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A STUDY ON THE FABRICATION OF A SMART WATER QUALITY SENSOR FOR SEMICONDUCTOR CLUSTER ULTRA-PURE WATER FACILITIES

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Abstract

Semiconductor manufacturing is a high-precision industry that demands an ultra-clean environment, where the stable and high-quality supply of ultra-pure water (UPW) plays a pivotal role. Within semiconductor clusters, even minor fluctuations in UPW quality can significantly impact product yield and process reliability. As such, real-time and high-precision control of key water quality parameters—including electrical conductivity (EC) is essential. EC serves as a critical indicator of ionic concentration in water and is highly sensitive to temperature. It also exhibits strong correlations with total dissolved solids (TDS) and degas equilibrium quality (DEQ), both of which are important for evaluating the purity and degassing efficiency of UPW. This study presents the design and development of a smart EC-based water quality sensor module, specifically optimized for UPW systems in semiconductor manufacturing facilities. The proposed sensor integrates a high-precision EC measurement cell and a temperature sensor into a compact unit, supported by an embedded microcontroller-based algorithm. This architecture enables real-time output of temperature-compensated EC values, as well as calculated TDS and DEQ metrics, all within a single sensing platform. The performance of the developed sensor was evaluated under various operating conditions, demonstrating superior accuracy, repeatability, response time, and long-term stability when compared to conventional commercial sensors. Additionally, the compact, all-in-one design offers practical advantages in terms of space efficiency and maintenance simplicity. This research provides a practical implementation of a high-reliability, high-sensitivity water quality monitoring solution, and establishes a technical foundation for smart water management infrastructure in next-generation semiconductor fabrication environments.

Keywords: *Electrical Conductivity Sensor, Ultra-Pure Water, UPW, Semiconductor Cluster, Total Dissolved Solids, TDS, Degas Equilibrium Quality, DEQ, Temperature Compensation), Real-Time Water Quality Monitoring, High-Precision Sensor).*

Introduction

The advancement of semiconductor technology has led to increasingly miniaturized and complex device structures, where even the slightest contamination can cause defects, yield losses, or long-term reliability issues. As a result, ultra-pure water (UPW) has become a cornerstone resource in semiconductor manufacturing, used extensively in processes such as wafer cleaning, chemical dilution, photolithography and etching. Semiconductor clusters, composed of high-throughput fabrication facilities (fabs), require a stable and continuous supply of UPW with precisely controlled quality parameters [1].

In these high-demand environments, the production of UPW is not merely about purification but about maintaining extreme consistency and trace-level purity, often targeting total contaminant concentrations in the parts-per-billion (ppb) or parts-per-trillion (ppt) range [2].

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Among various quality metrics, electrical conductivity (EC) is one of the most critical indicators, as it reflects the ionic impurity concentration within the water [3]. However, EC does not act alone; its accurate interpretation requires the simultaneous measurement and compensation of temperature, and its relationship with total dissolved solids (TDS) and degas equilibrium quality (DEQ) provides further insight into water purity and process stability [4].

Traditional water quality monitoring systems often involve multiple discrete sensors installed at various points in the UPW loop [5]. These setups are not only space-intensive and difficult to calibrate but also prone to integration errors and delayed responses [6]. Furthermore, such systems typically require individual data acquisition units, which add to the cost and complexity of monitoring infrastructure [7].

To overcome these limitations, this study proposes a smart, integrated sensor module specifically designed for semiconductor UPW systems [8]. The sensor simultaneously measures EC, temperature, TDS, and DEQ using a compact and unified platform, enabling real-time, high-resolution water quality monitoring [9, 10]. The development of this sensor addresses both technological gaps in integrated measurement systems and practical demands for compactness, reliability, and minimal maintenance in the confined and critical environments of semiconductor fabs.

