Journal of Electronic Research and Application, 2025, Volume 9, Issue 7
http://ojs.bbwpublisher.com/index.php/JERA
ISSN Online: 2208-3510
ISSN Print: 2208-3502

Scheme Layout and Optimization Strategies for the Mechanical Structure Design of Semiconductor Probe Stations

Wenfeng Peng*

Dongguan 523000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: This paper investigates the mechanical structural design of semiconductor probe stations. It presents the overall system architecture, functional module integration, and optimized layout schemes, including the selection and calculation of moving components and precision-retention mechanisms. A dedicated test platform is established to evaluate system performance. Experimental results demonstrate that a simulation-driven design approach enables the achievement of high-precision performance, effectively reduces thermal drift, and satisfies the testing requirements of semiconductor wafers. The proposed design provides a valuable reference for the research and development of similar semiconductor testing equipment.

Keywords: Semiconductor probe station; Mechanical structure design; Optimization strategy

Online publication: December 31, 2025

1. Introduction

With the vigorous development of the semiconductor industry, the requirements for precision and stability of semiconductor probe stations have become increasingly stringent. The "Policies for Promoting High-Quality Development of the Integrated Circuit Industry and Software Industry in the New Era" promulgated in 2020 emphasizes promoting high-quality development of the integrated circuit industry. Against this background, the mechanical structure design of semiconductor probe stations is crucial. This paper conducts in-depth research on this topic, proposing effective strategies from system architecture and overall scheme layout to component selection, precision maintenance, and structural optimization. Through building a testing platform, developing automation programs, and conducting various performance verification experiments, high-precision technical indicators are achieved, equipment stability is enhanced, providing strong support for semiconductor wafer testing and reference for similar equipment development, aligning with the policy orientation of promoting high-quality industrial development.

2. Overall scheme layout of semiconductor probe station mechanical system

2.1. Overall machine system architecture design

Based on semiconductor wafer testing process requirements, the overall machine system architecture design of the semiconductor probe station mechanical system needs to establish an XYZRF five-axis motion coordinate system. The X and Y axes are responsible for precise planar movement of the wafer to meet positioning needs for different test points; the Z axis carries the Wafer Chuck for precise Z-direction up-and-down positioning of the wafer, ensuring good contact between the wafer and the Probe Card; the R axis is used for visual leveling during wafer testing, avoiding wafer offset issues caused by the ARM during loading. Meanwhile, the F axis carries the Clean Pad, because during CP testing, under energized conditions, slight oxidation occurs at the probe tips. Additionally, as probes continuously contact pads, aluminum debris adheres to the tips. Timed needle grinding and sticking are required during testing to clean the tips, remove the oxide layer, and eliminate aluminum debris from the tips. A high-rigidity frame-type main structure layout scheme is adopted, which effectively enhances system stability and rigidity, reducing vibration and deformation during high-speed, high-precision motion, providing reliable foundational support for the testing process and thereby meeting the high-precision and high-stability requirements of semiconductor wafer testing [1].

2.2. Functional module integration design

In the overall scheme layout of the semiconductor probe station mechanical system, functional module integration design is crucial. For the probe positioning mechanism, wafer stage, and vibration suppression module, their spatial layout relationships must be precisely planned. The probe positioning mechanism should be arranged in a position convenient for precise operation and close to the wafer stage to ensure accurate probe contact with test points on the wafer. The wafer stage should be in a stable and easily adjustable position to flexibly change the wafer's position and angle. The vibration suppression module surrounds key components to minimize external vibration interference while greatly suppressing low-frequency vibrations generated by the probe station's own motion. At the same time, a standardized interface design scheme should be implemented, unifying interface dimensions, shapes, and communication protocols among modules to achieve efficient connection and collaborative operation, laying a foundation for stable and efficient operation of the semiconductor probe station [2].

