Field measurement analyses and improvement simulation of airflow parallelism in a wafer-griding cleanroom

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Abstract. Cleanrooms are essential in the semiconductor industry, where the environment must be strictly regulated to prevent contamination that could affect product quality. However, many factors are crucial, and the process can be complex, such as temperature, relative humidity, airflow distribution, particle counts, and pressure. This study conducted a cleanroom for wafer grinding wheels with the highest level of cleanliness, cleanroom class 1, utilizing a ceiling covered by Ultra-Low Particulate Air (ULPA) filter. In order to ensure that the design conforms to the standard, Testing, Adjusting, and Balancing (TAB) were conducted prior to field measurements. According to the findings, all cleanroom specifications were met. However, the airflow rate exceeds the design, causing the pressurization to increase. In addition, the study also utilized simulation to simulate airflow parallelism to decrease angle deflection. The average airflow velocity measured is 0.42 m/s. By reducing the airflow to the required limit of 0.35 m/s, the deflection of the angle can be reduced by 10%. Other parameters, such as airflow rate and pressurization, remain within the standard. In addition, lowering the airflow rate can lead to energy savings.

1 Introduction

Cleanrooms for semiconductors are the most stringent in the entire world. When photolithography linewidths fall below 0.1 micron, the corresponding cleanroom classifications are typically class 10 or class 100 (ISO 4 or ISO 5), with some even employing a more stringent cleanliness level concentration at class 1 (ISO 3) [1-2]. Frequently, cleanrooms of class 100 or higher feature ceiling coverage of 100% ULPA filters to prevent any area from lacking unidirectional airflow. By directing ULPA filter air vertically from the ULPA filters in the ceiling in a straight line to below the flooring, elevated cleanroom flooring ensures the highest possible laminar flow [3]. Adherence to the airflow parallelism standard is essential for the unidirectional flow cleanroom to effectively demonstrate the airflow pattern and illustrate the equipment's impact on airflow. The deflection angle of parallelism, as specified by the National Environmental Balancing Bureau (NEBB) [4], should not exceed 14° from the center when measured from a height of 915 mm (36 inches) above the floor.

The design of effective air distribution patterns is critical for particle removal in cleanrooms. In previous decades, various studies were conducted to investigate air distribution characteristics. Hu et al. [5] determined the deflection angle and non-uniform characteristics of air velocity while examining air turbulence in a cleanroom equipped with fan filter units (FFUs). In their study, Cheng et al. [6] utilized computational fluid dynamics (CFD) to examine the effects on airflow uniformity of various parameters, including the width of the cleanroom, the porosity and height of the raised floor, and the inlet velocity profile. The uniformity of airflow, which subsequently impacts the distribution of particles within a cleanroom, is influenced by the release rate of an air supply [7]. Thongsri and Pimsarn [8] discovered that between 0.25 and 0.65 m/s, the airflow from the fan filter unit (FFU) could effectively obstruct particles. The effects of air change rate and the free area ratio of a raised floor on particle concentrations were examined by Khoo et al. [9]. It was noted that an increase in these parameters led to a reduction in the mean particle concentration. A study conducted by Vutla et al. [10] discovered that optimal flow is achieved with floor-tile ventilation covering the entire surface area. Particulate accumulation is drawn under laminar airflow (LAF) conditions, which produces the best flow by drawing the accumulation of particles. On the contrary, floor-tile ventilation in 50% of the area generates deflected airflow streamlines that facilitate the deposition of pollutants.

Many studies have been undertaken in unidirectional flow cleanrooms. However, there is still a lack of understanding of airflow parallelism to estimate angle deflection. This study conducted field measurements to test, verify, and certify the cleanroom complies with the guidelines and standards. Findings from these simulations are carefully examined to gain insights into airflow parallelism. The airflow pattern within a cleanroom with the unidirectional flow will be numerically simulated in this study with several cases.