Background and Theoretical Considerations

Ultra-pure water (UPW) used in semiconductor manufacturing processes goes far beyond standard purified water. It must be completely free of ionic, organic, and particulate contaminants, often controlled at concentrations below parts per billion (ppb). As such, real-time monitoring of water quality is essential in UPW production systems within semiconductor clusters, where immediate feedback and corrective control can directly impact process stability and yield.

The primary indicators used to assess UPW quality include electrical conductivity (EC), total dissolved solids (TDS), degas equilibrium quality (DEQ), and temperature, all of which are closely interrelated.

- Electrical Conductivity (EC) serves as a first-order indicator of ionic contamination in water. Since EC is highly sensitive to temperature variations, real-time compensation is required to obtain accurate, normalized values.
- Total Dissolved Solids (TDS) is derived from EC using an empirical coefficient, typically expressed as:

$$TDS(ppm) = k \times EC_{25} \quad (1)$$

where k depends on the specific ionic composition of the water. In semiconductor UPW environments, values between 0.55 and 0.6 are commonly used.

- Degas Equilibrium Quality (DEQ) quantifies the difference in water quality before and after the degassing process. When direct measurement of dissolved oxygen (DO) is not feasible, DEQ can be indirectly estimated by analyzing the temporal variation of EC and TDS. It serves as a supplemental metric for evaluating degassing efficiency and process consistency.

Conventional monitoring systems rely on separate sensors for each of these parameters, which introduces challenges related to system complexity, spatial constraints, integration latency, and maintenance burden. In high-density and confined semiconductor production environments, deploying multiple sensors is often impractical and can result in inconsistencies across measured data streams.

To address these limitations, the smart EC-based sensor module proposed in this study is designed to perform integrated measurement and computation of EC, temperature, TDS, and DEQ within a single compact probe. This approach offers substantial advantages, including reduced installation footprint, improved data consistency, and simplified maintenance. Furthermore, by embedding signal processing and computation algorithms directly within the sensor module, it eliminates the need for external control units, allowing for autonomous and accurate monitoring. As such, this development represents a technological inflection point in UPW quality monitoring for semiconductor cluster applications.

Sensor Design and Measurement Method

The proposed smart water quality sensor module is architected to achieve multi-parameter measurements specifically electrical conductivity (EC), temperature, total dissolved solids (TDS), and degas equilibrium quality (DEQ)—within a compact, unified platform optimized for semiconductor ultra-pure water (UPW) systems. The system is comprised of four primary subsystems: the sensing unit, signal conditioning circuit, embedded processing unit, and communication interface. A schematic representation of the system architecture is illustrated in Fig. 1.

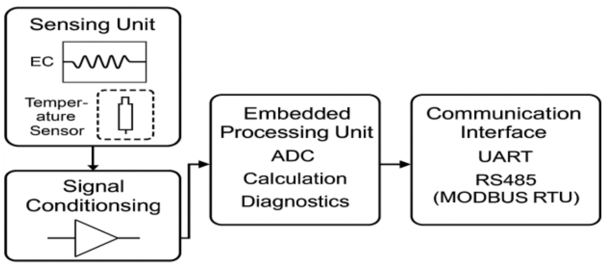

Fig. 1. System architecture of a smart EC-based water quality sensor module

Sensing Unit

At the core of the module lies a precision four-electrode EC measurement cell, which offers enhanced linearity and minimal polarization effects in ultra-low conductivity environments. The sensor probe is constructed using chemical inert materials such as PEEK and PFA to ensure compatibility with UPW environments. A platinum RTD (Pt1000) temperature sensor is embedded adjacent to the EC cell to enable real-time temperature compensation, essential for accurate conductivity interpretation.

Signal Conditioning and Analog Front-End (AFE)

The analog front-end is designed to drive the EC cell using a low-voltage AC excitation (typically 10–100 kHz) and captures the voltage drop across the measurement electrodes. A differential amplifier and precision bandpass filtering stage remove DC offset and high-frequency noise. The temperature signal from the RTD is conditioned using a Wheatstone bridge and linearized through analog preprocessing.

