

Article

Numerical Simulation-Based Study of Controlled Particle Deposition Technology for Wafer Surfaces

Ziheng Zhang ^{1,2,*}, Jun Ren ^{1,2,*}, Yue Liu ³ and Junjie Liu ^{3,*}¹ State Key Laboratory of Clean and Efficient Coal Utilization, Taiyuan University of Technology, Taiyuan 030024, China; zhangziheng1123@link.tyut.edu.cn² College of Chemistry and Chemical Engineering, Taiyuan University of Technology, Taiyuan 030024, China³ Environment Metrology Center, National Institute of Metrology, Beijing 100029, China; liu-yue@nim.ac.cn

* Correspondence: renjun@tyut.edu.cn (J.R.); liujj@nim.ac.cn (J.L.)

Abstract

Scanning surface inspection systems (SSISs) require standard wafers (SWs) with traceable particle characteristics for accurate calibration. Achieving controlled particle deposition on wafer surfaces is essential for the fabrication of such SWs. In this study, numerical simulations were conducted using Fluent to systematically investigate the effects of key deposition parameters—including nozzle diameter, nozzle-to-wafer distance, chamber volume, rotation speed, and particle size—on deposition efficiency and uniformity. Based on the simulation results, a generation–deposition system was developed, incorporating a differential mobility classifier (DMC) to produce monodisperse aerosols. The particles used in the experiments were polystyrene latex (PSL) particles with diameters of 70 nm, 100 nm, 140 nm, and 200 nm; the wafers used were 50 mm silicon wafers. Experimental validation was carried out using scanning electron microscopy (SEM) and SSISs. The optimal deposition conditions were identified as a nozzle diameter of 4 mm, nozzle-to-wafer distance of 15 mm, chamber volume greater than 657 cm³, and a rotation speed of 0.314 rad/s. Under these unified parameters, particles with diameters ≥ 100 nm could be effectively deposited, while smaller particles required additional adjustments. The developed system enables the preparation of SW with traceable particle sizes and uniform deposition, fulfilling the fundamental requirements for SSIS calibration.

Keywords: monodisperse aerosol; numerical simulation; particle deposition; standard wafers; scanning surface inspection systems



Academic Editor: Andrea Atrai

Received: 12 April 2025

Revised: 9 June 2025

Accepted: 13 June 2025

Published: 20 June 2025

Citation: Zhang, Z.; Ren, J.; Liu, Y.; Liu, J. Numerical Simulation-Based Study of Controlled Particle Deposition Technology for Wafer Surfaces. *Appl. Sci.* **2025**, *15*, 6970. <https://doi.org/10.3390/app15136970>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Surface defects constitute a primary yield-determining factor in semiconductor manufacturing, directly impacting production efficiency and device reliability [1,2]. Industry data demonstrate that particulate contamination accounts for over 60% of wafer yield loss, significantly exceeding other process-related issues and emerging as a critical bottleneck in semiconductor technology advancement [3]. Since defect prevention during fabrication proves more effective than post-process cleaning, scanning surface inspection systems (SSISs) have been universally adopted at key process stages [4,5]. Nevertheless, SSIS technology faces two fundamental limitations:

1. Its light-scattering-based detection mechanism cannot reliably distinguish weak scattering signals from sub-critical defects [6,7];

2. The system's inability to provide direct defect imaging necessitates establishing a reference correlation between standard particle sizes and scattering intensities, requiring subsequent conversion of measured signals into equivalent standard dimensions [8].

Therefore, SSIS calibration using standard wafers (SWs) becomes essential to guarantee detection accuracy and consistency. SWs are a type of standard material primarily characterized by controlled particulate contamination [9,10]. The composition, particle size, and deposition patterns on these wafers are precisely regulated. Researchers achieve controlled particle deposition on the wafer surface through the electric mobility technology screening of particle size [11,12], combined with electrostatic force [13–15], inertial force [16–18], thermophoretic force [19,20] and other multi-physical field effects for deposition behavior regulation. However, the existing technology still has significant limitations. The electrical deposition system is highly efficient, but the electric field parameters need to be adjusted dynamically according to the characteristics of the particles, which quickly leads to non-uniform deposition. The non-electrical deposition system can avoid charge interference. However, it is challenging to meet the demand for high-precision calibration due to the high complexity of the equipment and the residual contamination of liquid droplets. In addition, the simulation of aerosol dynamics inside the deposition chamber is still insufficient, and the quantitative analysis of turbulence effects and particle–flow coupling is lacking.

To address the above challenges, this study utilizes computational fluid dynamics (CFD) to simulate and optimize the flow field parameters within the deposition chamber. The influence of particle size, chamber geometry, and the coupling of external force fields on particle deposition behavior on the wafer surface is systematically analyzed. Based on the simulation outcomes, an integrated generation–deposition system was developed for the preparation of standard wafers (SWs). Polystyrene latex (PSL) particles with diameters of 70 nm, 100 nm, 140 nm, and 200 nm were used to generate monodisperse aerosols via an aerosol generator and a particle size classifier, and these were subsequently deposited onto silicon wafers using the optimized deposition chamber. This work provides theoretical guidance for the engineering-scale fabrication of SWs and proposes a novel calibration solution for scanning surface inspection systems (SSISs).

2. Materials and Methods

2.1. Numerical Simulation Methods

2.1.1. Modeling and Parameters

As shown in Figure 1, the model grid and deposition schematic of the chamber are presented. The deposition chamber has a bottom diameter of 200 mm and a height of 120 mm, making it compatible with the standard 50 mm wafer size. In this study, particle motion and deposition distribution on the wafer wall were analyzed by modifying the chamber structure and adjusting particle properties. To achieve uniform deposition, the effects of nozzle diameter, nozzle-to-wafer distance, chamber volume, rotational speed, and particle diameter were investigated.

Table 1 summarizes the physical properties and parameter values varied in the simulation, with their effects on deposition evaluated and discussed in the subsequent results section using the modified geometrical model as the experimental reference.

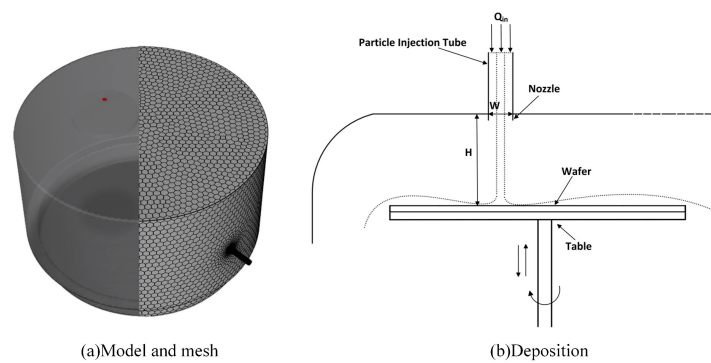


Figure 1. Schematic of model and mesh and deposition.

Table 1. Parameters of surface deposition simulation.