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2 Methodology

2.1 Cleanroom layout and classification

A cleanroom is a controlled environment designed to maintain extremely low levels of particulate contamination, allowing for precise and sterile processes in industries like semiconductor manufacturing. The cleanroom layout and classification are essential aspects of ensuring that specific cleanliness standards are met for different areas within the facility. Figure 1 shows a cleanroom layout with three distinct areas, each classified according to its cleanliness level (see Table 1). The primary objective of this study is to comprehensively investigate the semiconductor cleanrooms belonging to different classification standards: Class 1000, Class 10, and Class 1. Specifically for the cleanroom class 1 standard, the test of airflow parallelism is a must.

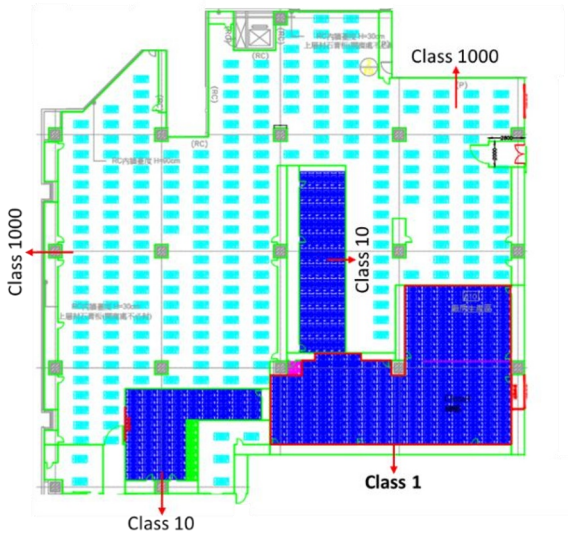


Fig. 1. Cleanroom layout and classification

Table 1. Cleanroom standard and design conditions

Room Name	Particle Counts (Particle/ft^3)	Temperature (°C)	Relative Humidity (%)	Room Pressure (mmAq)
Cleanroom Class 1	1 @ 0.1 µm	22±2	25±5	+2.5
Cleanroom Class 10	10 @ 0.1 µm	22±2	≤50	+2.0
Cleanroom Class 1000	1000 @ 0.5 µm	22±2	≤50	+1.5

2.2 TAB and Field Measurement

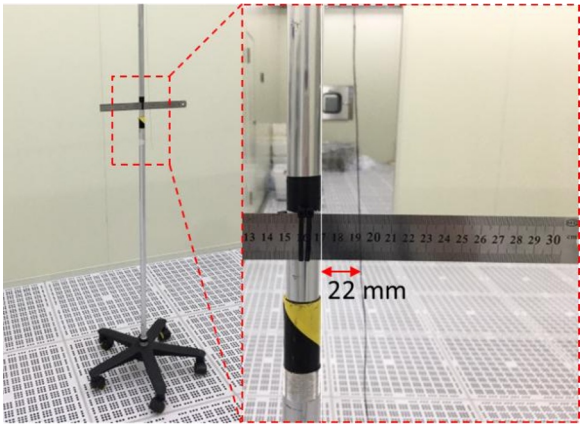
TAB is crucial in commissioning and maintaining Heating, Ventilation, and Air Conditioning (HVAC) systems. It involves systematic processes and procedures to ensure the HVAC system functions efficiently and meets the desired performance criteria. Adjusting involves making necessary modifications to the HVAC system to ensure that it operates as the design standard. The field measurement was carried out in the cleanroom. The measurement data were used as the basis of the parameters as the boundary conditions in CFD simulation. The apparatus for field measurements was calibrated within a 1-year due date for accurate and precise measurement data. The parameters that needed to be measured were particle counts, air velocity, temperature, relative humidity, and pressurization.

