Vol. 20 (2026): Proceedings of 2026 International Conference on Materials Science, Energy Engineering and Automation Control (ICMSEAC 2026)
E-ISSN: 3105-0522 P-ISSN: 3105-0514
DOI: https://doi.org/10.70267/mseac.2026189199

Applications of Single-Electron Devices for Nanoscale Quantum Precision Measurement

Yanbo Wang*

School of Microelectronics, Tianjin University, Tianjin, China

**Corresponding author: Yanbo Wang.*

Abstract

Single-electron devices with the Coulomb blockade effect and single-electron tunneling effect are able to accurately control the quantum state of an electron. This paper systematically investigates its application in this field as the core carrier to overcome the limitations of traditional measurement technology and realize nanoscale quantum precision measurement. The paper conducts a deep analysis about its technical principle, typical device structure, and performance optimization mechanism. Firstly elaborating the core physics behind single-electron phenomena and key features of devices; secondly taking devices including Single-Electron Transistors (SETs), and single-electron boxes as examples detailing their applications in regulating quantum states, detecting nanoscale magnetic/electric fields, and characterizing single-molecule charges. Emphasize the novel designs and measurement performances of new devices like twisted bilayer graphene quantum dot SETs and room-temperature silicon-based SETs. Lastly discuss existing device-related issues regarding stability, integration, and environmental interference, and look forward to future developments in quantum sensing, quantum computing, and biomedicine. Our research shows that through precise control of quantum effects, single-electron devices enable ultra-high sensitivity measurements of physical quantities at the nanoscale, which is a revolutionary solution for atomic-level detection and brings great scientific value and engineering applications.

Keywords

single-electron devices, precisely manipulate, stability, integration, engineering application prospects

1. Introduction

The development of nanotechnology and quantum technologies has created an urgent demand for high-precision measurement techniques in many areas like condensed matter physics, quantum biology, clinical medicine etc., which requires accurate detection of faint physical signals at the nanoscale and even the atomic scale (e.g., single-electron spin or single-molecule charge)[1]. Traditional measurement techniques show poor microscopic detection ability. However, they suffer from some intrinsic limitations, e.g., insufficient spatial resolution, low measurement sensitivity, and require extreme working conditions, i.e., ultrahigh vacuum and cryogenic temperatures [2]. Single-electron devices (SEDs), dominated by Coulomb blockade and single-electron tunneling effects as their core operating principles, allow us to precisely manipulate the transport behavior and quantum states of individual electrons. By leveraging the discrete nature of charge transport, SEDs offer superior performance in nanoscale measurements with ultrahigh sensitivity and excellent spatial resolution [3], e.g., single-electron transistors (SETs) made of twisted bilayer graphene quantum dots achieve precise single-electron charge detection at room temperature, while the hybrid integration between single-electron boxes and nanocavities proposes a novel strategy for quantum state storage and readout [4]. Deep research into the applications of SEDs in nanoscale quantum precision measurement will not only advance quantum metrology and provide important characterization tools for studying atomic-scale material structures and physical properties, but also establish a solid technical foundation for developing core devices in quantum computing, quantum sensing, and so forth, carrying great scientific value and engineering significance [5].

Single-electron device research began in the middle of the 20th century. In 1968, I. Giaever firstly observed the Coulomb blockade phenomenon in dielectric thin films containing metallic nanoparticles, setting up the basis of this research field. In 1987, Fulton et al. fabricated the first metal-based SET and confirmed the periodic characteristics of single-electron tunneling. With the rapid progress of nanofabrication technologies in recent years, SED structures became more diverse. Besides traditional metal-, and semiconductor-based SETs, novel architecture proposals were put forward, such as twisted-bilayer graphene quantum dot SETs and room-temperature silicon-based SETs.

Many promising research achievements have been reported recently in the field of nanoscale quantum precision measurement. In 2023, Huang et al. developed a SET based on twisted bilayer graphene quantum dots, where its size could be precisely tunable ranging from 1 – 5 nm, achieving highly sensitive detection of single-electron charge. In 2024, the Reiner group realized high-fidelity initialization and manipulation of quantum states in a four-qubit register through improved control over electron spins and nuclear spins, providing a new technical solution for quantum precision measurement. In the same year, Fang et al. found that spin defects in van der Waals layered materials can act as optically addressable quantum sensors. Ultrahigh-resolution magnetic-field imaging at the nanometer scale is achieved after being modulated by single-electron devices.

