

## Postprint of Applied Basic Research on Superconducting Electronic Devices

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### Abstract

Superconducting electronics represents an interdisciplinary field that integrates superconducting physics with electronic technology. Grounded in microscopic superconducting theory and diverse quantum effects, it utilizes Nb-based superconducting thin films as the principal material system, with Josephson junctions and superconducting planar micro-/nano-structures serving as the primary structural units. This enables the realization of various superconducting electronic devices and circuits, encompassing passive devices, microwave active devices, sensors/detectors, among others. These devices and circuits exhibit incomparable advantages over traditional semiconductor counterparts regarding noise performance, operational speed, power consumption, and bandwidth, thereby playing an irreplaceable role in ultra-high-sensitivity detection, quantum information processing, quantum metrology, high-performance computing, and frontier fundamental research. Nevertheless, Western countries have consistently enforced strict embargoes on high-performance superconducting devices and circuits toward our nation.

### Full Text

#### Preamble

Strategic Priority Research Program (Category B) of the Chinese Academy of Sciences

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Basic Research on Superconducting Electronic Device Applications

### 1. Background and Significance

Superconducting electronics is an interdisciplinary field combining superconducting physics with electronic technology. Grounded in microscopic supercon-

ducting theory and various quantum effects, it primarily employs Nb-based superconducting thin films as the material system and Josephson junctions and superconducting planar micro/nano structures as the main structural units. This enables the creation of diverse superconducting electronic devices and circuits, including passive components, microwave active devices, and sensors/detectors. These devices offer unparalleled advantages over conventional semiconductor counterparts in terms of noise, speed, power consumption, and bandwidth, playing an irreplaceable role in ultra-high sensitivity detection, quantum information processing, quantum metrology, high-performance computing, and frontier basic research. However, Western countries have long imposed strict embargoes on high-performance superconducting devices and circuits.

This program is positioned as basic research on superconducting electronic device applications. Considering the latest international developments and trends in superconducting electronics, it targets the urgent national needs in population health, information security, radio astronomy, mineral resource exploration, and defense construction. Focusing on ultra-high sensitivity low-temperature superconducting sensors and detectors as the breakthrough point, the program aims to build an integrated ecological research environment spanning materials, devices, and applications. It seeks to establish a R&D platform for high-end superconducting devices and circuits, cultivate an internationally competitive research team, and achieve China's international leadership and sustainable development capabilities in superconducting electronics research and applications.

The program is hosted by the Shanghai Institute of Microsystem and Information Technology (SIMIT), with participating units including the Purple Mountain Observatory, the University of Science and Technology of China, and the Shanghai Institute of Ceramics. These four organizations combine their strengths and complement each other, working closely with domestic and international partners to jointly advance the development of superconducting electronic devices and their applications. The program has identified three core scientific problems: "Surface and interface regulation methods and mechanisms of low-dimensional superconducting thin films and heterostructures," "Noise mechanism research on superconducting quantum devices," and "Novel superconducting quantum effects and mechanisms in complex materials," proposing reasonable research ideas and solutions. Through inheritance, development, and breakthrough innovation, the program has deployed four interactive projects: "Exploration of Superconducting Quantum Effects and Electronic Devices," "Frontier Application Exploration of Superconducting Quantum Devices," "Basic Process Research on Superconducting Micro/Nano Devices," and "Research on New Superconducting Materials, Physical Properties, and Electronic Structures," comprehensively carrying out research on superconducting electronic devices and their frontier applications to solve China's critical problems regarding high-performance core superconducting devices and major basic questions in superconducting electronics, while promoting interdisciplinary integration and development.

## 2. Progress Achieved

Over the nearly four years since implementation, multiple research tasks have exceeded the targets and assessment indicators specified in the implementation plan. The program has achieved a number of research results with independent intellectual property rights that reach internationally advanced levels, with some achieving international leadership in core components, process lines, frontier applications, and new material research. Key progress includes:

### 2.1. Important Breakthroughs in Basic Research on Superconducting New Materials Design, Synthesis, Comprehensive Regulation, and Physical Properties

The program discovered a novel iron-based superconductor ( $\text{Li}_{0.8}\text{Fe}_{0.2}\text{OHFeSe}$ ) with a completely new structural unit, exhibiting a superconducting transition temperature of 40 K and coexisting superconductivity with antiferromagnetic order. It also discovered high-temperature superconductivity in graphene-protected ultrathin BSCCO heterostructures. By regulating the thickness and gate voltage of 1T-TaS<sub>2</sub> thin films, the charge density wave structure was controlled, and gate voltage was found to induce superconductivity (Figure 1 [Figure 1: see original paper]). A two-dimensional electron gas based on black phosphorus thin films was constructed, showing quantum oscillations in magnetoresistance at extremely low temperatures. A new FeS superconducting material was discovered, and high-quality 1111-type iron-based superconducting single crystals were successfully fabricated for the first time. These advances have significantly enhanced China's research capabilities in superconducting materials and new principle devices, laying an important foundation for frontier application research.