Aerosol Flow Rate = 0.3 L/min					
	D_p/nm	$D_{\text{nozzle}}/\text{mm}$	H/mm	V/cm^3	$N/\text{rad}\cdot\text{s}^{-1}$
D_{nozzle}	300	1, 2, 4, 6, 8	15	3650	0
H	300	4	5, 15, 50	3650	0
V	300	4	15	81, 657, 3650	0
N	300	4	15	3650	0.314, 3.14, 31.4
D_p	70, 100, 200, 300	4	15	3650	0

D_{nozzle} —nozzle diameter; H —nozzle-to-wafer distance; V —chamber volume; N —rotational speed; D_p —particle diameter.

2.1.2. Solver Settings

Fluent was used to construct the numerical model of aerosol particle deposition and to define the boundary conditions for both the fluid and discrete phases. Adapted numerical algorithms were employed to ensure the accuracy and stability of the calculations. The specific boundary conditions and solution algorithms used in this study are as follows:

1. Viscous model: To compute non-uniform, high-curvature rotating flow fields, the realizable $k-\epsilon$ model is employed as the turbulence model. For near-wall treatment, the enhanced wall model is chosen to ensure compatibility with both boundary layer conditions, balancing computational efficiency and accuracy. Additionally, the curvature correction option is enabled to achieve a more accurate simulation of velocity and shear stress distribution.
2. Fluid boundary conditions: The inlet is defined as a velocity inlet with a flow velocity of 0.4 m/s, a turbulence intensity of 4%, and a hydrodynamic diameter of 4 mm. The outlet is set as a pressure outlet with a gauge pressure of 100 Pa. All wall surfaces are specified as static, no-slip boundaries with a roughness height of 0 m and a roughness constant of 0.5.
3. DPM boundary conditions: The particles are monodisperse, spherical, and inert, with a density of 1050 kg/m^3 , and their initial velocity at the inlet is synchronized with the airflow (0.4 m/s). The interaction rules between particles and walls are defined as follows: the wafer surface adopts the Trap condition, the inlet and outlet are set as Escape, and all other walls are set as Reflect. The forces acting on the particles include gravity, Saffman force, trailing force, and rotational shear. The discrete random walk (DRW) model is employed to simulate diffusion and vortex effects.
4. Numerical solution strategy: The transient pressure-based solver is employed, utilizing the “SIMPLE” algorithm for pressure–velocity coupling with a convergence residual of 10^{-4} . The “PRESTO!” (Pressure Staggering Option) and “Standard” schemes are both interpolation options in ANSYS 2022 Fluent used to calculate pressure values on control volume faces. For pressure term discretization, the “PRESTO!” scheme is

applied in rotational cases, while the “Standard” scheme is used for non-rotational cases. The momentum, turbulence, and convection terms are discretized using the “Second-Order Upwind scheme”.

2.2. Experimental Materials and Methods

Table 2 presents the primary materials and instrumentation parameters used in the experiments:

Table 2. Primary materials and instrumentation.

Materials and Instrumentation	Parameters and Models	Manufacturer	Sourced
PSL standard suspension	70–200 nm	National Institute of Metrology, China	Beijing, China
Clean wafers	50 mm	Topvender	Beijing, China
Atomization generator	ATM 220	Topas GmbH	Dresden, Germany
Cold dryer	HLW-10 AC	Hailvwang	Hangzhou, China
Neutralizer	5.520	Grimm	Ainring, Germany
Differential mobility classifier	55-U	Grimm	Ainring, Germany
Condenser particle counter	3775	TSI Inc.	Shoreview, MN, USA
Scanning mobility particle sizer	S 82	TSI Inc.	Shoreview, MN, USA
Scanning surface inspection system	E3200	AK OPTICS	Beijing, China
Scanning electron microscope	Ultra 55	ZEISS	Oberkochen, Germany

Figure 2 illustrates the particle generation–deposition system. A diluted polystyrene latex (PSL) suspension was prepared by mixing a PSL standard suspension (1:2000 mass ratio) with deionized water. This mixture was used to generate monodisperse polystyrene aerosol particles. The suspension was atomized using a pneumatic atomization generator to produce droplets containing PSL particles. These droplets were subsequently dried using a heating and diffusion dryer to remove moisture, resulting in solid aerosol particles. The aerosol was then charge-neutralized and classified by a differential mobility classifier (DMC) to obtain a monodisperse sample with the desired particle size. The size distribution was measured by a scanning mobility particle sizer (SMPS), and a portion of the aerosol flow was directed into the deposition chamber, which was connected to a condensation particle counter (CPC) for real-time concentration monitoring.

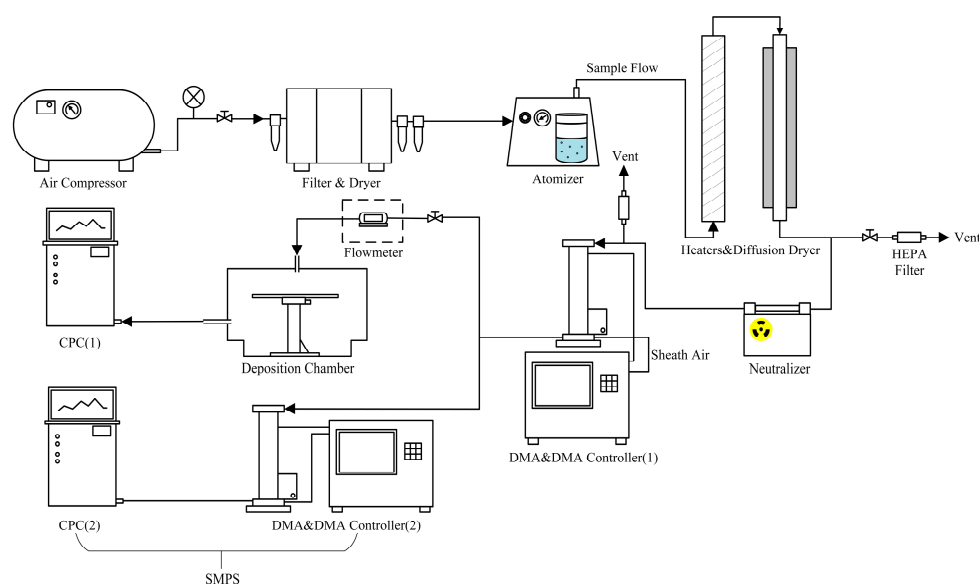


Figure 2. Schematic diagram of particle generation and deposition device. CPC (1) and CPC (2) are two separate units used for particle counting before and after deposition, respectively.

To ensure the stability and cleanliness of the aerosol generation process, a three-stage purified air supply system was used. Compressed air was first provided by an air compressor with a discharge pressure of 0.5 MPa and a flow rate of 156 L/min. It was then cooled and dehumidified using a refrigerated dryer with a rated capacity of 1.5 Nm³/min. Finally, the air passed through a series of three precision filters with filtration ratings of 3 µm, 1 µm, and 0.01 µm, respectively, effectively removing particulates, oil mist, and moisture. This purification system ensured a clean and stable carrier gas throughout the aerosol generation and deposition process.