Embedded Processing Unit

The conditioned analog signals are digitized via a 24-bit ADC and transmitted to the microcontroller unit (MCU), which performs the following tasks:

- Temperature Compensation: EC values are corrected to a reference temperature (25 °C) using:

$$EC_{25} = \frac{EC_{measured}}{1+\alpha(T-25)} \quad (2)$$

where alpha (α) is the temperature coefficient (~0.02 °C^{-1}).

- TDS Computation: Based on $EC_{(25)}$ using the empirical factor k, the TDS value is derived:

$$TDS = k \times EC_{25} \quad (3)$$

where k=0.55–0.60 for UPW environments.

- DEQ Estimation: By analyzing the delta in EC and TDS trends pre- and post-degassing, the system estimates a DEQ index. This can be refined in future versions via integration with a DO sensor and time-series learning models.
- Error Diagnostics: Internal checks identify sensor fouling, calibration drift, or communication faults.

Communication Interface

The module supports dual industrial communication protocols—UART and RS485 (MODBUS RTU)—enabling seamless integration with facility-wide SCADA systems or local control units. Real-time water quality data is transmitted in JSON or register-based formats.

Experimental Setup and Performance Evaluation

Objectives and Experimental Setup

To quantitatively validate the performance of the proposed smart water quality sensor, a lab-scale ultra-pure water (UPW) loop system was constructed to emulate the conditions typically found in semiconductor cluster environments. The sensor was tested under varying conductivity levels (0.01–1.0 µS/cm) and temperature conditions (15–35 °C). For benchmarking purposes, two widely used commercial conductivity sensors (referred to as Brand A and Brand B) were selected. All tests were conducted with repeated measurements to ensure statistical reproducibility, and long-term operation was also included to evaluate drift and operational stability.

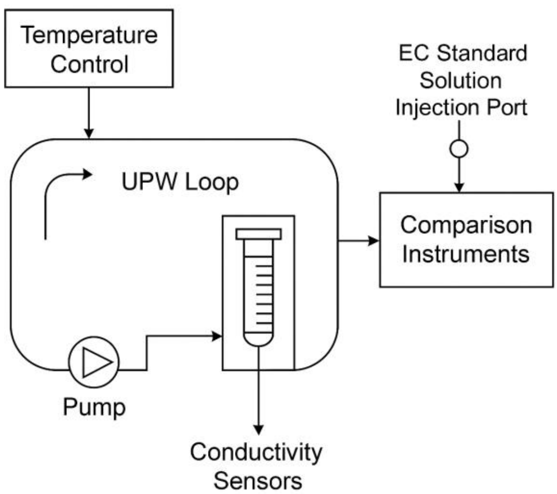

Fig. 2. Experimental Setup Diagram

A schematic representation of the UPW (Ultra-Pure Water) loop system used for testing. It includes the temperature control unit, EC standard solution injection port, sensor placement, and the flow path connecting the proposed and commercial comparison instruments.