### 2.2. Major Breakthroughs in Independent R&D of Core Superconducting Devices with Internationally Advanced Performance and Application Verification

**(1) High-performance superconducting nanowire single-photon detectors (SNSPD) with high detection efficiency and low dark count rates have been independently developed, achieving internationally leading performance levels (Figure 2 [Figure 2: see original paper]).** The correlation between optical absorption efficiency and intrinsic detection efficiency of SNSPDs was elucidated. By optimizing device film thickness and geometric parameters, a compact mechanical cryocooler-based NbN SNSPD system at 1,550 nm wavelength achieved 90% detection efficiency (at 2.1 K operating temperature, dark count rate 10 Hz, timing jitter < 80 ps), significantly exceeding the 立项 assessment target of 20% detection efficiency. Dark count characteristics were thoroughly analyzed, clarifying the origin of background dark counts. The program pioneered on-chip integrated filter SNSPD devices, effectively suppressing background dark counts and achieving high-performance devices with dark counts 1 Hz and detection efficiency 50%. The operating wavelength

of SNSPD devices was extended to the visible band, with detection efficiencies exceeding 70% at core wavelengths including 532, 850, 940, and 1,064 nm. The correlation between timing jitter and signal-to-noise ratio was clarified, and by increasing the device's critical current, SNSPD devices with timing jitter less than 20 ps were developed. These high-performance devices provide crucial support for quantum information processing.

**(2) Addressing the poor reliability of SQUID devices in field environments, an original design concept integrating the chip with readout circuitry was proposed, successfully developing the world's simplest SQUID device (Figure 3 [Figure 3: see original paper]), which substantially improves device stability and reliability.** In device manufacturing, the program achieved domestic production of a series of SQUID devices for the first time, with magnetic field sensitivity reaching 3.5 fT/ $\sqrt{\text{Hz}}$ , fulfilling the program assessment target of 5 fT/ $\sqrt{\text{Hz}}$ . Fully self-designed and fabricated Nb-based SQUID magnetometers and gradiometers have reached internationally advanced performance levels, with some indicators achieving international leadership, and have made important application progress in biomagnetic imaging and geophysical exploration.

**(3) For the first time internationally, NbN-based SQUID magnetometers were successfully developed, with device noise performance better than 10 fT/ $\sqrt{\text{Hz}}$  and noise corner frequency below 10 Hz, comparable to Nb SQUID devices with potential for further improvement.** The successful development of NbN SQUID devices not only opens new directions for SQUID research and applications but also provides core technology with independent intellectual property rights for the sustainable development of the center.

**(4) In the area of terahertz superconducting detectors, the program achieved cryogenic integration of quantum cascade lasers and superconducting hot electron bolometer (HEB) mixers, successfully developing a miniaturized compact heterodyne integrated receiver.** At 2.7 THz, the receiver achieved a noise temperature of 1,000 K and an intermediate frequency noise bandwidth of 4 GHz, reaching internationally advanced performance levels and meeting actual astronomical application requirements. An 850 nm band 8×8 pixel superconducting MKID detector array was successfully developed with an equivalent noise power of  $8 \times 10^{-1}$  W/ $\sqrt{\text{Hz}}$ .

### **2.3. Application of Independently Developed Superconducting Devices in Multiple Frontier Application Fields, Meeting National Strategic Needs in Important Areas**

**(1) SNSPDs have significantly advanced China's quantum information technology.** Leveraging the advantages of high detection efficiency and low dark count rates, the program collaborated with Academician Pan Jianwei's team at USTC to successfully conduct experimental verification of quan-

tum communication, quantum fingerprinting, and quantum teleportation. (I) Quantum communication: The team successively achieved 200 km measurement-device-independent quantum key distribution (MDI-QKD), 200 km 2-node network MDI-QKD, and 400 km MDI-QKD (the current world record). Related results were published in multiple academic papers (including 2 PRL papers and 1 PRX paper), with the 200 km MDI-QKD achievement selected as one of China's Top Ten Scientific and Technological Advances of 2014 by the Chinese Academy of Sciences and Chinese Academy of Engineering. (II) Quantum fingerprinting: Using ultra-low dark count SNSPD devices, quantum fingerprint identification was implemented in a 20 km optical fiber line, achieving quantum channel capacity beyond classical communication, with the paper published in PRL. (III) Quantum teleportation: Using high-efficiency SNSPD devices, quantum state teleportation between independent quantum sources with pre-distributed entanglement was first achieved over a 30 km fiber link, laying a solid foundation for future scalable quantum networks, with the paper published in Nature Photonics.