2.3 Airflow Parallelism Test

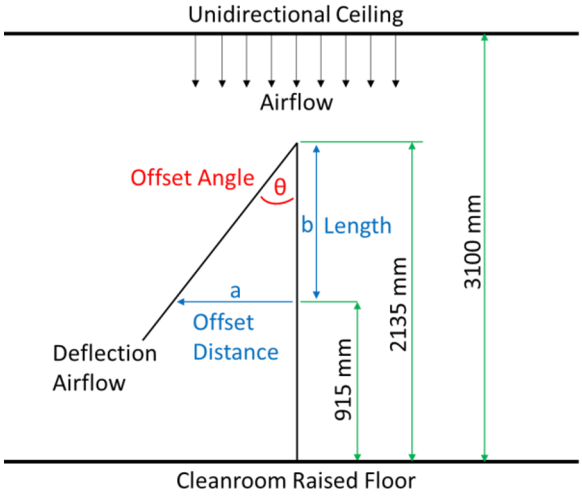
In this study, the deflection of the angle was measured using cotton thread to visualize the airflow parallelism. In addition, various mediums, including non-contaminating items such as vapor, stream, or string, are used to visualize the airflow. The objective of the airflow parallelism test is to demonstrate the actual airflow pattern throughout the unidirectional cleanroom. It can also show how the equipment inside the cleanroom affects airflow. Inside a cleanroom, the airflow should be laminar and uniform. When measured higher than 915 mm (36 inches) above the floor, the deflection angle of parallelism shall not be greater than 14° from the center. The procedure test of airflow parallelism is shown in Figure 2. The deflection of the angle can be obtained using Equation (1).

$$\theta = tan^{-1}(a/b) \quad (1)$$

where: A = angular offset – degree, a = deflection distance, b = vertical height.



(a) photograph



(b) schematic diagram

Fig. 2. Airflow parallelism test

2.4 CFD Simulation

This CFD simulation aims to analyze the airflow parallelism within a Cleanroom Class 1 and identify any deflection angles present in the airflow. The cleanroom's geometry design in Figure 3 is based on the actual size per the site situation to ensure accurate results. The polyhedral mesh type is used in this study. Implementing three distinct mesh types, coarse (805,568), medium (1,522,780), and fine (2,284,980), was critical to the simulation process. The fine mesh arrangement was chosen after great consideration. This fine mesh was carefully examined to ensure its quality and refinement using mesh independence investigations, ensuring the simulation results converged appropriately.

Boundary conditions were constructed using field measurement data to ensure the simulation closely matched real-world situations. This crucial phase ensures that the simulation findings closely match the airflow parameters in the cleanroom class 1 environment. The input for the face velocity from the ULPA filter is obtained and the same as the field measurement data. The return air comes through the raised floor with a porosity of 50%. The turbulence model used in this simulation was the RNG k-ε. The simulation comprised a substantial 5000 iterations.

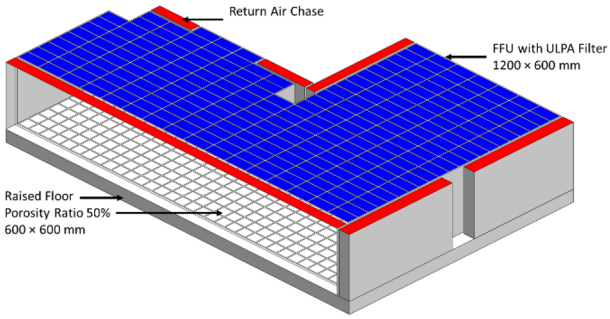


Fig. 3. Geometry model of cleanroom class 1

3 Results and discussion

3.1 Air velocity

Airflow velocity was determined through field measurements in three distinct categories of cleanrooms: class 1000, class 10, and class 1. In accordance with design specifications, the minimum face velocity was 0.35 m/s. The findings, which are depicted in Figure 4, indicate that the measured airflow velocities from the FFUs surpassed the intended design criteria. Before TAB was utilized to fine-tune it, the air velocity had increased to 0.6 m/s. Things became more consistent after TAB; the air velocity now fluctuated between 0.37 and 0.47 m/s, with no longer any significant fluctuations. This demonstrates that TAB was successful in stabilizing and improving the airflow overall. The average velocity was determined to be 0.42 m/s for class 1000 cleanrooms, 0.5 m/s for class 10 cleanrooms, and 0.45 m/s for class 1 cleanrooms. The results of this study suggest that the airflow velocities in the cleanrooms are exceeding the allowed limits, potentially impacting their overall performance and operational efficiency.