Figure 3 illustrates the schematic of the particle deposition chamber, a sealed unit composed of a high-efficiency fan filter unit (FFU), a stand, a platform, a wafer base, a nozzle, and an exhaust hole. The FFU ensures chamber cleanliness before and after deposition. The stand stabilizes the platform and allows deposition height adjustments with 1 mm accuracy. The platform provides controlled deposition conditions, including rotation and temperature variations. The wafer base prevents direct contact between the wafer and rough surfaces, maintaining its stability during rotation, translation, and changes in the deposition position. The chamber features a single inlet nozzle mounted on a horizontally movable baffle plate, enabling selective deposition area adjustments. Exhaust holes facilitate gas circulation within the FFU and particle detection in the CPC. During the deposition process, the optimal parameters were identified as follows: nozzle diameter of 4 mm, deposition height of 15 mm, chamber volume greater than 657 cm³, rotation speed of 0.314 rad/s, and aerosol flow rate of 0.3 L/min. Polystyrene latex (PSL) particles with diameters ranging from 70 to 200 nm were used.

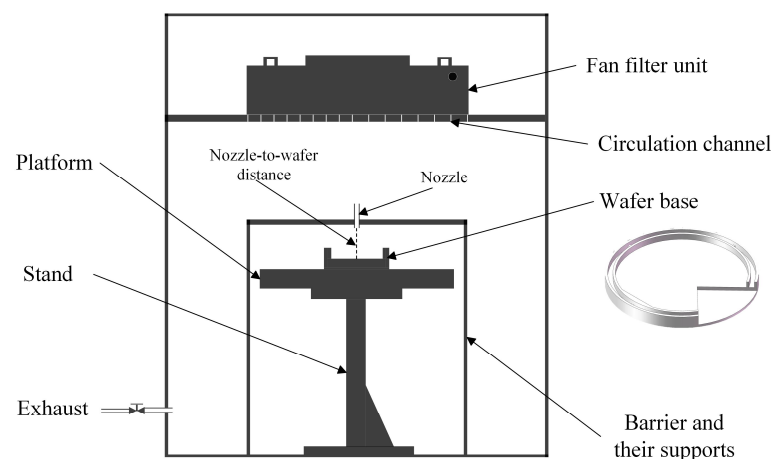


Figure 3. Schematic of deposition chamber and its components.

To evaluate deposition results, the distribution and size of particles on the wafer surface must be determined. A calibrated SSIS can fulfill some of these requirements by comparing light scattering signals and analyzing scanning results based on calibration data. However, its accuracy depends on the precision of the light scattering model. In contrast, scanning electron microscopy (SEM) employs a high-energy electron beam to scan the sample surface, utilizing electron interactions with sample atoms to generate secondary and backscattered electron signals. These signals are captured by a detector and converted into images and data, enabling precise particle size measurement for traceability.

3. Results and Discussion

This chapter is divided into three main sections. The first discusses the monodispersity of PSL suspensions and aerosol samples. The second discusses the results of numerical simulations. The third discusses the preparation of SW samples.

3.1. Simulation Results and Analysis

Numerical simulation results, represented by the DPM concentration on the wafer surface, specifically analyzed the concentration distribution and the size of the deposition spots. The following sections examine the impact of different deposition chamber configurations on deposition outcomes from four key aspects. Additionally, the deposition behavior of PSL particles with varying sizes under the optimized chamber configuration is discussed.

3.1.1. Nozzle Diameter

In this study, the impact of nozzle diameter on the spatial distribution characteristics of aerosol particle deposition was systematically analyzed by evaluating five nozzle sizes, as illustrated in Figure 4. To ensure consistency in the number of incident particles, the aerosol volumetric flow rate was kept constant at 0.3 L/min for all nozzle diameters. As a result, the outlet velocity decreased with increasing nozzle diameter.

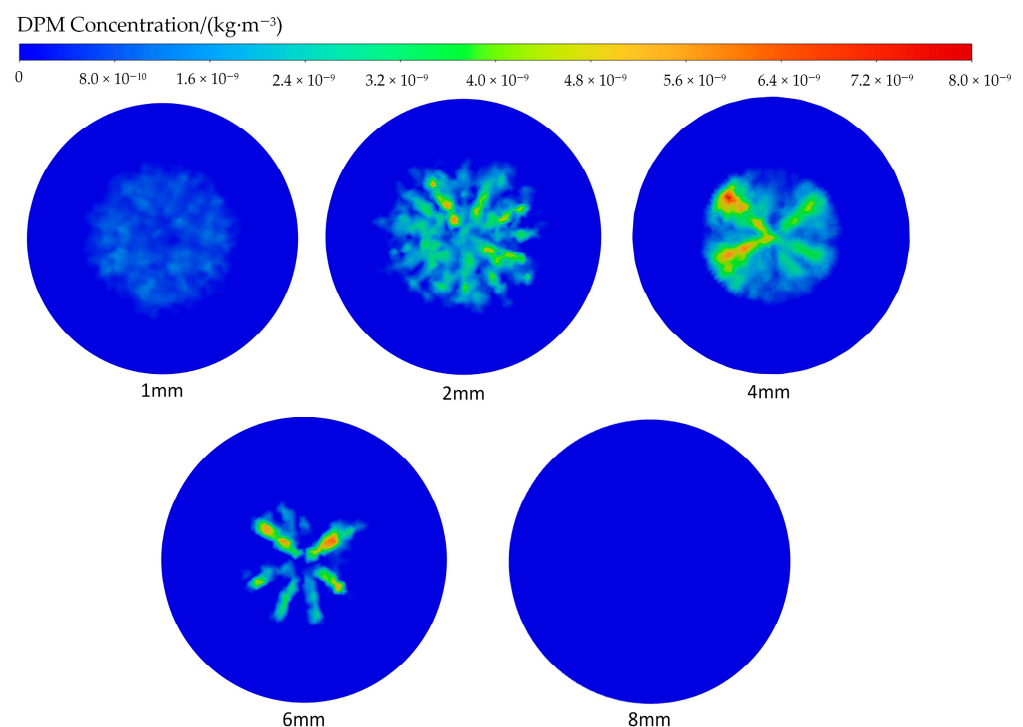


Figure 4. Deposition distribution contours for different nozzle sizes.

Numerical simulation results indicate that the nozzle diameter has a significant influence on the morphology of deposition spots. When the nozzle diameter is small, the higher flow velocity causes inertial forces to dominate the deposition process, resulting in regular circular deposition spots. As the nozzle diameter increases, the flow velocity decreases, leading to a transition where diffusion-driven deposition becomes dominant, causing noticeable changes in spot morphology. When the nozzle diameter reaches 8 mm, the excessively low velocity weakens inertial forces, significantly reducing deposition efficiency and resulting in irregular deposition spot shapes.

Further analysis reveals that a smaller nozzle diameter generates higher airflow velocity, enhancing turbulent mixing effects and improving deposition uniformity. In contrast, an excessively large nozzle diameter leads to lower airflow velocity, allowing particles to be carried away by the flow rather than being deposited in the target region, ultimately reducing deposition efficiency.