At present, the development of single-electron devices for quantum precision measurement exhibits three major trends. First, innovations in device materials and structures: two-dimensional materials and topological insulators are adopted to improve the room-temperature stability and measurement sensitivity of devices [6]. Second, expansion of measurement dimensions to enable simultaneous detection of multiple physical quantities, such as magnetic field, electric field, and temperature. Third, deep integration with quantum technologies, including quantum memory and quantum entanglement, to further boost measurement accuracy.

Based on the state-of-the-art research progress, practical application status, and engineering bottlenecks of single-electron devices and nanoscale quantum precision measurement, the overall research objectives of this paper are defined as follows. This paper systematically reviews the core physical mechanisms and mainstream device configurations of single-electron devices. On this basis, it systematically analyzes the technical routes and measured performance of single-electron transistors for high-precision nanoscale detection of multiple physical quantities, including charge, spin, electric field, and temperature. Meanwhile, this work summarizes the critical bottlenecks that limit large-scale manufacturing and practical engineering deployment of SEDs, compares the optimization effects and applicability of different technical approaches, and provides technical references to enhance device performance. Finally, combining the theoretical performance limits of devices, the maturity of micro-nano fabrication processes, and practical industrial demands, this paper predicts the future development trends of single-electron quantum measurement technology. It provides a theoretical basis and technical support for structural innovation, performance upgrades, and engineering development of novel single-electron quantum sensing devices.

2. Core Physics and Typical Structures of Single-Electron Devices

2.1 Core Physical Mechanisms

2.1.1 Coulomb Blockade Effect

The Coulomb blockade effect constitutes the fundamental operating mechanism of single-electron devices. At the nanoscale, the central island exhibits ultralow capacitance, making the charging energy of a single electron far larger than the thermal fluctuation energy. Consequently, electron tunneling through the island is suppressed. For a simple electrode-island-electron structure, the charging energy generated after a single electron tunnels onto the island can be expressed as follows:

$$E_C=\frac{e^2}{2C} \quad (1)$$

where e=1.602×10^{-19} C denotes the elementary charge; C_Σ represents the total capacitance of the island (typically less than 10−18 F). When the charging energy satisfies E_C >>$k_B T$ (k_B =1.38×10^{-23} J/K is the Boltzmann constant, and T stands for absolute temperature), the energy supplied by thermal fluctuations is insufficient for electrons to surmount the charging energy barrier, thereby entering the Coulomb blockade regime.

Another mandatory condition is that the tunnel junction resistance R_T must exceed the quantum resistance R_Q=h/e^2, where h is Planck's constant. This guarantees a sufficiently long residence time of electrons on the island, approximated as $\tau \approx R_T C_\Sigma$, so that quantum fluctuations of charge can be neglected. In research on silicon quantum devices, Prati verified that once the two criteria above are met, electron transport exhibits clear discreteness, laying the physical foundation for high-precision single-electron measurement [2].

2.1.2 Single-Electron Tunneling Effect

Single-electron tunneling means that electrons pass over a potential barrier with higher than their energy by quantum mechanics. Single-electron tunneling dominates the charge transport in single-electron devices. Tunneling current I has been given as follows:

$$I=\frac{2\pi e}{\hbar}\sum_{i,j}|H_{ij}|^2\delta\left(E_i\text{-}E_j\text{-}eV\right) \quad (2)$$

where $\hbar$=h/2π represents the reduced Planck constant; Hij is the tunneling matrix element between electron transitions from the initial state i to the final state j; Ei and Ej are the electron energies of the initial and final states, respectively; V is the bias voltage applied across the tunnel junction. Le et al., in researching the physical characteristics of single-electron transistors (SETs), employed it to accurately characterize single-electron tunneling. It was validated and precise in analyzing current–voltage characteristics.

In current conduction in an SET, there are two tunnel junctions such as source–island junction and island–drain junction where electrons sequentially tunnel. Gate voltage controls exactly the electrostatic potential of the island so that one can control switching of tunneling on and off. When measuring quantum precision, changes of external physical quantities (magnetic and electric fields etc.) change the tunneling matrix element Hij or the potential of the island, thus controlling the tunneling current. Quantitative measurement of target physical quantities can be achieved via detection of the current signal.