**(2) Large-active-area SNSPD devices were used to achieve 532 nm wavelength satellite laser ranging.** In collaboration with the Shanghai Astronomical Observatory, using the observatory's 60 cm telescope at Sheshan Station, the team successfully completed ranging measurements of the LARES satellite at 3,000 km distance from the station with 8 mm precision. The results were published in Optics Express and selected as a Spotlight on Optics article by the Optical Society of America (OSA). The latest results have successfully observed Russian Glonass satellites at nearly 20,000 km distance with approximately 2 cm precision.

**(3) In geophysical exploration, based on optimized SQUID sensors and detection systems, multiple field tests and system optimizations verified detection depths reaching 1,500 m, with superconducting TEM showing clear advantages in shallow layers.** Through segmented amplification achieving 500 ms signals, the detection depth is projected to exceed 4,000 m, providing better methods for future deep resource exploration.

**(4) In biomagnetic imaging, the program studied the impact of environmental magnetic field fluctuations on ultra-low-field magnetic resonance imaging quality in unshielded environments, achieving full-tensor environmental magnetic gradient compensation and developing multi-channel magnetic resonance imaging, which greatly improved image quality and imaging efficiency.** Unshielded 4-channel and 9-channel magnetocardiography systems were developed (Figure 4 [Figure 4: see original paper]) and deployed in three hospitals for collaborative clinical studies, obtaining typical magnetocardiograms from healthy individuals and patients with myocardial ischemia. A 36-channel magnetocardiography system has entered the overall optimization phase.

**(5) A prototype superconducting HEB heterodyne receiver for the Antarctic 5 m THz telescope was successfully developed.** At 1.29 THz,

the receiver noise temperature was below 600 K, reaching internationally advanced performance levels.

#### **2.4. Establishment of an Internationally Advanced Superconducting Device Process Line**

The program has mastered and established superconducting SQUID and SNSPD detector chip fabrication technology, essentially solving China's critical problem of access to high-end superconducting sensors/detectors. Basic unit processes such as electron beam lithography and UV lithography for superconducting devices were independently developed, with process parameters established and standardized process documentation formed. Preliminary mastery of Nb-based large-scale superconducting integration technology has laid a critical foundation for developing new superconducting quantum devices and superconducting integrated circuits. The ongoing second-phase device process line and the in-situ electronic structure research platform based on the Shanghai Synchrotron Radiation Facility (Figure 5 [Figure 5: see original paper]) will further enhance the program's R&D capabilities in materials physics and device physics, which is of great significance for sustainable development.

Since the program's launch, over 150 SCI papers have been published (exceeding the program assessment target of 100), including more than 20 papers in top-tier international journals such as Science, Nature, and PRL (exceeding the program assessment target of >5). A total of 69 patents have been applied for, with 15 already granted. The program has also cultivated a large number of young talents, particularly establishing a high-quality platform and process support team according to the program's characteristics. The team has become the largest and most internationally competitive professional superconducting electronics research team in China. Project 4 leader Professor Chen Xianhui received the 2013 National Natural Science Award (First Class) and the 2015 highest international award in superconducting materials research, and was elected as an academician of the Chinese Academy of Sciences.

### **3. Originality**

Superconducting electronics is a strategic high-tech field. Due to the superior performance of devices, it has always played an irreplaceable role in meeting national strategic needs, defense technology development, and frontier basic research. In terms of industrialization, there are also several small high-tech companies internationally. However, Western advanced countries have long implemented strict blockades and controls on superconducting electronics technology and products for China. Since the launch of this program, China has initially achieved independent control of fully self-developed high-performance superconducting sensors and detectors, providing high-performance devices for the rapid development of China's information technology and playing a very important role in meeting major national needs. The program has also conducted

application demonstration and verification in frontier superconducting application fields (such as basic science, geophysics, biomedicine, astrophysics, and quantum information), which will have significant implications for subsequent industrial development.