Based on this analysis and experimental requirements, a nozzle diameter of 4 mm was determined to be optimal, as it ensures effective deposition while meeting the control

requirements for deposition spot size. At this nozzle diameter, the appearance of a star-shaped pattern in the deposition concentration distribution is attributed to the combined effects of deposition non-uniformity and the simplifications introduced in the simulation boundary conditions.

3.1.2. Nozzle-to-Wafer Distance

Based on the dimensionless constant h/D_w proposed by Bae et al. in deposition experiments—where h represents the nozzle-to-wafer distance and D_w denotes the wafer diameter—it has been observed that when h/D_w exceeds 2.0, the deposition rate is inversely proportional to the nozzle-to-wafer distance [21]. As an essential variable, airflow height directly influences particle–substrate interactions and deposition performance. To further investigate the spatial distribution characteristics of particle deposition, this study systematically examines the comprehensive effect of incident height on deposition behavior. The deposition distribution contours for different nozzle-to-wafer distances are illustrated in Figure 5.

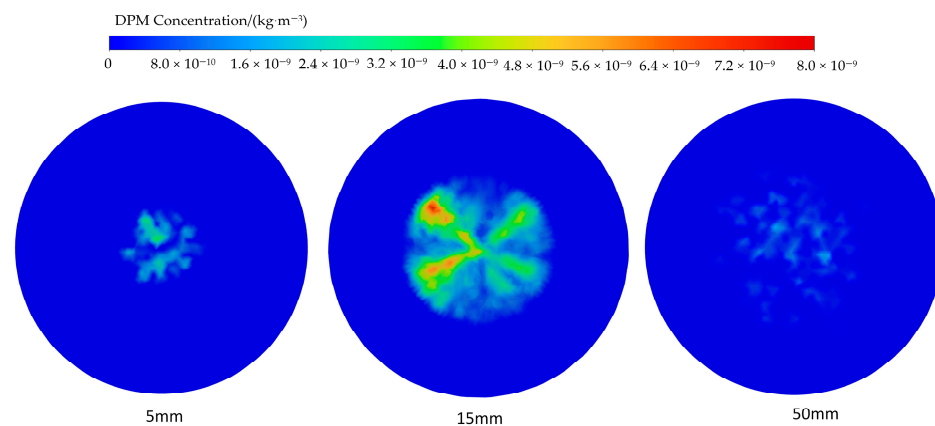


Figure 5. Deposition distribution contours for different nozzle-to-wafer distances.

A nozzle-to-wafer distance of 5 mm was selected based on the design of impactor-type samplers, where inertial forces dominate and the nozzle height is typically 1.2 to 1.8 times the nozzle diameter. Simulation results show that the deposition rate is high at this height. However, the deposition spots are overly concentrated, which causes excessive particle aggregation and reduces deposition uniformity. In contrast, at a nozzle-to-wafer distance of 50 mm, deposition spots become scattered and fail to form a coherent deposition pattern. This is because the contact probability between particles and the wafer surface decreases significantly, with most particles being carried away by the airflow, resulting in a sharp decline in deposition efficiency.

Compared to the nozzle-to-wafer distances of 5 mm and 50 mm, a height of 15 mm yields the best deposition uniformity, with a relatively high DPM concentration. Simulation results show that at this height, aerosol streamlines exhibit optimal adherence to the wafer surface, achieving a balance between inertial and diffusive forces. This balance leads to significant advantages in both deposition efficiency and concentration distribution. Based on a comprehensive comparison of the simulation results at different nozzle-to-wafer distances, 15 mm is identified as the optimal nozzle-to-wafer distance.

3.1.3. Chamber Volume

The volume of the deposition chamber affects the deposition efficiency, while the relative positions of the inlet and outlet significantly alter the flow field characteristics. As illustrated in Figure 6, this study employs numerical simulations to analyze the deposition behavior in three different chamber volumes—V1, V2, and V3—corresponding to 81 cm³,

657 cm³, and 3650 cm³, respectively. Additionally, the effect of the relative positioning of the inlet and outlet on deposition behavior is examined.

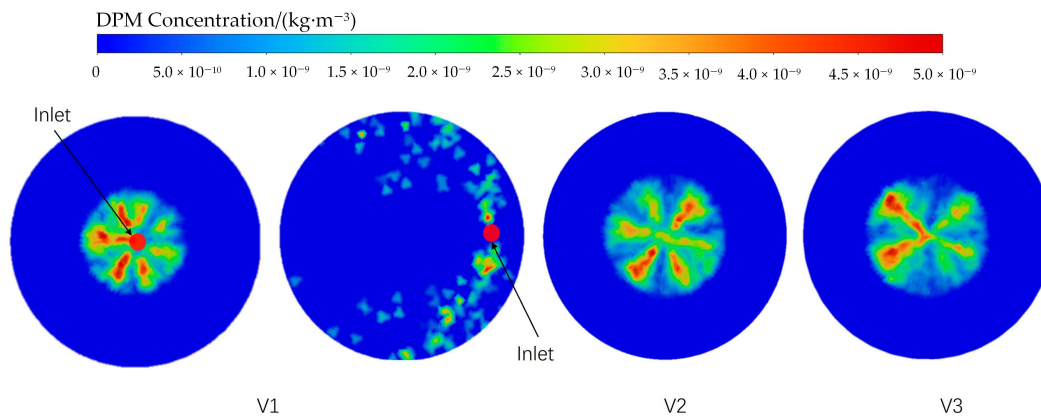


Figure 6. Deposition distribution contours for different deposition sizes and relative positions.

In general, in small-volume chambers, the incident particle flow is primarily concentrated near the wafer surface, suggesting that smaller chambers may exhibit higher particle collection efficiency under the same deposition conditions. However, simulation results indicate that the smallest chamber volume (V1) results in the smallest deposition spot size and the lowest deposition efficiency. As the chamber volume increases, the deposition spot size gradually enlarges and stabilizes when the chamber volume reaches V2, beyond which further increases in volume have a negligible effect on both deposition spot size and efficiency.

Furthermore, under the smallest chamber volume (V1), two different inlet and outlet configurations—horizontal and vertical—are explored. The simulation results show that under the horizontal configuration, deposition spots are distributed along both sides of a fan-shaped region on the wafer surface, whereas under the vertical configuration, the deposition spots exhibit a circular distribution pattern.

Based on these findings, to optimize deposition performance, prevent irregular deposition spot distributions, and ensure deposition efficiency, this study determines that the deposition chamber volume should be maintained above V2. Additionally, a horizontally arranged inlet and outlet design is adopted to enhance deposition stability and controllability.

3.1.4. Rotation Speed

Rotation directly influences deposition efficiency and spot morphology by altering the airflow field distribution and particle transport behavior. Among these factors, rotation speed is the most critical control parameter affecting deposition uniformity, efficiency, and spot morphology. To enhance deposition uniformity while maintaining a certain level of deposition efficiency, precise control of wafer rotation speed is required during the deposition process. Studies indicate that as the rotation speed increases, the gradient of the rotational shear stress difference from the wafer center to the edge also increases, resulting in position-dependent forces acting on the wafer surface. In general, higher rotational shear stress leads to lower deposition efficiency, meaning that deposition efficiency at the wafer center is lower than at the wafer edge.