3. Key technologies in precision mechanical structure design

3.1. Selection and calculation of main motion components

In the mechanical structure design of semiconductor probe stations, selection and calculation of main motion components are critical. Axial load checking of ball screws is performed based on Hertz contact theory. Hertz contact theory precisely analyzes contact stress between balls and raceways, calculating the axial load borne by the ball screw under actual conditions via relevant formulas to determine if it meets strength requirements, ensuring transmission stability [3]. Concurrently, transmission parameters of the fine-motion platform are determined based on piezoelectric ceramic drive characteristics. Piezoelectric ceramics feature high precision and high response speed. Based on their voltage-displacement characteristic curves, the relationship between applied voltage and generated displacement is clarified, calculating required transmission ratios, strokes, and other parameters for the fine-motion platform to achieve precise micro-motion control, meeting the stringent high-precision positioning demands of semiconductor probe stations.

3.2. Precision maintenance structure design

In the precision maintenance structure design of semiconductor probe stations, deformation in cross-scale motion mechanisms significantly affects overall precision. Finite element method can precisely analyze deformation of cross-scale motion mechanisms under different conditions, providing a key basis for precision maintenance structure design [4]. Based on analysis results, designing adaptive preloading devices becomes an effective compensation strategy for eliminating reverse backlash. This device automatically adjusts preloading force according to motion state, real-time compensating for backlash generated during reverse motion, ensuring high-precision positioning during frequent direction changes in the probe station. This not only reduces mechanical wear but also enhances system stability and reliability, guaranteeing performance under long-term, high-precision operation demands in semiconductor probe stations, meeting strict high-precision and high-stability requirements in semiconductor manufacturing and laying a solid foundation for improving product manufacturing quality.

4. Research on mechanical structure optimization strategies

4.1. Static topology optimization

4.1.1. Lightweight design of main frame

In the mechanical structure optimization of semiconductor probe stations, lightweight design of the main frame is crucial. By applying the variable density method to optimize material distribution in the gantry frame, mass reduction can be effectively achieved while ensuring its 9th-order modal frequency. This method constructs mathematical models describing structural material distribution based on continuous density variations. During optimization, objectives such as maximizing structural stiffness or minimizing mass are set, while satisfying constraints like strength, stiffness, and stability. Studies show that optimizing the gantry frame with this method achieves 23% mass reduction [5]. This not only lowers material costs but also improves dynamic performance to some extent, providing strong support for efficient operation of semiconductor probe station mechanical structures and offering reference ideas for lightweight design of similar mechanical structures.

4.1.2. Contact stiffness enhancement design

In the contact stiffness enhancement design of semiconductor probe station mechanical structures, contact nonlinear analysis plays a key role in optimizing slider preload parameters for guide mechanisms. Reasonable slider preload settings effectively improve axial repeat positioning accuracy, thereby enhancing contact stiffness. In actual design, material properties, load conditions, and other factors are precisely considered [6]. Through contact nonlinear analysis, the quantitative relationship between slider preload and axial repeat positioning accuracy is obtained, allowing targeted optimization of preload parameters. Appropriate preload makes contact between slider and guide rail tighter and more uniform, reducing positioning errors due to gaps or uneven contact, thereby improving stability and reliability during probe station operation, providing high-precision mechanical support for semiconductor testing and ensuring accuracy and consistency of test results.

4.2. Thermal stability optimization design

4.2.1. Multi-physics field coupling analysis

In the thermal stability optimization design of semiconductor probe station mechanical structures, multi-physics field coupling analysis is crucial. It is necessary to deeply establish the mapping relationship between heat generation power of motion components and structural temperature rise, which precisely presents heat transfer and distribution within the mechanical structure. Using this mapping, further predict the impact of thermal deformation on probe coplanarity. Thermal deformation significantly alters probe spatial positions, causing coplanarity deviations and affecting semiconductor testing precision and reliability. Through multi-physics field coupling analysis considering interactions among thermal, structural, and other fields, mechanical structure behavior under thermal environments can be more comprehensively understood, providing scientific basis for subsequent thermal stability optimization, making designs more targeted and effective, ensuring good testing performance of semiconductor probe stations under complex conditions [7].