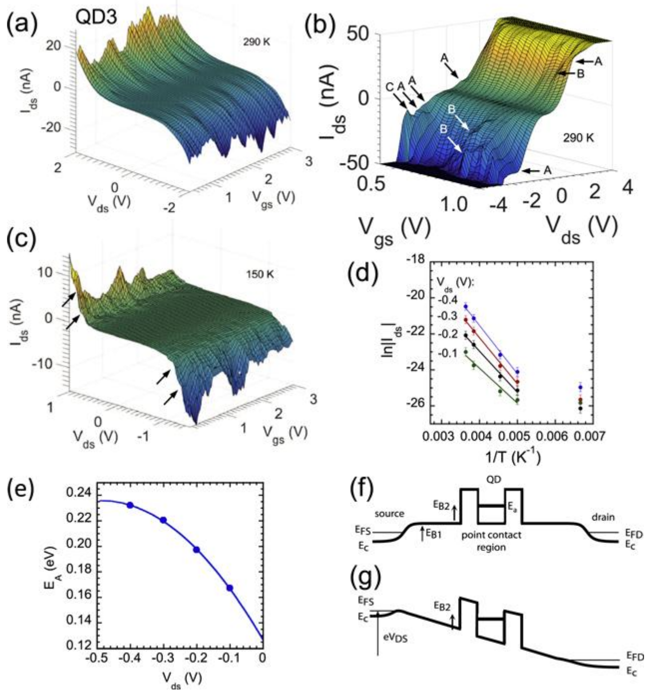
2.2 Typical Configurations of Single-Electron Devices

2.2.1 Single-Electron Transistor (SET)

Single-electron transistor (SET): One of the most prevalent types of single-electron devices; it has a source (S), a drain (D), a gate (G), and a nanoscale island sandwiching the source and drain. Source and drain connect to the island via a tunnel junction, whereas the gate capacitively couples to the island through an insulator to control the island's electrostatic potential. Depending on the materials used, we categorize SETs into metal-based, semiconductor-based, and two-dimensional material-based SETs. Metal-based SETs. For example, Al–AlO_x architectures exist. Tunnel junction capacitance and resistance can be easily tuned but exhibit poor stability at room temperature. Semiconductor-based SETs and Silicon-based SETs belong to this type. Different quantum confinement effects can be observed at room temperature in silicon SETs with several-nanometer sizes, making them ideal candidates for nanoscale charge detection [7], as shown in Fig. 1.

Twisted bilayer graphene quantum dot SETs based on two-dimensional materials: They are fabricated using mechanical exfoliation and dry transfer methods. Quantum dots have precise control over sizes ranging from 1 to 5 nm and exhibit ultrahigh charge sensitivity. Key performance metrics of SETs include charge sensitivity (on the order of 10^{-18} C), operating temperatures ranging from room temperature down to liquid helium temperature, and response frequencies up to 10^6 Hz. Because of these properties, SETs are the optimal candidate for nanoscale quantum precision measurement.

Figure 1: Quantum Confinement Effect [7]



2.2.2 Single-Electron Box

Single-electron box A simple single-electron device. This device has a nanoisland coupled to two electrodes through tunnel junctions without any gate electrode. Operation of this device depends upon the Coulomb blockade effect; if the capacitance of the island is very small then the charging energy of one electron far exceeds the thermal fluctuation energy. Electrons have to overcome the charging energy barrier to tunnel onto the island which results in non-linear current characteristics of the device.

Petropoulos et al. designed a nanoscale single-electron box with floating leads. By optimizing the device architecture, they enhanced the sensitivity of their sensor towards ambient electric fields allowing them to apply it in quantum sensing. Single-electron box has simple geometry, easy fabrication process and low cost. In addition, it can be combined with other structures like nanocavities and quantum dots for quantum-state storage and readout.

2.2.3 Single-Electron Electrometer

The single-electron electrometer is an example of charge-sensing devices that operate based on the Coulomb blockade effect. Similar to SETs but specifically optimized for superior charge sensitivity [3]. Usually, the design uses a symmetric structure consisting of electrode-tunnel junction-island-tunnel junction-electrode. External charge or electric field signal could be detected by observing changes in the charge state of the central island. Charge-detection sensitivity reaches the order of 10^{-18} C with a fast response rate up to 10^6 Hz. Applications in quantum precision measurement are the precise characterization of carrier concentration in semiconductors, charge detection of electronic states in quantum dots, and charge measurement of biomolecules (DNA, proteins) [8].