As shown in Figure 7, particle deposition patterns were compared at four different rotation speeds. The results reveal that as the rotation speed increases, the morphology of the deposition spots becomes increasingly unstable, exhibiting an outward diffusion trend. At the highest rotation speed (31.4 rad/s), particles mainly accumulate at the wafer

edge. This pattern aligns with the expected relationship between shear force and deposition efficiency. As shear force increases, deposition efficiency decreases toward the wafer center.

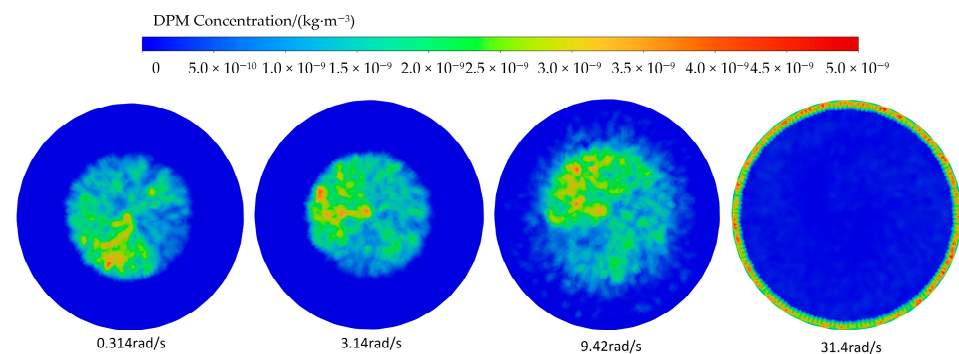


Figure 7. Deposition distribution contours for different rotational speeds.

Additionally, high rotation speeds intensify turbulence and vortex effects in the airflow, which influence deposition in two opposing ways: on one hand, turbulence-induced particle entrainment can enhance deposition efficiency, but on the other hand, the increased rotational shear stress reduces deposition efficiency. Overall, as the rotation speed increases, the reduction in deposition efficiency due to shear stress outweighs the enhancement from turbulence effects. Consequently, a moderate reduction in rotation speed helps mitigate shear stress gradients, maintain uniform particle distribution, and prevent excessive particle accumulation at the wafer edge.

Based on these findings, this study selects a rotation speed of 0.314 rad/s to achieve a balance between deposition efficiency and spot uniformity. At this speed, both the concentration distribution and uniformity of deposition spots are well maintained.

3.1.5. Particle Size

In this study, the particle size range was 70 nm to 300 nm, with the DPM phase set as monodisperse particles. In the Lagrangian model, particles were simplified as mass-bearing points with no volume, and particle–particle interactions were neglected. Since the volume fraction remained below 10% throughout the calculations, particle size variations did not significantly affect the flow field but influenced the transport and distribution of the discrete phase within the flow.

Figure 8 illustrates the deposition spot distributions of particles with different sizes on the wafer surface. For particles larger than 100 nm, deposition was primarily concentrated beneath the nozzle, with a slight increase in spot size as particle size increased. The deposition efficiency remained around 40%. In contrast, 70 nm particles exhibited a nearly uniform distribution across the entire wafer surface, with a deposition efficiency of approximately 17%.

Two main factors contributed to this phenomenon:

1. For smaller particles, diffusion was the dominant deposition mechanism, while inertial effects were insufficient. As a result, fewer particles were deposited directly beneath the nozzle, and most gradually diffused into lower-concentration regions further away.
2. Vortices formed by the airflow near the wafer surface significantly influenced smaller particles. The lower the particle mass, the more susceptible it was to turbulence-induced vortex effects, which enhanced particle–surface contact and deposition. Since the experiment considered any particle contacting the wafer as captured, small particles exhibited a broader deposition area.

Based on these results, deposition parameters can remain largely unchanged for particles larger than 100 nm. However, for particles smaller than 100 nm, additional parameter adjustments are necessary to control the deposition spot size and particle count.

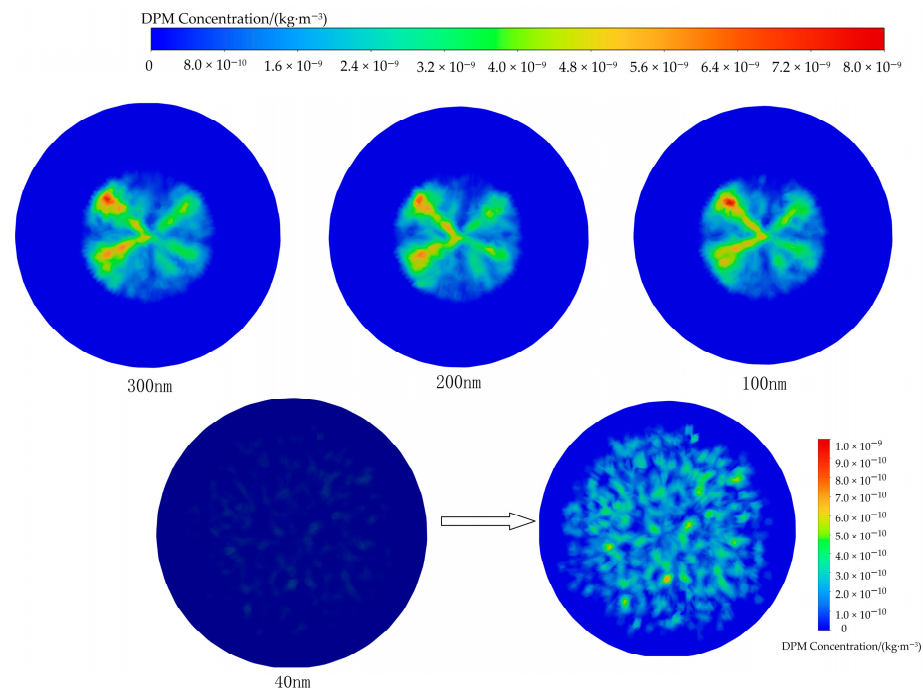


Figure 8. Deposition distribution contours for different-sized particles.

3.2. Aerosol Sample Monodispersity

In this study, SEM was used to verify the monodispersity of the PSL suspension. The suspension was first diluted to a specific concentration, after which 1 mL was dispensed onto a clean wafer surface. Following air-drying in a cleanroom, SEM images were conducted to traceably validate the particle sizes of the dried solids. Figure 9 illustrates the SEM characterization results for four characteristic particle sizes: 70 nm, 100 nm, 140 nm, and 200 nm. The scanning results show that the particle sizes of all samples align with their nominal values, with an error of less than 0.5%. The particle size distribution meets traceability requirements, demonstrating the suitability of the suspension as a raw material for preparing monodisperse aerosols and enabling the generation of initial aerosols in the 70–200 nm range.

As illustrated in Figure 10, the positions of the prominent peaks in the particle size spectra align with the expected particle sizes. However, additional peaks appear at smaller particle sizes. This phenomenon is related to the charge balance of the monodisperse aerosol sample.