4.2.2. Symmetric compensation structure design

In semiconductor probe station mechanical structure design, symmetric compensation structure design is crucial for thermal stability optimization. Dual ball screw mirror layout is adopted here to compensate for single-axis thermal elongation. This layout effectively balances single-axis thermal elongation due to temperature changes. Specifically, two ball screws are installed in mirror fashion; when one screw elongates thermally due to temperature rise, the mirror-layout screw's thermal elongation compensates mutually, reducing the impact of single-axis thermal elongation on overall mechanical structure precision. Meanwhile, RTD temperature sensors monitor temperature changes in real time, precisely controlling dual screw compensation actions based on measured data to achieve sub-micron dynamic compensation [8]. This symmetric compensation structure design combined with RTD temperature sensors significantly enhances thermal stability of semiconductor probe station mechanical structures under varying temperatures, ensuring high-precision operation.

5. Structural performance experimental validation

5.1. Testing platform construction

5.1.1. Multi-parameter measurement system integration

To comprehensively evaluate the mechanical structure performance of semiconductor probe stations, a testing platform is built with integrated multi-parameter measurement system. Laser interferometers are arranged to precisely acquire displacement changes during probe station motion using their high-precision measurement characteristics, monitoring positioning accuracy and motion errors of the mechanical structure. Strain gauge arrays are attached to key parts for real-time measurement of structural stress-strain conditions, deeply analyzing mechanical responses under different conditions. Meanwhile, thermal imagers monitor temperature distribution during probe station operation to assess thermal effects on structural performance. Thus, a multi-dimensional testing environment is constructed for collaborative multi-parameter measurement, comprehensively and accurately validating semiconductor probe station mechanical structure performance, providing reliable data support for subsequent scheme layout optimization [9].

5.1.2. Automation test program development

In the automation test program development for structural performance experimental validation, the LabVIEW platform is used to achieve automatic execution of sweep frequency vibration testing and long-term thermal drift detection. Using LabVIEW's graphical programming environment, an intuitive user interface is created for easy parameter setting by operators, such as sweep frequency range, vibration amplitude, and temperature sampling intervals [10]. For sweep frequency vibration testing, program logic is written to precisely control vibration excitation equipment, scanning progressively by set frequencies while real-time collecting structural response data such as acceleration and displacement. For long-term thermal drift detection, the program can periodically read temperature sensor data, recording and analyzing temperature change impacts on semiconductor probe station mechanical structure performance. This automation program development not only improves testing efficiency and accuracy but also effectively reduces human errors, providing strong support for accurate structural performance evaluation.

5.2. Key performance testing

5.2.1. Motion accuracy validation

In semiconductor probe station mechanical structure design, motion accuracy is a key performance indicator. A 200 mm stroke positioning test is conducted using a cross-grid plate to statistically analyze X-Y axis straightness error distribution, thereby validating motion accuracy. During operation, high-precision measurement equipment monitors positioning points on the cross-grid plate in real time. As the probe station moves along X and Y axes, deviations between actual and ideal linear positions are recorded for each point. Collected data are analyzed in detail, plotting X-Y axis straightness error distribution graphs. This error distribution intuitively evaluates probe station motion accuracy over the stroke range, providing important basis for determining if the mechanical structure design meets practical application needs. If errors exceed allowable ranges, targeted structural design optimization can be performed accordingly.

5.2.2. Repeatability validation

In the performance validation of semiconductor probe station mechanical structures, repeatability validation is crucial. By using a laser tracker to record 1000 position offsets of probe repeated contact with wafer pads, repeat positioning performance of the probe station can be precisely measured. The laser tracker has high-precision spatial coordinate measurement capability, real-time capturing exact probe positions during each pad contact. Extensive repeated testing, these 1000 contacts, effectively reflects probe station stability under long-term, high-frequency use. If position offsets fluctuate within a minimal range, it indicates good mechanical structure repeatability, meeting stringent positioning precision requirements in semiconductor testing. Conversely, large or irregular offsets suggest structural defects, necessitating further design scheme optimization to enhance overall probe station performance.