2.3 Measurement Characteristics and Advantages of Single-Electron Devices

The main advantages of single-electron devices for nanoscale quantum precision measurement include:

Ultrahigh spatial resolution: Core functional elements such as nanoislands and quantum dots usually have sizes ranging between 1 nm to 10 nm, much smaller than the probe tip of traditional measurement instruments; they allow local detection at the nanoscale and even atomic scale. Twisted bilayer graphene quantum dot SETs have quantum dots that are just 1–5 nm in size, which can resolve charge variation down to the level of individual atoms;

Extraordinary detection sensitivity. Single-electron devices exhibit high sensitivities towards changes in the quantum states (charge, spin) of individual electrons, resulting in a lower detection limit compared to conventional electronic measurement equipment. To give some references, the charge detection limit of SETs is 10^{-18} C, whereas the electric field detection limit of single-electron boxes is 10^{-6} V/m. Using SETs on a four-qubit register, Reiner et al. achieved high-fidelity manipulation and readout of electron spins, thus realizing single-spin detection sensitivity;

Precise manipulation of single-electron quantum states. Single-electron devices provide precise control of the quantum state of individual electrons by using electrical, optical or magnetic means, so that one can actively regulate their measurement procedure. An example is for spin defects in van der Waals layered materials, where optical spin-state initialization together with electrical modulation through SETs allows ultrahigh-resolution magnetic-field imaging. In quantum dot SETs, the gate voltage may be used to dynamically tune the Coulomb blockade threshold, therefore amplifying and filtering the detected signals.

3. Applications of Single-Electron Transistors (SETs) in Nanoscale Quantum Precision Measurement

3.1 Nanoscale Charge Measurement

3.1.1 Design and Applications of Twisted Bilayer Graphene Quantum Dot SETs

Twisted Bilayer Graphene (TBG) possesses a distinctive electronic structure. The moiré superlattice formed by its twisted stacking introduces an energy band gap, rendering it an ideal candidate for quantum dot fabrication. Huang et al. designed and fabricated twisted-bilayer graphene quantum-dot SETs. Bilayer graphene with a twist angle of 1.1° was first prepared via mechanical exfoliation. Electron beam lithography and dry etching were subsequently used to define quantum dot regions ranging from 1 nm to 5 nm, as well as metallic source, drain, and gate electrodes.

Charge detection schemes of these SETs rely upon the Coulomb oscillation effect; when sweeping the gate voltage, the energy level alignment of quantum dots changes, which causes periodical variation of the probability of electrons tunneling through the tunnel junctions leading to periodic oscillations of the source-drain current known as Coulomb oscillations. The injection/removal of one electron shifts the position of Coulomb-oscillation peaks, from which we can detect individual charges using the measured shift. We have experimentally demonstrated that our device had a charge sensitivity of 10^{-19} C with a spatial resolution of up to 1 nm, even at room temperature, allowing us to precisely measure the charge on single molecules.

This SET has been employed to monitor charge variations during single molecule adsorption. When target molecules (e.g., DNA fragments) are adsorbed onto it, the charge state of quantum dot will change causing a shift of Coulomb oscillation peaks. From analyzing the peak shifts, we can gain information regarding the charge characteristics and adsorption kinetics of molecules. In their research on nanowire-based biological probes, Li et al. exploited the charge sensing ability of SETs to allow real-time monitoring of biomolecular charge, offering a novel tool for single-molecule biological research [8]

3.1.2 Room-Temperature Silicon-Based SETs

The conventional silicon-based SETs need cryogenic operation to realize the Coulomb blockade effect. Through optimization on device geometry, Durrani et al. fabricated nanoscale silicon-based SETs working at room temperature. The key idea is using quantum confinement effect to enhance the Coulomb blockade. The quantum dot area has been patterned through electron-beam lithography and wet etching down to less than 5nm so that its energy-level splitting much larger than the thermal fluctuation energy at room temperature.

Distinct Coulomb oscillations are observed at 300K with a period of 0.2V and excellent charge sensitivity. Application scenarios include local measuring of carrier concentration in semiconductors or characterizing energy levels of quantum dot devices. To study silicon quantum devices, Prati used SETs with similar architecture to accurately characterize electronic states in silicon quantum dots which verified reliability of room-temperature silicon SETs for charge detection.

3.2 Nanoscale Spin Measurement

3.2.1 Spin Measurement in Four-Qubit Registers

Four-qubit register proposed by Reiner et al., using SETs as core readouts to implement high-fidelity initialization, manipulation, and measurement of electron and nuclear spins. Qubits are made of semiconductor quantum dots; each qubit has its own capacitive connection to an individual SET.

Charge sensitivity of SETs can be used to sense changes of spin states of qubits due to their spin-charge coupling effect: the spin state (spin-up/spin-down) of a qubit influences the charge distribution inside the quantum dot through exchange interaction that alters Coulomb blockade characteristics of the SET. Different source-drain currents will be achieved depending on different spin configurations which we track current fluctuations to read out the spin states. Electron-spin measurement fidelity reaches 99.5%, and nuclear-spin fidelity reaches 99.2%. Measurement time is only 100 ns.