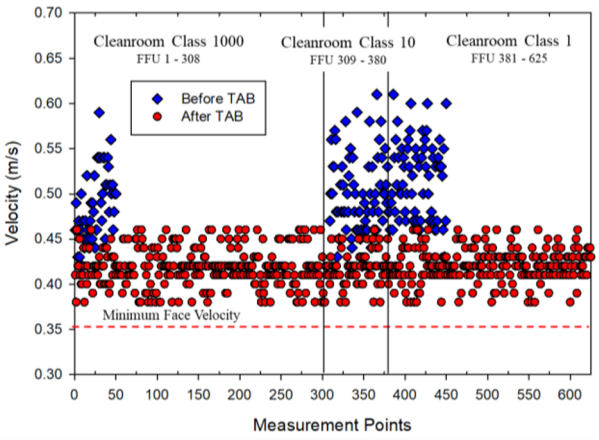


Fig. 4. Airflow measurement for cleanroom class 1000, 10, 1

3.2 Particle counts

Field measurements of particle counts were conducted in three distinct types of cleanrooms: class 1000, class 10, and class 1, each designed to meet specific cleanliness requirements. The measurements focused on particles at two critical sizes: 0.5 µm and 5 µm, which are vital parameters for evaluating cleanroom performance. The design standards for these cleanrooms were stringent, with class 1000 allowing a maximum of 1000 particles per ft^3 at 0.5 µm, class 10 permitting a maximum of 10 particles per ft^3 at the same size, and class 1 allowing only 1 particle per ft^3 at 0.5 µm.

The collected data, as presented in Figure 5, revealed that particle counts in all three cleanroom classes consistently met or exceeded these stringent design standards. Notably, it was observed that particles at 0.5 µm exhibited a higher count than those at 5 µm, underscoring the effectiveness of the cleanroom's filtration and control systems in efficiently removing smaller contaminants, ensuring the cleanroom's ability to maintain the required levels of cleanliness and protect sensitive processes and products.

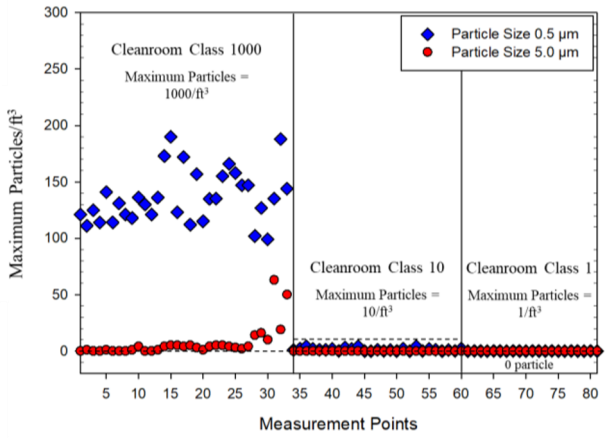
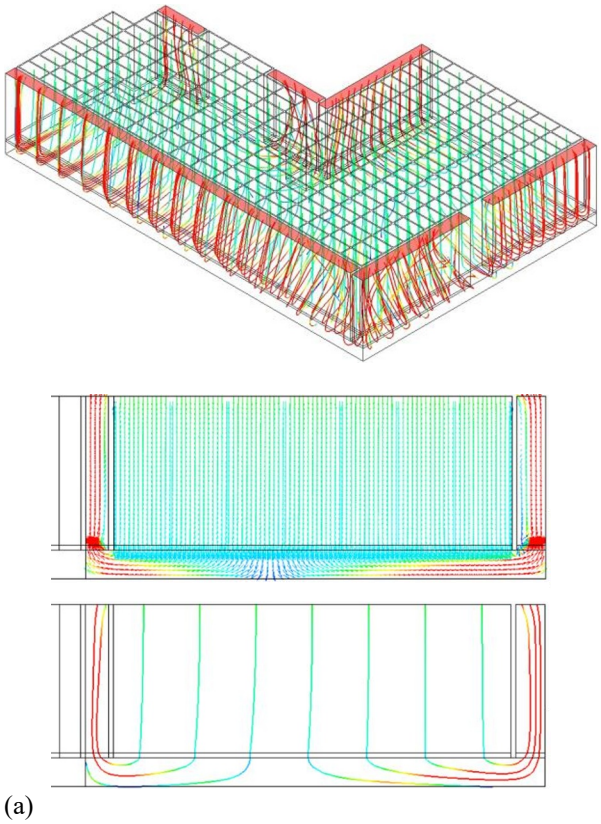