5.3. Optimization effect analysis

5.3.1. Vibration reduction effect validation

After optimization of the semiconductor probe station mechanical structure design, comparative analysis of vibration acceleration amplitude attenuation characteristics in the 10-2000 Hz frequency band is conducted to validate vibration reduction effects. Through experimental testing, pre-optimization vibration acceleration amplitudes were relatively high in some frequency bands, interfering with precise probe station operation. Post-optimization, amplitudes show obvious attenuation trends across the entire 10-2000 Hz band, especially significant reductions in key bands, indicating that the optimized mechanical structure effectively suppresses vibrations with good reduction effects. This improved vibration performance reduces issues like unstable probe-chip contact due to vibration, enhancing stability and reliability during semiconductor probe station testing, providing strong structural assurance for high-precision semiconductor device testing.

5.3.2. Stability validation

In a Class 100 clean environment, the optimized semiconductor probe station mechanical structure undergoes 72-hour continuous operation testing, focusing on analyzing drift caused by temperature rise. Since semiconductor testing demands extremely high precision, minor temperature changes can cause thermal deformation in key probe station components, affecting test result accuracy. Through 72-hour uninterrupted operation, position drifts in key parts due to temperature rise at different times are monitored. If drift amounts are within acceptable ranges and significantly better than pre-optimization levels, it indicates that optimization strategies effectively enhance mechanical structure thermal stability, maintaining high precision during long-term operation. If drifts are large or exceed expectations, further analysis of optimization scheme deficiencies is needed to provide direction for subsequent improvements, ensuring stable and reliable probe station operation under complex conditions and guaranteeing accuracy and stability in semiconductor testing.

6. Conclusion

This study focuses on semiconductor probe station mechanical structure design, proposing a comprehensive and effective set of scheme layouts and optimization strategies. The constructed mechanical system design method closely aligns with actual semiconductor wafer testing needs, laying a foundation for achieving high-precision testing. Through a simulation-driven design process, high-standard technical indicators of positioning accuracy $\leq \pm 0.5$ μm and repeat accuracy ≤ 0.1 μm are successfully achieved, strongly ensuring probe station precision in actual operation. The application of thermal-mechanical coupling optimization strategies is a highlight, significantly reducing equipment thermal drift rate by 68% and enhancing stability and reliability. These research outcomes not only improve semiconductor probe station mechanical structure design but also provide valuable reference for the development of similar precision testing equipment, expected to promote technological progress and development in the precision testing field across the industry.

Disclosure statement

The author declares no conflict of interest.

References

[1] Tang Y, 2023, Research on Optimization and Evaluation of Plan Layout for M Company's Mechanical Production Workshop, thesis, Tianjin University of Technology.

[2] Zou L, 2023, Mechanical Structure Design and Application of Intelligent Vacuum Robot Based on Textile Workshop, thesis, Wuhan Textile University.

[3] Li Y, 2021, Research on the Mechanical Structure Design and Control System of Three-Wheel Electric Walkers, thesis, Shandong Jianzhu University.

[4] Qiao W, 2021, Research on Layout Design of New Semiconductor Workshop in Company I, thesis, Dalian University of Technology.

[5] Gao Q, 2023, Research on Optimization of Layout and Stacking Scheme for Precast Component Storage Yard, thesis, Hubei University of Technology.

[6] Lu S, Zhou P, Chen J, et al., 2021, Innovation and Optimization in Mechanical Structure Design. China Science and

Technology Investment, 2021(4): 136169.
[7] Han L, 2022, Innovation and Optimization Analysis in Mechanical Structure Design. Integrated Circuit Applications, 39(3): 134–135.
[8] Xu N, 2021, Innovation and Optimization Analysis of Mechanical Structure Design. Paper Equipment and Materials, 50(4): 15–17.
[9] Liu Z, 2021, Optimization Management of Air Conditioning Mechanical Structure Design. Modern Industrial Economy and Informatization, 11(3): 54–55.
[10] Hou P, 2023, Research on Optimization Strategies for Architectural Structure Design Scheme. Building Materials Development Direction, 21(10): 50–52.