Taking the 200 nm monodisperse aerosol as an example, when the X-ray neutralizer reached charge equilibrium, the aerosol contained 200 nm particles carrying one, two, or three charges. The corresponding electrical mobility (Z) follows the relationship $Z_1 < Z_2 < Z_3$, meaning that particles with more charges exhibit higher electrical mobility. Since electrical mobility determines how particles are classified in the SMPS, multiply charged larger particles appear at positions corresponding to smaller single-charged particles, leading to additional peaks in the SMPS results [22].

According to the Boltzmann charge equilibrium principle, larger particles have a higher probability of carrying multiple charges. As a result, the secondary peaks become more pronounced for 140 nm and 200 nm aerosol samples. Additionally, for the 70 nm and 100 nm aerosols, peaks also appear at sizes larger than the prominent peaks. This may be

due to the presence of oversized particles in the PSL standard suspension or the formation of small aggregates during the atomization process.

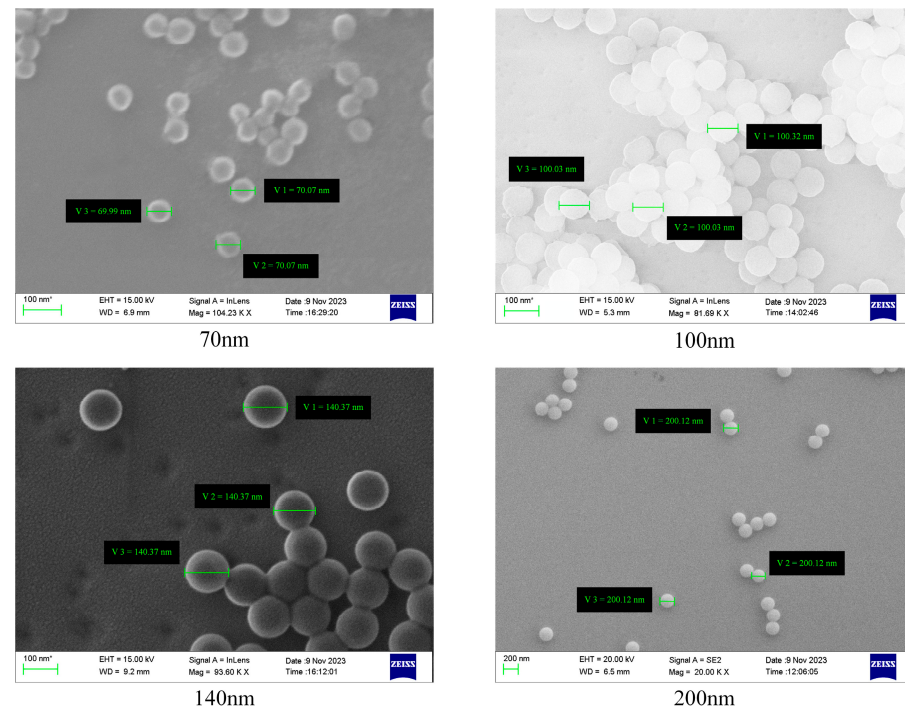


Figure 9. SEM images of samples with different particle sizes.

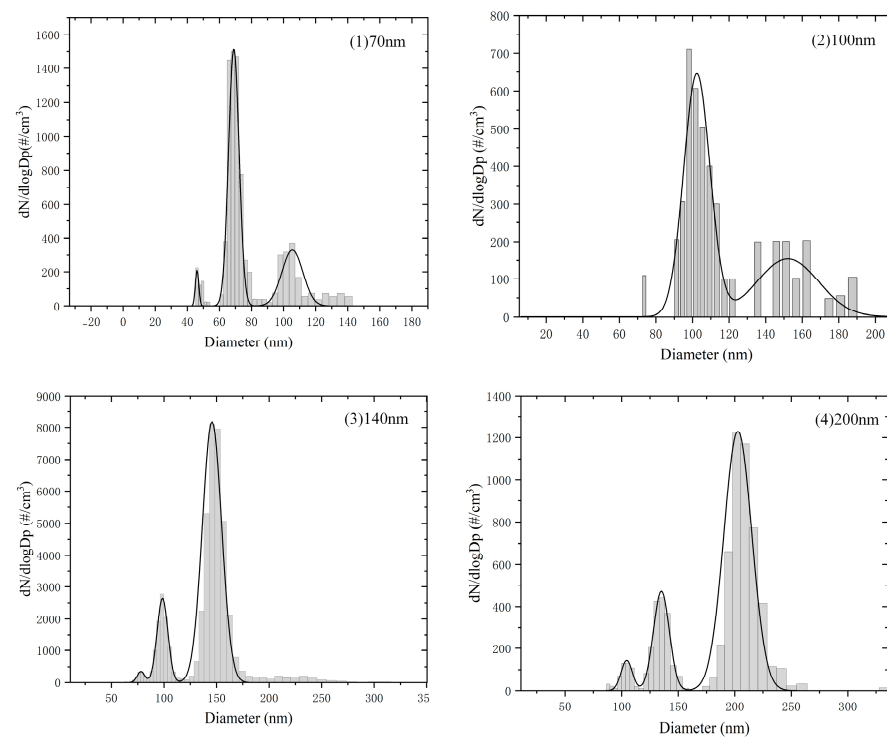


Figure 10. SMPS particle size distribution spectrum after two neutralizations.

3.3. Standard Wafer Sample

The deposition efficiency is defined as the ratio of the number of deposited particles to the number of incident particles and can be expressed as

$$\eta = \frac{N_D}{N_{in}} = \frac{C_D V_D}{N_{in}} = \frac{C_D \cdot H_{spot} \cdot S_{spot}}{Q_{in} \cdot C_p \cdot t} \quad (1)$$

where Q_{in} : fluid flow rate; C_p : aerosol particle concentration; t : deposition time; C_D : deposition concentration; H_{spot} : height of the boundary layer above the sediment spot; S_{spot} : deposition spot area.

Figure 11 presents the SSIS scans of wafer samples with four different particle sizes, while Table 3 summarizes the number of deposited particles and deposition efficiency for each sample. The results indicate that, except for the 70 nm wafer samples, each wafer contains approximately 2000 to 3000 deposited particles, with a deposition efficiency of around 28%. This level of deposition meets the particle quantity requirements for SSIS calibration.