Fig. 5. Particle counts measurement for cleanroom class 1000, 10, 1.

3.3 Airflow Parallelism

The cleanroom classes 1, 10, and 100 (ISO 3, 4, 5) must execute the airflow parallelism test to ensure laminar airflow. Class 1,000; 10,000; 100,000 (ISO 6, 7, 8) cleanrooms have turbulent airflow and are therefore exempt from the airflow parallelism test. In this field investigation, the airflow parallelism test was conducted for cleanroom class and class 10. There are sixteen measuring points for class 10 and twenty-four for class 1 cleanrooms.

According to the regulation, the angle deflection must be less than 14°. The angle deflection varies based on site-specific data. However, the outcomes are still below the maximum allowed design. Some of that nearly reached 14°. The cleanroom class 1 shows a somewhat reduced deflection of angle if we compared with the cleanroom class 10. The results are shown in Figure 6. The CFD simulation was conducted only for cleanroom class 1. First, the baseline case was simulated using the identical field measurement-derived parameters. It indicates that the trend closely follows the measurements. Because a portion of the angle deflection is close to the design's maximum limit, we strive to improve and reduce the angle deflection. Aside from that, an extremely intense airflow rate occurs, causing the airflow rate and pressure to exceed the norm. In this work, we attempt to simulate the design standard airflow rate, which should be ≥0.35 m/s. The results demonstrated that the angle deflection can be lowered when the airflow is likewise decreased. The reduction is around 10% compared to the baseline design. The airflow decrease is not only reduced the deflection of angle, but also may contribute to the energy consumption.



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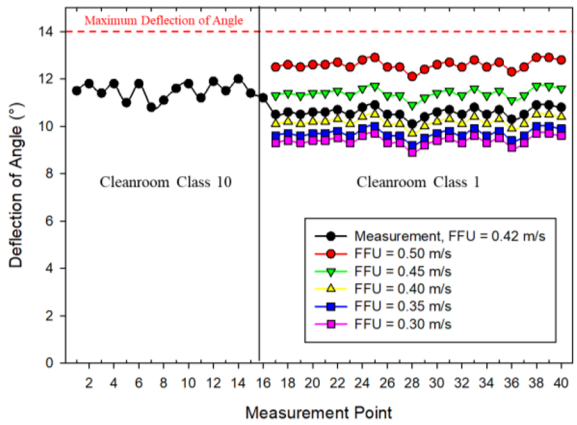

(b)

Fig. 6. Airflow parallelism results (a) deflection of angle (b) at different face velocity

4 Conclusions

The critical importance of performing Testing, Adjusting, and Balancing (TAB) prior to measurements in order to ensure accuracy and reliability. Aside from the technicalities, we discovered that increased air velocity not only causes angle deflection but also may consumes a significant amount of energy. These findings highlight TAB's practical importance as a proactive measure, not only for precise measurements but also in the broader context of promoting energy efficiency across multiple applications.

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