This technology finds applications in quantum state readout for quantum computing and spin dynamics research in condensed matter physics. For quantum computing, fast response of SETs meet real-time demands of quantum error correction. Meanwhile, in condensed matter physics, our technique allows us to study various microscale physical phenomena like spin-orbit coupling and spin relaxation [9].

3.2.2 Combined Optical-Electrical Measurement of Spin Defects in Van Der Waals Layered Materials

Fang et al. found that the spin defects in van der Waals layered materials (e.g., WSe_2, MoS_2) were optically addressable. By combining the electrical modulation and readout capability of SETs, they built a hybrid optical-electrical measurement system with ultrahigh-resolution magnetic field imaging at the nanoscale. This system includes three parts: the van der Waals layered material layer containing spin defects; an SET sensing unit; and an optical excitation and detection subsystem.

In detail, laser illumination firstly pumped spin defects into a certain spin state. External magnetic fields induce energy level splitting through the Zeeman effect. The transition between different spins triggers a charge-transfer process that perturbs the Coulomb-blockade behavior of the SET, leading to detectable changes in SET current. At the same time, the fluorescence intensity from spin defects depends on their spin states, providing additional optical signals that identify the spin configuration. With this method, the magnetic-field detection sensitivity reaches 10^{-12} T/Hz, while the spatial resolution reaches 5 nm.

It has potential applications for probing local magnetic ordering in quantum materials and for microscale magnetic field imaging in biomedicine. It enables mapping of the magnetic field distribution within individual magnetic domains in quantum material research. Magnetic nanoparticles could be labeled to realize magnetic imaging of single cells [10] in biomedical applications.

3.3 Nanoscale Electric Field and Temperature Measurement

3.3.1 Applications of SETs in Electric Field Measurement

Electric field detection with SETs is based on electric-field-induced charge modulation. External electric fields shift the electrostatic potential of the SET nanoisland, altering the Coulomb blockade threshold voltage. Quantitative measurement of the electric field is achieved by recording the offset of the threshold voltage. Petropoulos et al. developed nanoscale single-electron boxes with floating leads; optimized electrode structures improve the electric-field response sensitivity and achieve an ultra-low electric-field detection limit [11].

The devices can be used to characterize the internal electric-field distribution in semiconductor devices and to develop nanoscale electric-field sensors. For semiconductor chip manufacturing, SET arrays can map on-chip electric field distribution to optimize device layout. In environmental monitoring, they can detect faint electric-field signals.

3.3.2 SET-Based Nanoscale Temperature Measurement

The Coulomb oscillation characteristics of SETs exhibit strong temperature dependence. Elevated temperature increases thermal fluctuation energy, weakens the Coulomb blockade effect, reduces the amplitude of Coulomb oscillation peaks, and broadens their linewidth. This property enables SETs to be deployed for nanoscale thermometry. The temperature sensing principle relies on the quantitative relationship between the amplitude of Coulomb oscillation peaks and temperature:

$$A(T)=A_0\exp\left(-\frac{kT}{E_C}\right) \tag{3}$$

In Equation (3), A(T): amplitude of the Coulomb oscillation peak at temperature T; A_0: peak amplitude at zero temperature; EC: charging energy. Local temperature could be quantified through measuring change in Coulomb oscillation peak amplitude via this formula.

Durrani et al. verified that room-temperature silicon-based SETs have good thermometric performances in their experiment. It has measurable temperature range from 100 – 400 K with 0.1 K resolution. This technique is applicable for characterizing thermal distribution of nanoelectronic devices as well as localized temperature detection in biological tissues. For example, in reliability research on nanodevices, one may map out the localized thermal profile when operating devices so as to optimize the design of thermal dissipation. Nanoscale temperature sensing also allows real-time monitoring of cellular metabolic activity in biomedicine.

4. Extended Applications of Single-Electron Devices

4.1 Applications of Single-Electron Electrometers in Single-Molecule and Biomedical Measurement

With their ultrahigh charge sensitivity, single-electron electrometers have unique advantages in detecting single molecules and biomedical targets [10], with main applications including single-molecule charge characterization and dynamic monitoring of biomolecular interactions. Single-molecule charge measurement: Single-electron electrometers measure the charge variation induced by single molecules adsorbing on the device's surface to determine the molecular charge properties. For instance, Li et al. combined single-electron electrometers with nanowire biological probes to precisely detect the charge of DNA molecules. They immobilize DNA molecules on nanowires through biological modification, so that their intrinsic charge shifts cause an offset of the electrometer's Coulomb blockade threshold; thus, one can quantify the total charge and charge distribution of DNA molecules based on these offsets. This method has achieved single-electron charge resolution, providing an innovative tool for single-molecule biological research.