The originality of this program is reflected in the following aspects:

- (1) Developed a Li ionic liquid gating method to achieve complex charge density wave structures and Mott insulating state-induced superconductivity, demonstrating that ionic liquid gating technology is a new approach for studying physical mechanisms involving charge and spin instabilities and for discovering new superconducting systems.
- (2) Developed an ultrathin Bi2212/graphene heterostructure preparation method. Even when Bi2212 is only half a unit cell thick, the heterostructure still exhibits superconducting transitions above liquid nitrogen temperature, providing a material basis for studying low-dimensional superconducting materials and new principle devices.
- (3) Clarified the origin of background dark counts in SNSPDs and developed on-chip integrated filter methods to suppress background dark counts, successfully fabricating high-efficiency, low-dark-count SNSPD devices.
- (4) Addressing the poor reliability of SQUID devices in field environments, the program adopted a chip-readout circuit integration design concept, successfully developing the world's simplest SQUID device, which significantly improves device stability and reliability in practical application environments.

## 5. Recommendations for Future Development in National Disciplines, Industry Advancement, and Talent Cultivation

The goal of this program is to build a world-class applied basic research center for superconducting electronics and establish an internationally advanced superconducting electronics device process line. This will fill the gap between China and developed countries in this strategic field and is of great strategic significance. Recommendations for related fields are as follows:

- (1) Long-term stable support is needed. While attaching great importance to the hardware construction of device microfabrication platforms, platform maintenance should be well managed to sustainably carry out process research and accumulate process experience. The platform's capabilities should be further enhanced to alleviate the contradiction between different requirements for innovative exploration and technical 攻关, enabling development from unit devices toward array devices and large-scale integration to form an irreplaceable international competitive advantage.
- (2) Strengthen talent cultivation in superconducting electronics, including not only young scientific research 骨干 talents but also basic process technology

talents, advocating a craftsman spirit. This will ensure the sustainable development of the superconducting electronics field.

- (3) Strengthen cooperation with industry. On one hand, promote the construction and maintenance of advanced superconducting micro/nano processing technology support platforms; on the other hand, accelerate the synchronous transfer of technology and talent to industry to shorten the transformation cycle of achievements. Under the guidance of IEC/IEEE, expand international cooperation, encourage national and international standardization work, and enhance China's voice in the industrialization of superconducting electronics.

Based on the significant progress achieved by the host unit in superconducting sensors, detectors, and related system technologies, SIMIT established the "Superconducting Sensor Technology Center" at its Jiading branch in 2015, specifically responsible for the R&D and promotion of superconducting electronics products. In 2015, the center received support from the Shanghai "Jiading-Zhangjiang" key project "Flexible Pilot Platform for Superconducting Quantum Devices," comprehensively promoting the R&D of SNSPDs, SQUIDs, biomagnetic imaging series products, single-photon detection series products, and geophysical exploration series products. Currently, SNSPD devices and systems as well as SQUID devices based on program achievements have achieved small-batch commercial sales. To accelerate SNSPD industrialization, Shanghai Futon Technology Co., Ltd. has been invested and established to specifically carry out system technology development and commercial operation of SNSPDs, accumulating experience for future larger-scale industrialization of superconducting electronics.

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### Expert Evaluations

**Shen Zhixun:** This is a high-level program regardless of scope. The program covers four research areas, all at the best domestic level, with some reaching world-leading status. As requested, I focus my evaluation on the quality of Professor Chen Xianhui's project based on my expertise in superconducting materials and physics, which can extend to reflect the quality of the entire program. I note that superconducting heterostructures and ultrathin film gating regulation are important research contents linking materials and devices. The program team has demonstrated high-level synergy and excellent work, and this vertically integrated research approach is precisely the advantage of this project.

This is a world-leading project. In 2008, Chen Xianhui's group first reported that F-doped SmFeAsO achieved a superconducting transition temperature of 43 K at ambient pressure, breaking the McMillan limit of conventional BCS theory and proving that iron-based superconductors are a second class of unconventional superconductors distinct from copper oxide superconductors. Shortly thereafter, Chen's group collaborated closely with multiple international groups to systematically study the physical properties of "1111" and "122" type iron-based

superconductors. They proposed electronic phase diagrams for  $\text{SmFeAsO}_{1-x}\text{Fx}$  and  $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$  systems, discovering coexistence of antiferromagnetic order and superconductivity in the underdoped region of the phase diagram. Additionally, Chen's group discovered strong iron isotope effects in  $\text{SmFeAsO}_{1-x}\text{Fx}$  and  $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$  systems. This discovery indicates that electron-phonon interactions play a role in superconductivity and that new spin-lattice coupling effects should be seriously considered. Chen's group has also been dedicated to growing high-quality single crystals, successfully applying the self-flux method to grow high-quality iron-based superconducting single crystals. This is currently the most widely used synthesis method in the field and has promoted research on iron-based superconducting single crystals. In recent years, Professor Chen Xi-anhui has focused on FeSe-derived materials and synthesized a new iron-based superconductor  $(\text{Li}_{0.8}\text{Fe}_{0.2})\text{OHFeSe}$  with a superconducting temperature of 43 K, providing a new material platform for further study of high-temperature superconductivity in FeSe-based superconductors.