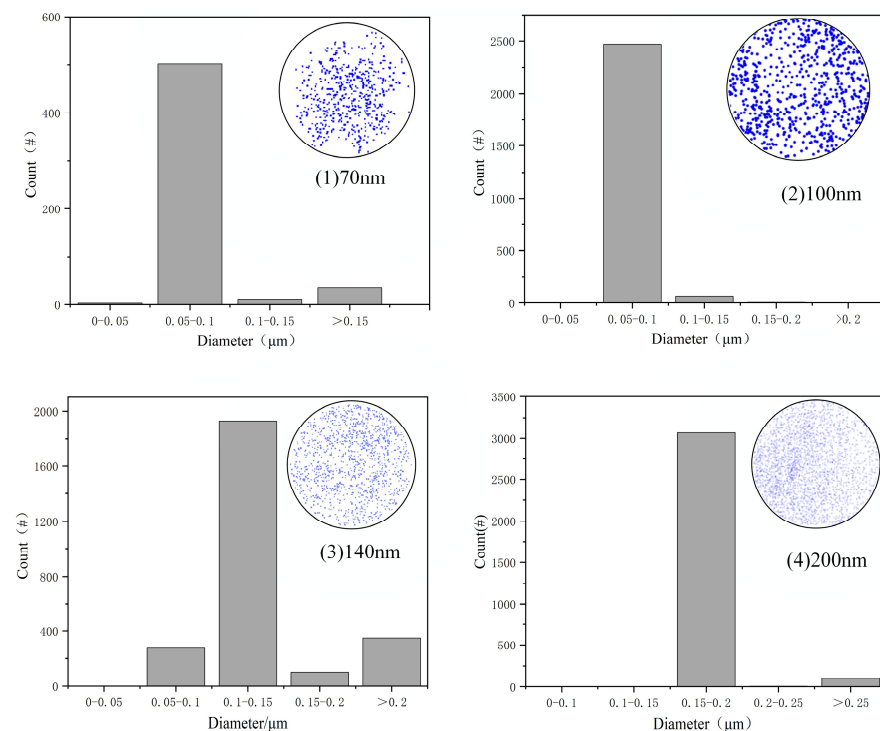


Figure 11. SSIS scanning results of standard wafers with different particle sizes. ‘#’ indicates the number of defects observed.

Table 3. Deposition number and deposition efficiency of standard wafers with different particle sizes.

Particle Size/nm	Number of Deposited Particles/#	Deposition Efficiency/%
70	502	6.5%
100	2470	27.4%
140	2031	29.6%
200	3069	28.4%

Note: ‘#’ indicates the number of defects observed.

Under the optimized experimental conditions—namely, a nozzle diameter of 4 mm, a deposition height of 15 mm, a chamber volume exceeding 657 cm³, and a rotation speed of 0.314 rad/s—Figure 11 presents the SSIS scans of wafer samples with four different particle sizes, while Table 3 summarizes the corresponding particle counts and deposition efficiencies. The results show that, with the exception of the 70 nm samples, each wafer

contained approximately 2000 to 3000 deposited particles, corresponding to a deposition efficiency of approximately 28%. This level of particle loading satisfies the requirements for SSIS calibration.

It should be noted that the SSIS result images do not include a scale bar. This is due to two main reasons: (1) SSIS operates by analyzing light scattering signals and converting them into particle size information based on the system's internal calibration curves; as such, the output images typically do not represent real physical dimensions or include scale references. (2) The particle dots in SSIS images are visually enlarged to enhance visibility, and their sizes do not directly correspond to the actual dimensions on the wafer. Therefore, including a scale bar could be misleading.

Figure 12 compares the deposition efficiency between simulation and experiment for different particle sizes. The data analysis shows that the trend of deposition efficiency with increasing particle size is consistent between the two. However, the simulated results are consistently higher than the experimental results across all particle sizes, with differences ranging from 9.1% to 11.62%. This discrepancy primarily stems from the simplified treatment of kinetic behavior in the numerical simulation compared to actual working conditions.

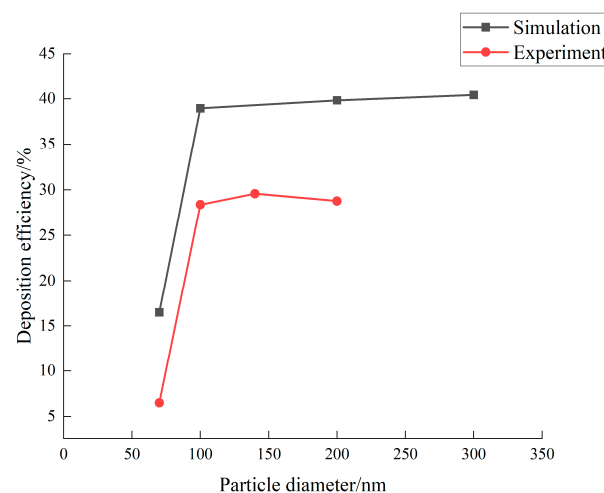


Figure 12. Comparison of deposition efficiency between simulation and experiment.

The deposition efficiency is highly dependent on particle size, with the 70 nm wafer samples exhibiting lower deposition efficiency than other particle sizes. This discrepancy aligns with the numerical simulation results. Overall, the four wafer samples with different particle sizes demonstrated good monodispersity and uniform deposition during the SSIS scan calibration process. This confirms that the generation–deposition system is capable of producing standard wafers that meet the requirements for SSIS calibration.

4. Conclusions

In this study, by generating monodisperse aerosols, numerically simulating the particle deposition chamber, and establishing the generation–deposition system, four SW samples meeting the SSIS calibration requirements were successfully prepared with particle sizes ranging from 70 to 200 nm. The main conclusions drawn from the experiment are as follows:

1. Fluent simulations identified the optimal parameters for area deposition as a 4 mm nozzle diameter, 15 mm nozzle-to-wafer distance, deposition chamber volume greater than 657 cm³, and a rotation speed of 0.314 rad/s. Under these conditions, uniform deposition can be achieved with a spot diameter of 23.7 mm and a deposition efficiency of 33.1%. Particles ≥ 100 nm can be stably deposited under standardized

- parameters, whereas particles <100 nm require adjustments to other parameters to improve deposition efficiency.
2. SEM analysis confirmed that the standard PSL suspension used in the experiment aligns with the nominal particle size, making it a suitable raw material for monodisperse aerosol generation. Although multiple particle size peaks were observed in the SMPS scan spectrum, the number concentration at the main peak corresponding to the target particle size was significantly higher than that of the other peaks. Analysis of this phenomenon indicates that SMPS scanning data can serve as a reliable basis for particle size distribution measurement.
 3. System validation based on simulation results successfully produced four SW samples (70–200 nm). Experimental results confirmed that the deposition efficiency reached 28% for all samples except the 70 nm sample. SSIS testing further verified that these samples meet the requirements for SSIS calibration.