Dynamic monitoring of biomolecular processes: Single-electron electrometers monitor real-time charge fluctuations originating from biomolecular interactions such as antigen-antibody binding or enzyme-substrate reactions. Charge is transferred when molecules bind during enzyme-substrate reactions, thereby modulating the electrometer's current output and enabling continuous tracking of reaction progress by monitoring the current signal. It has achieved a temporal resolution of 10 ms and allows the investigation of the kinetics of biomolecular reactions.

4.2 Applications of Single-Electron Devices in Nanophotonic Measurement

The hybrid integration of single-electron devices and nanophotonics offers a novel approach to nanophotonic characterization. A single-electron transistor (SET) is integrated into a rare-earth quantum memory to enable optically controlled readout of quantum states. This hybrid device comprises three parts: rare-earth-ion-doped nanocrystals, an SET unit, and an optical excitation and detection module. Working principle: laser pulses firstly write photonic quantum states onto the spin states of rare-earth ions; the SET reads quantum states via capacitive coupling, and the optical module verifies quantum state information. It has achieved a quantum-state readout fidelity of 95% and a storage time of 1 ms.

A typical example uses high-power AlGaN deep-ultraviolet micro-LEDs, together with the current-sensing capability of SETs, to characterize the nanoscale light-intensity distribution during lithography. In our experiment, the SET arrays are used as photodetectors to map the deep-UV light intensity distribution on the photoresist and monitor nanoscale lithographic patterns. Our experimental results demonstrate that it can achieve a light detection sensitivity down to 10^{-12} W/cm^2 and a spatial resolution up to 50 nm

5. Technical Challenges and Solutions for Single-Electron Devices

5.1 Stability Issues and Corresponding Solutions

When deployed for quantum precision measurement, single-electron devices mainly suffer from charge noise and spin decoherence, which severely degrade measurement accuracy, maximum detection duration, and sensing sensitivity. On the one hand, the nanoisland is susceptible to random potential fluctuations induced by impurity and trap charges in dielectric substrates such as SiO_2, leading to drifts in Coulomb oscillation peaks with an offset of around 10^{-3} V, thereby degrading the precision of quantum measurements. On the other hand, electron spins are vulnerable to lattice vibrations, stray magnetic fields, and other environmental perturbations, resulting in spin decoherence. At room temperature, the electron spin coherence time is merely 100 ns, which greatly limits measurement duration and the upper limit of detection sensitivity.

Two mainstream approaches, including material optimization and quantum control technology, have been employed to overcome these drawbacks. For material optimization, we first adopt high-purity substrates and two-dimensional materials such as twisted bilayer graphene and hexagonal boron nitride (h-BN), which can suppress interference from substrate trap charges. Huang et al. introduced h-BN as an insulating layer for twisted bilayer graphene quantum dot SETs, with a prominent reduction in charge noise. Second, we utilize isotopically purified materials to remove disturbances from nuclear spins. Previous work used isotopically purified silicon in four-qubit registers to extend electron spin coherence time to up to 1 μs [9].

In quantum control techniques, dynamic feedback control monitors the real-time positions of Coulomb-oscillation peaks. It compensates for charge-noise drift by dynamically adjusting gate voltages, thereby confining peak displacement to an extremely low level. Dynamical decoupling protocols, such as CPMG sequences, can also be used to suppress spin decoherence. This method has extended spin coherence time to 1 ms when implemented in a van der Waals spin-defect system, thereby greatly improving the quantum measurement performance of single-electron devices.

5.2 Integration and Compatibility Limitations

There are two major drawbacks in single-electron devices: low integration density and poor process compatibility preventing them from being fabricated and applied at a system level. First, low integration density is still the bottleneck. Typical SET arrays contain less than 100 unit cells, far away from the requirement for large-scale quantum measurements like nanoscale imaging or multi-qubit detection. Secondly, poor compatibility means mismatched traditional single-electron fabrication flows against mature CMOS processes; this makes it hard to integrate monolithically with standard signal processing circuits, and designing measurement systems becomes complicated.