The impact of this project is reflected in Professor Chen's publications and major awards: the Matthias Prize in Superconducting Materials Research (one of the most prestigious awards in this field globally), election as an academician of the Chinese Academy of Sciences, and the First Class National Natural Science Award.

**John Clarke:** I read the progress reports of the two projects with great interest and offer my evaluation below.

### **Project 1: Exploration of Superconducting Quantum Effects and Electronic Device Research**

The research group has achieved remarkable progress in two main areas: Superconducting Nanowire Single-Photon Detectors (SNSPD). Over the past four years, the group has improved the system detection efficiency (SDE) from about 21% at 100 Hz dark count rate (DCR) to >90% at 10 Hz DCR at a wavelength of 1,550 nm and temperature of 2.1 K. This is a new world record for NbN-SNSPDs. Similar breakthroughs have been achieved at 1,064, 940, 850, and 532 nm wavelengths. The group successfully reduced the background dark count rate by two orders of magnitude compared to conventional SNSPDs, reaching the sub-Hz level, by integrating multilayer thin-film bandpass filters onto the fabricated SNSPDs. These are all record-breaking achievements.

### **Robust SQUIDs for Outdoor Applications**

The SQUID research group redesigned the SQUID chip and electronics with simplicity and robustness as primary considerations. They developed SQUID electronics with only one operational amplifier, the simplest structure reported to date, which is ideal for system integration and outdoor operation. The improved system maintains acceptable noise levels while greatly improving bandwidth and slew rate. The group also developed planar SQUID magnetometers and gradiometers with 3.6 cm baselines. The white magnetic field noise of the SQUID magnetometer is 3.5 fT/ $\sqrt{\text{Hz}}$ . The magnetic field gradient noise is 100 fT/m/ $\sqrt{\text{Hz}}$  with an intrinsic balance of  $2 \times 10^{-4}$ .

## Project 2: Frontier Application Exploration of Superconducting Quantum Devices

This group has achieved impressive progress in SNSPDs and SQUIDs: **Break-through results in quantum information processing.** The group demonstrated a series of quantum key distribution (QKD) experiments such as 200 km MDI-QKD, 400 km MDI-QKD, and 200 km 2-node MDI-QKD network, with the 400 km MDI-QKD being the world record for QKD distance. Other important achievements include quantum fingerprinting, quantum teleportation using independent sources in fiber networks, and entangled single-photon source characterization. Other SNSPD applications include demonstrations in satellite LIDAR (Light Detection and Ranging), single-photon imaging, single-photon source characterization, and quantum random number generation.

**SQUID Applications:** The full-tensor environmental magnetic gradient compensation system demonstrated in the project greatly improves image quality in urban unshielded environments. The 4-channel system achieves higher signal-to-noise ratio and imaging efficiency. The SQUID-based airborne full-tensor magnetic gradient measurement system has a resolution of 0.05 nT/m in the 0.01-5 Hz bandwidth. The ground TEM system using the new SQUID structure completed testing on Hengsha Island. While coil receivers typically obtain useful information down to 400-700 m, the SQUID system remains effective down to 1,400 m and even 2,500 m in cases with low-resistivity overburden.

Other progress includes the development of two 4-channel and one 9-channel wire-wound hardware gradiometer systems for magnetocardiography, which have been installed in hospitals for clinical trials; a 36-channel system based on fluxgates is being optimized; studies of magnetic nanoparticle relaxation for protein-protein interactions at ultra-low fields; and scientists from SIMIT contributing as first authors to the “ultra-low-field-MRI” section of the article “SQUIDs in biomagnetism: a roadmap towards improved healthcare” in *Superconducting Science and Technology*.

Overall, I am impressed by the high quality of completion and the large number of papers in high-level journals produced by the two projects above. The two projects, “Exploration of Superconducting Quantum Effects and Electronic Device Research” and “Frontier Application Exploration of Superconducting Quantum Devices,” have created multiple important “firsts” in international scientific research. Although the program has only been running for four years, I am surprised by the fruitful scientific achievements already accomplished. This achievement reflects the outstanding leadership of the program and the hard work of team members.

*Note: Figure translations are in progress. See original paper for figures.*

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