.85%. The thermal diffusion effect imposes an upward diffusion flux on precursor molecules, directing them away from the hot substrate and causing them to accumulate above the thermal boundary layer, thus reducing the reactant flux reaching the substrate surface.
- (2) ΔT is the dominant driving force of the thermal diffusion effect. As ΔT increases from 1100 to 1700 K, the absolute value of TDC_GR increases from 48.38% to 56.39%, and TDC_GU increases from 2.29% to 5.29%. An increase in ΔT exacerbates the accumulation of precursors above the thermal boundary layer, severely hindering their transport toward the substrate. Pressure has a minor influence on TDC_GR, but a significant influence on TDC_GU. As pressure increases from 7500 to 12,500 Pa, TDC_GU decreases from 4.19% to 1.93%. Higher pressure increases molecular collisions and enhances radial gas mixing, counteracting concentration differences from thermal diffusion.
- (3) Increasing the substrate rotation speed thins the boundary layer and reduces the absolute value of TDC_GR by approximately 10%. A lower carrier gas flow rate increases precursor residence time and partial pressure, thus offsetting the flux loss caused by thermal diffusion.
- (4) Through comparative analysis, the optimal process parameter combination ($\Delta T = 1400$ K, $p = 12,500$ Pa, $\omega = 800$ rpm, $Q = 50$ slm) was determined, achieving a deposition rate of $10.71 \mu\text{m/h}$ and a non-uniformity of 0.45%. This provides a theoretical basis for the precise control of the SiC-CVD process.
- (5) The present study employs a 2D axisymmetric model, which is sufficient for analyzing heat transfer and thermal diffusion but cannot fully capture 3D flow characteristics, such as asymmetric recirculation zones or inlet jet deflection, in real reactors. Further investigation adopting a 3D model is necessary to quantitatively elucidate

the impact of complex flows on precursor transport and film uniformity, enabling a more comprehensive understanding of SiC-CVD.

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References

- Kimoto, T.; Yonezawa, Y. Current status and perspectives of ultrahigh-voltage SiC power devices. *Mater. Sci. Semicond. Process.* **2018**, *78*, 43–56.
- Li, Q.; Zhang, Y.; Ji, B.; Zhang, S.; Tu, R. Improvement of SiC deposition uniformity in CVD reactor by showerhead with baffle. *J. Cryst. Growth* **2023**, *615*, 127621.
- Bijjargi, Y.S.; Shinde, V.M.; Mudgal, A.; Kumar, H.; Prasad, N.E. CFD modeling and optimal design of SiC deposition on the fuel combustion nozzle in a commercial CVD reactor. *Ceram. Int.* **2022**, *48*, 11043–11055.
- Sato, H.; Goto, T.; Okuno, A.; Yoshikawa, A. Preparation of SiC coatings on graphite substrates via CVD using polysilaethylene. *J. Cryst. Growth* **2025**, *649*, 128040.
- Chen, J.; Gong, Y.; Yang, Z.-G. Failure analysis on the abnormal cracking of Si₃N₄ ceramic substrates for SiC power modules in new energy vehicles. *Microelectron. Reliab.* **2024**, *155*, 115432.
- Nguyen, T.-K.; Phan, H.-P.; Han, J.; Dinh, T.; Md Faisal, A.R.; Dimitrijević, S.; Zhu, Y.; Nguyen, N.-T.; Dao, D.V. Highly sensitive p-type 4H-SiC van der Pauw sensor. *RSC Adv.* **2018**, *8*, 3009–3013.
- Wu, K.; Mei, Q.; Liu, H.; Zhou, S.; Gao, B.; Li, C.; Liu, S.; Wan, L. Vapor Deposition Growth of SiC Crystal on 4H-SiC Substrate by Molecular Dynamics Simulation. *Crystals* **2023**, *13*, 715.
- Kordina, O.; Hallin, C.; Ellison, A.; Bakin, A.S.; Ivanov, I.G.; Henry, A.; Yakimova, R.; Touminen, M.; Vehanen, A.; Janzén, E. High temperature chemical vapor deposition of SiC. *Appl. Phys. Lett.* **1996**, *69*, 1456–1458.
- Zhou, J.; Lin, B.; Xue, J.; Li, S.; Liao, Y.; Zhao, P.; Sui, T. Damage characteristics and material removal mechanisms of CVD-SiC in nanotests: A comparative with sintered SiC. *Int. J. Refract. Met. Hard Mater.* **2024**, *118*, 106892.
- Kaloyeros, A.E.; Arkles, B. Silicon Carbide Thin Film Technologies: Recent Advances in Processing, Properties, and Applications—Part I Thermal and Plasma CVD. *ECS J. Solid State Sci. Technol.* **2023**, *12*, 123456.
- Kaloyeros, A.E.; Arkles, B. Silicon Carbide Thin Films: Innovations in Property, Process, and Applications. In *Silicon Carbide—From Materials Science to Nanotechnology and Microelectronics*; IntechOpen: London, UK, 2025; pp. 1–30.
- Song, B.; Gao, B.; Han, P.; Yu, Y. Surface Kinetic Mechanisms of Epitaxial Chemical Vapour Deposition of 4H Silicon Carbide Growth by Methyltrichlorosilane-H₂ Gaseous System. *Materials* **2022**, *15*, 12345.
- Gavalas, M.; Gallou, Y.; Chaussende, D.; Blanquet, E.; Mercier, F.; Zekentes, K. Progress in Polycrystalline SiC Growth by Low Pressure Chemical Vapor Deposition and Material Characterization. *Micromachines* **2025**, *16*, 276.
- Deivendran, B.; Shinde, V.M.; Kumar, H.; Eswara Prasad, N. 3D Modeling and optimization of SiC deposition from CH₃SiCl₃/H₂ in a commercial hot wall reactor. *J. Cryst. Growth* **2021**, *554*, 125567.
- Li, J.; Wang, J.; Pei, Y.; Wang, G. Research and optimization of ZnO-MOCVD process parameters using CFD and genetic algorithm. *Ceram. Int.* **2020**, *46*, 685–695.
- Zuo, R.; Yu, H.; Xu, N.; He, X. Influence of Gas Mixing and Heating on Gas-Phase Reactions in GaN MOCVD Growth. *ECS J. Solid State Sci. Technol.* **2012**, *1*, P46–P53.