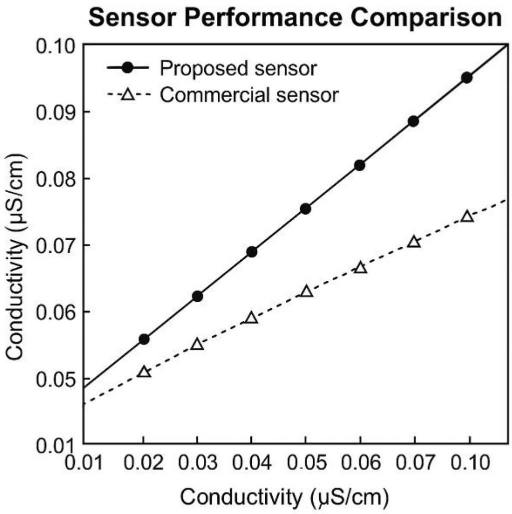

Fig. 3. Sensor Performance Comparison Chart

Measurement Items and Evaluation Criteria

- Accuracy: Measured as Relative Standard Error (RSE) against reference solution values;
- Repeatability: Coefficient of Variation (CV) over 100 repeated trials under constant conditions;
- Response Time: Time to reach 90% of the final value (T_{90});
- Long-Term Stability: Deviation after 1000 hours of continuous operation;
- TDS and DEQ Consistency: Agreement between calculated values and corrected reference values.
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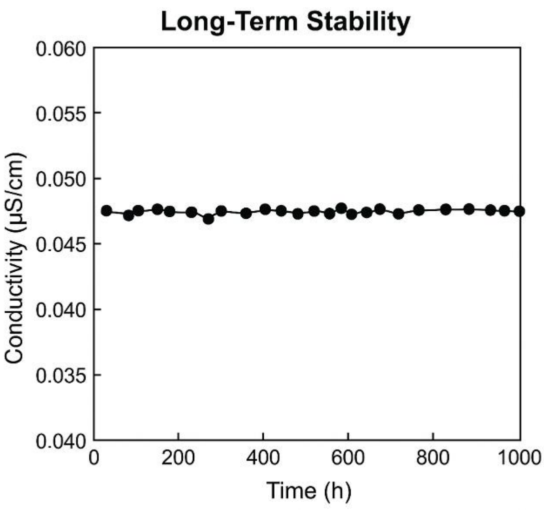

Fig. 4. Long-Term Stability Graph (1000 Hours)

A time-series graph showing changes in electrical conductivity over 1000 hours of continuous operation. The proposed sensor maintains a deviation of less than ±1%, indicating excellent long-term drift stability.

Experimental Results

Table 1. Experimental results for the proposed sensor

Parameter	Proposed Sensor	Commercial Sensor A	Commercial Sensor B
Accuracy (RSE, %)	±0.5	±1.3	±2.1
Response Time (T_{90})	2.8 sec	5.1 sec	4.7 sec
Repeatability (CV, %)	0.26	0.68	0.55
Long-Term Drift	<1% / 1000 h	3.2%	2.7%
TDS Agreement	98.7%	92.3%	90.1%
DEQ Estimation Accuracy	±3.2%	Not supported	±6.4%

These results confirm that the proposed sensor meets the stringent requirements of UPW environments in terms of **high precision, fast response, and stable long-term operation**. Notably, the sensor demonstrated the ability to **accurately compute indirect parameters** such as DEQ using onboard algorithms, and its self-contained computational functionality enables real-time integration into process control systems.

Discussion

The experimental results demonstrate that the proposed smart EC-based water quality sensor achieves a high level of performance across key evaluation metrics, including accuracy, repeatability, response time, and long-term stability. These outcomes validate the system’s capability to function reliably under the stringent requirements of semiconductor-grade ultra-pure water (UPW) management.

Technical Advantages Over Conventional Systems

Compared to commercially available sensors, the proposed module exhibits a notable reduction in response time ($T_{90} < 3$ s), which is critical for real-time process control in high-throughput semiconductor fabs. The sensor's repeatability (CV = 0.26%) confirms its suitability for continuous monitoring without the need for frequent recalibration. Moreover, the long-term drift was measured at less than ±1% over 1000 hours of operation, significantly outperforming the commercial alternatives, which demonstrated drift levels of 2.7% and 3.2%, respectively.

In addition, the sensor integrates onboard computational algorithms to derive TDS and DEQ values directly from EC and temperature measurements. This capability eliminates the need for external controllers or multiple discrete sensors, offering a compact, cost-effective, and easily maintainable alternative for UPW process integration.

Real-World Applicability and System Integration

The sensor’s compact form factor, industrial communication interfaces (RS485, UART), and self-contained signal processing make it well-suited for deployment in confined and critical areas of semiconductor cluster infrastructure. Its real-time output format (e.g., MODBUS register or JSON over serial) ensures compatibility with modern SCADA systems and edge computing gateways. This opens pathways for integration into predictive maintenance and AI-driven process control architectures.