Two technical solutions, including process optimization and array architecture design, are proposed to address those constraints. Process improvement: The first one is that replacing conventional electron-beam lithography by using Nanoimprint lithography for the parallel fabrication of SET arrays can increase the throughput up to 100× and reduce manufacturing costs down to 90%; the second one is developing CMOS-compatible fabrication workflows. We fabricate room-temperature silicon-based SETs on 130 nm CMOS platforms to monolithically co-integrate single-electron sensors with CMOS signal-processing circuits so no process matching is needed.

Array design optimization: Shared source/drain and gate control circuits are used to suppress crosstalk among array units. Auxiliary algorithms compensate the deviation due to device-to-device uniformity. In nanoscale imaging, multi-SET data fusion limits the measurement error below 5%. Moreover, hybrid integrated arrays combining single-electron devices and photonic components (quantum memory arrays integrated with SETs and rare-earth-doped nanocrystals), allow multi-channel quantum state storage and high-precision measurement, extending the large-scale application scenarios for single-electron devices.

5.3 Environmental Interference Immunity

Single-electron devices' measurements are extremely sensitive to external noises; stray electromagnetic fields and temperature fluctuations dominate as the main sources of interferences which compromise their operational stability and measurement accuracy. Electromagnetic interference: The geomagnetic field and stray electric/magnetic fields produced by the surroundings interfere with the Coulomb blockade characteristics and electron spin states of single-electron devices leading to measurement errors. Temperature interference: Ambient temperature variations change the ratio between the charging energy EC and thermal fluctuation energy kBT, destabilize the Coulomb blockade regime, undermine accurate sensing. Two effective countermeasures include electromagnetism shielding and precise temperature regulation.

Electromagnetic shielding: Multi-layer composite shielding structures can attenuate stray magnetic fields. Permalloy-copper composite shielding layers provide a shielding effectiveness of 100 dB, reducing stray magnetic field intensity from 10^{-5} T to 10^{-12} T [10]; A grounded metal housing protects against stray electric fields, reducing electric-field noise down to 10^{-6} V/m, eliminating electromagnetic measurement deviations. Temperature control: Miniature thermostats precisely regulate the device's operating temperature within a 0.1 K fluctuation range so that the charging energy stays far higher than the thermal fluctuation energy, maintaining stable Coulomb blockade. Moreover, temperature-compensation circuits obtain real-time ambient temperature information and dynamically compensate for changes in threshold voltage induced by temperature variation, improving the stability and measurement precision of single-electron devices under complex environment conditions.

6. Conclusions and Outlook

6.1 Research Conclusions

In this paper we have systematically studied the applications of single-electron devices in nanoscale quantum precision measurement, covering their physical mechanisms, device performances, application merits, and technical bottlenecks. Our results can be summarized as follows: First, based on the Coulomb blockade and single-electron tunneling effects, single-electron devices allow us to precisely manipulate and detect single-electron quantum states. With ultrahigh charge- and magnetic-field sensitivity and superior spatial resolution of 1–5 nm, these devices act as core sensors in state-of-the-art nanoscale quantum precision measurement providing irreplaceable advantages in microscopic quantum sensing and high-precision characterization.

Second, among all types of single-electron devices, single-electron transistor (SETs), is the most mature and widely used one for quantum metrology. Twisted bilayer graphene quantum dot SETs provide room-temperature high-sensitivity single-charge detection; silicon-based room-temperature SETs show good CMOS compatibility for circuit integration; SETs embedded into four-qubit registers realize high-fidelity electron spin measurement with a fidelity of 99.5% which fully demonstrates the application potential of different kinds of SET material systems.

Third, besides SETs, other typical single-electron devices like single-electron boxes and single-electron electrometers also play vital roles in quantum sensing and single-molecule measurement. Single-electron boxes offer ultrahigh sensitivity for electric field detection whereas single-electron electrometers allow real-time dynamic monitoring of single molecule's charge signal.

Furthermore, the hybrid integration between single-electron devices and nanophotonics provides an innovative way towards quantum state storage and multidimensional quantum precision measurement. Finally, the bottleneck limiting the practical deployment of single-electron devices includes not enough measurement stability, low integration density and poor immunity to environmental interference. New materials such as two-dimensional materials and isotopically purified materials, CMOS-compatible processes and parallel lithography, along with quantum control technologies such as dynamic feedback and dynamical decoupling efficiently suppress charge noise, spin decoherence and electromagnetic/temperature perturbations greatly enhancing the measurement performance and practicability of single-electron devices.