Author Contributions: Conceptualization, J.R. and J.L.; methodology, J.L., Y.L. and Z.Z.; software, Z.Z.; validation, J.R., J.L., Y.L. and Z.Z.; investigation, J.L., Y.L. and Z.Z.; writing—original draft preparation, Z.Z. and J.L.; writing—review and editing, J.R., J.L. and Z.Z.; visualization, Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Special Project for Quality and Technical Basic Capability Construction of the State Administration for Market Regulation (grant number ANL2508), and Key areas of basic scientific research business expenses of the National Institute of Metrology China (grant number AKYZD2308-1).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: We gratefully acknowledge the administrative and technical support provided by the State Key Laboratory of Clean and Efficient Coal Utilization, Taiyuan University of Technology, which was invaluable to this work. We also thank the Frontier Metrology Science Center, National Institute of Metrology, China, for the donation of materials used in the experiments. Any assistance that does not fall under author contributions or funding has been greatly appreciated.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

PSL	Polystyrene Latex
SSIS	Institute Scanning Surface Inspection System
SW	Standard Wafer
CFD	Computational Fluid Dynamics
SMPS	Scanning Mobility Particle Sizer
SEM	Scanning Electron Microscopy
CPC	Condenser Particle Counter
DMC	Differential Mobility Classifier

References

1. Ma, J.; Zhang, T.; Yang, C.; Cao, Y.; Xie, L.; Tian, H.; Li, X. Review of wafer surface defect detection methods. *Electronics* **2023**, *12*, 1787. [[CrossRef](#)]
2. Vines, L.; Monakhov, E.; Kuznetsov, A. Defects in semiconductors. *J. Appl. Phys.* **2022**, *132*, 150401. [[CrossRef](#)]

3. Chen, Y.; Ding, Y.; Zhao, F.; Zhang, E.; Wu, Z.; Shao, L. Surface defect detection methods for industrial products: A review. *Appl. Sci.* **2021**, *11*, 7657. [\[CrossRef\]](#)
4. Wang, X.; Jia, X.; Jiang, C.; Jiang, S. A wafer surface defect detection method built on generic object detection network. *Digit. Signal Process.* **2022**, *130*, 103718. [\[CrossRef\]](#)
5. Rasheed, A.; Zafar, B.; Rasheed, A.; Ali, N.; Sajid, M.; Dar, S.H.; Habib, U.; Shehryar, T.; Mahmood, M.T. Fabric defect detection using computer vision techniques: A comprehensive review. *Math. Probl. Eng.* **2020**, *2020*, 8189403. [\[CrossRef\]](#)
6. Zhu, J.; Liu, J.; Xu, T.; Yuan, S.; Zhang, Z.; Jiang, H.; Gu, H.; Zhou, R.; Liu, S. Optical Wafer Defect Inspection at the 10 nm Technology Node and Beyond. *Int. J. Extrem. Manuf.* **2022**, *4*, 032001. [\[CrossRef\]](#)
7. Wu, F.; Cao, P.; Du, Y.; Hu, H.; Yang, Y. Calibration and image reconstruction in a spot scanning detection system for surface defects. *Appl. Sci.* **2020**, *10*, 2503. [\[CrossRef\]](#)
8. Zhou, Z.D. Research on Spot-Scanning Multi-Mode Unpatterned Wafer Defect Inspection Technology and Signal Processing Method. Ph.D. Thesis, University of Science and Technology of China, Hefei, China, 2024. [\[CrossRef\]](#)
9. Wu, Q.; Zhao, H.; Liu, H. Dynamic visualization study of in situ cleaning of polystyrene microparticles off silicon wafer surface. *Phys. Fluids* **2024**, *36*, 113320. [\[CrossRef\]](#)
10. Lee, S.; Hong, S.; Oh, H.; Chae, S.K.; Kim, T. Study on uniform deposition on 300 mm silicon wafer with sub-100 nm sized particles for cleaning application. *Solid State Phenom.* **2021**, *314*, 209–213. [\[CrossRef\]](#)
11. Kazemimanesh, M.; Rahman, M.M.; Duca, D.; Johnson, T.J.; Addad, A.; Giannopoulos, G.; Focsa, C.; Boies, A.M. A comparative study on effective density, shape factor, and volatile mixing of non-spherical particles using tandem aerodynamic diameter, mobility diameter, and mass measurements. *J. Aerosol Sci.* **2022**, *161*, 105930. [\[CrossRef\]](#)
12. Lee, J.; He, S.; Song, G.; Hogan, C.J. Size distribution monitoring for chemical mechanical polishing slurries: An intercomparison of electron microscopy, dynamic light scattering, and differential mobility analysis. *Powder Technol.* **2022**, *396*, 395–405. [\[CrossRef\]](#)
13. Yook, S.J.; Fissan, H.; Engelke, T.; Asbach, C.; Van Der Zwaag, T.; Kim, J.H.; Wang, J.; Pui, D.Y.H. Classification of highly monodisperse nanoparticles of NIST-traceable sizes by TDMA and control of deposition spot size on a surface by electrophoresis. *J. Aerosol Sci.* **2008**, *39*, 537–548. [\[CrossRef\]](#)
14. Cho, Y.; Hong, S.; Lee, S.; Yang, J.; Chae, S.-K.; Kim, T. Investigation of a standard particle deposition system on wafer surface and its application to wafer cleaning. *ECS J. Solid State Sci. Technol.* **2019**, *8*, 768–774. [\[CrossRef\]](#)
15. Dick, W.D.; Hegner, L.A.; Li, L. 10 nm particle deposition capability for qualification of next-generation defect inspection tools. In Proceedings of the 2023 34th Annual SEMI Advanced Semiconductor Manufacturing Conference, New York, NY, USA, 1–4 May 2023. [\[CrossRef\]](#)
16. Lee, S.; Choi, S.; Cho, Y.; Oh, H.; Chae, S.-K.; Kim, T. Uniform deposition method of monodispersed SiO₂ nanoparticles on a 300-Mm Si wafer surface. *Rev. Sci. Instrum.* **2021**, *92*, 113704. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Tajima, N.; Iida, K.; Ehara, K.; Khumpuang, S.; Hara, S.; Sakurai, H. A method to deposit a known number of polystyrene latex particles on a flat surface. *Aerosol Sci. Technol.* **2019**, *53*, 1353–1366. [\[CrossRef\]](#)
18. Matsuno, K.; Mishima, H.; Arimatsu, M.; Kikuchi, S.; Shikami, S. The wafer preparation technology with nano size particle contamination by using single spin processor. In Proceedings of the 2006 IEEE International Symposium on Semiconductor Manufacturing, Tokyo, Japan, 25–27 September 2006. [\[CrossRef\]](#)
19. Li, S.; Ali, K.; Algarni, S.; Alqahtani, T.; Ahmad, S.; ElSeabee, F.A.A.; Ullah, H.; Jamshed, W.; Irshad, K. Numerical analysis of thermophoretic particle deposition in a Magneto-Marangoni convective dusty tangent hyperbolic nanofluid Flow—Thermal and Magnetic features. *Nanotechnol. Rev.* **2024**, *13*, 20230190. [\[CrossRef\]](#)
20. Abbas, M.; Khan, N.; Hashmi, M.S.; Alhefthi, R.K.; Inc, M. Significance of heat generation and thermophoretic particle deposition in Marangoni convective driven boundary layer flow of cross nanofluid with activation energy. *Case Stud. Therm. Eng.* **2024**, *59*, 104427. [\[CrossRef\]](#)
21. Bae, G.N.; Lee, C.S.; Park, S.O. Measurement of Particle Deposition Velocity Toward a Horizontal Semiconductor Wafer by Using a Wafer Surface Scanner. *Aerosol Sci. Technol.* **1994**, *21*, 72–82. [\[CrossRef\]](#)
22. Flagan, R.C. History of electrical aerosol measurements. *Aerosol Sci. Technol.* **1998**, *28*, 301–380. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.