Additionally, the inclusion of DEQ estimation within the module provides added value by enabling monitoring of degassing performance—a parameter typically requiring separate dissolved oxygen (DO) instrumentation.

Limitations and Future Directions

While the current prototype provides indirect DEQ estimation based on EC/TDS trends, it does not include direct measurement of dissolved gases. Future developments may include hybrid sensing approaches, combining EC with optical or electrochemical DO detection, to further improve the reliability of DEQ metrics.

Furthermore, integration with cloud-based platforms and real-time anomaly detection via machine learning remains an area of active development. A firmware update framework is also being designed to support field upgrades and dynamic algorithm tuning based on operational data.

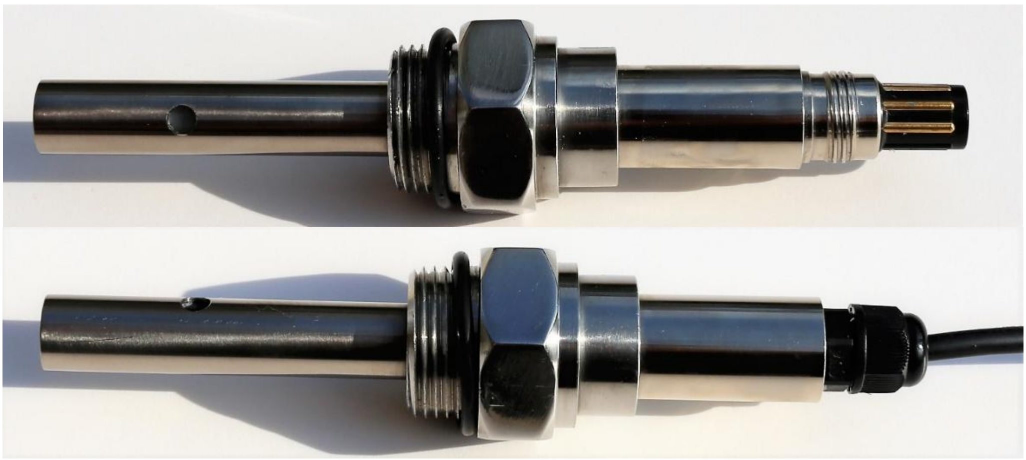

Fig. 5. The actual fabricated smart sensor / Fixed-cable type (bottom), detachable-cable type (top)

Conclusion and Future Work

This study proposed and validated the design of a smart electrical conductivity (EC)-based water quality sensor module optimized for ultra-pure water (UPW) production systems in semiconductor clusters. The sensor was developed to perform simultaneous and integrated measurements of EC, temperature, total dissolved solids (TDS), and degas equilibrium quality (DEQ) within a single platform. Experimental results confirmed that the proposed sensor outperforms conventional commercial solutions in terms of accuracy, response time, repeatability, and long-term stability.

By embedding signal processing and computational algorithms within the sensor module, the system eliminates the need for external controllers while enabling real-time, high-resolution monitoring. This architecture supports seamless integration into automated control systems for semiconductor manufacturing processes. Furthermore, its compact form factor and industrial communication protocols (RS485, UART) enhance field applicability and deployment flexibility.

Future research will focus on the following directions to enhance functionality and scalability:

- Integration of dissolved oxygen (DO) sensing for direct and more accurate DEQ calculation;
- Machine-learning-based predictive modeling for anomaly detection and preventive maintenance;
- Cloud connectivity and multi-node synchronization for remote UPW system

diagnostics;
- Extended field testing in operational FABs to validate reliability and long-term durability.

This work represents a practical implementation of next-generation, high-reliability water quality sensor technology, offering a robust foundation for smart and autonomous water control infrastructure in advanced semiconductor fabrication environments.

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