6.2 Future Outlook

With continuous advances in quantum precision measurement, micro-nano fabrication, and novel two-dimensional material systems, the application potential of single-electron devices for nanoscale quantum metrology will be further unlocked. Future research and development will focus on four directions: integrated multi-physical-quantity measurement, room-temperature high-performance quantum sensing, large-scale array integration, and practical industrial deployment.

Integrated synchronous multi-physical-quantity measurement will become a major trend. Through structural innovations, multifunctional components such as spin defects could be integrated into high-performance twisted bilayer graphene quantum dot SETs, enabling simultaneous detection of charge, magnetic field, and other physical quantities, offering high-precision, multi-dimensional characterization tools for exploring multi-field coupling mechanisms in quantum materials.

The breakthrough in room-temperature, high-sensitivity quantum precision measurement is urgently needed. High-performance single-electron devices operate at low temperatures (mostly below 77K), limiting their use in biomedical diagnosis or room-temperature industrial inspection. In future work, we aim to use new functional materials such as topological insulators and two-dimensional magnetic materials, along with optimized quantum control algorithms, to overcome technical barriers such as room-temperature spin decoherence and thermal noise and ultimately realize high-sensitivity spin quantum measurement at ambient temperature.

Promote the integration of large-scale arrays and intelligent system implementation. As the iterative upgrade of microfabrication techniques, we expect there are over 1000 sets of SET arrays by 2030 which enables large-area ultrahigh-resolution nanoscale imaging. By combining single-electron measurement systems with quantum computing and artificial intelligence algorithms, they provide a way to process data in real time, compensate errors intelligently, analyze results quickly, significantly enhancing the efficiency and precision of quantum metrology.

Accelerate the industrial translation of single-electron devices for engineering and civil applications. Based on the ultrahigh single-molecule detection capability of single-electron electrometers, novel single-molecule diagnostic equipment can be developed for ultra-early detection of tumor biomarkers, thus promoting precision medicine. Besides, single-electron sensors can be integrated into semiconductor manufacturing lines for online high-precision detection of nanoscale chip defects, providing technical support for high-precision fabrication in the semiconductor industry.

In summary, as fundamental core devices for quantum precision measurement, performance iteration, and technological innovation in single-electron devices will continually promote advances in atomic-scale microscopic detection techniques, providing critical technical support for breakthrough research in condensed matter physics, quantum biology, clinical medicine, and precision manufacturing. They have profound research value and great prospects for industrialization.

References

[1] Le M H, Dinh H S. Some physical results of single electron transistor [J]. Science and Technology Development Journal - Natural Sciences, 2018, 1(6): 206–213.

[2] Prati E. Single electron effects in silicon quantum Devices [J]. Journal of Nanoparticle Research, 2013, 15(5).

[3] Wang D, Yang A. Miniaturized optics from structured nanoscale Cavities [J]. Progress in Quantum Electronics, 2024, 94: 100507.

[4] Zhong T, Kindem J M, Bartholomew J G, et al. Nanophotonic Rare-earth quantum memory with optically controlled Retrieval [J]. Science, 2017, 357(6358): 1392–1395.

[5] Feng F, Liu Y, Zhang K, et al. High-power AlGaN deep-ultraviolet micro-light-emitting diode displays for maskless Photolithography [J]. Nature Photonics, 2024, 19(1): 101–108.

[6] Huang Z, He Y, Cao J, et al. Single electron transistor based on twisted bilayer graphene quantum dots [J]. Journal of Physics D: Applied Physics, 2023, 57(11): 115104.

[7] Durrani Z A K, Jones M E, Wang C, et al. Excited states and quantum confinement in room temperature few nanometre scale silicon single electron transistors [J]. Nanotechnology, 2017, 28(12): 125208.

[8] Li H, Teal D, Liang Z, et al. Precise electrokinetic position and Three-dimensional orientation control of a nanowire bioprobe in Solution [J]. Nature Nanotechnology, 2023, 18(10): 1213–1221.

[9] Reiner J, Chung Y, Misha S H, et al. High-fidelity initialization and control of electron and nuclear spins in a four-qubit Register [J]. Nature Nanotechnology, 2024, 19(5): 605–611.

[10] Fang H-H, Wang X-J, Marie X, et al. Quantum sensing with optically accessible spin defects in van der Waals layered Materials [J]. Light: Science & Applications, 2024, 13(1).

[11] Petropoulos N, Wu X, Sokolov A, et al. Nanoscale Single-electron box with a floating lead for quantum sensing: Modeling and device Characterization [J]. Applied Physics Letters, 2024, 124(17).

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgment

This paper is an output of the science project.