17. Zhang, H.; Zuo, R.; Zhang, G. Effects of reaction-kinetic parameters on modeling reaction pathways in GaN MOVPE growth. *J. Cryst. Growth* **2017**, *478*, 193–204.
18. Kleijn, C.R.; Dorsman, R.; Kuijlaars, K.J.; Okkerse, M.; van Santen, H. Multi-scale modeling of chemical vapor deposition processes for thin film technology. *J. Cryst. Growth* **2007**, *303*, 362–380.
19. Mitrovic, B.; Gurary, A.; Kadinski, L. On the flow stability in vertical rotating disc MOCVD reactors under a wide range of process parameters. *J. Cryst. Growth* **2006**, *287*, 656–663.
20. Roy, K.; Murthy, P.V.S.N. Soret effect on the double diffusive convection instability due to viscous dissipation in a horizontal porous channel. *Int. J. Heat Mass Transf.* **2015**, *91*, 700–710.
21. Danielsson, O.H.; Henry, A.; Janzén, E. Growth rate predictions of chemical vapor deposited silicon carbide epitaxial layers. *J. Cryst. Growth* **2002**, *243*, 170–184.
22. Li, Q.; Luo, J.; Rummeli, M.H.; Liu, L. Numerical investigation on the influence of the Soret effect on graphene growth in chemical vapor deposition. *J. Cryst. Growth* **2023**, *614*, 127102.
23. Seo, J.-W.; Choi, K. Application of CFD simulation to silicon carbide deposition for nozzles with funnel. *J. Korean Ceram. Soc.* **2020**, *58*, 184–191.
24. Shinde, V.M.; Deivendran, B.; Kumar, H.; Eswara Prasad, N. Investigation of transport processes in a commercial hot wall CVD reactor with multi-substrates for high-quality pyrocarbon deposition. *Surf. Coat. Technol.* **2021**, *425*, 127682.
25. Zheng, G.; Sun, Y.; Liu, S.; Su, P.; Pei, J.; Zuo, R.; Liu, L. Numerical investigation on the effect of growth conditions on silicon carbide growth in chemical vapor deposition. *J. Cryst. Growth* **2025**, *657*, 127845.
26. Meziere, J.; Ucar, M.; Blanquet, E.; Pons, M.; Ferret, P.; Di Cioccio, L. Modeling and simulation of SiC CVD in the horizontal hot-wall reactor concept. *J. Cryst. Growth* **2004**, *267*, 436–451.
27. Zhang, G.; Li, T.; Liu, Y.; Sun, J.; Zhang, S. Optimization and Simulation on Gas Flow and Temperature Fields on the Homoepitaxial Growth of N-Doped 4H-SiC Wafers. *Micromachines* **2026**, *17*, 305.

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