



## Editorial

# Introduction to the special issue ‘Focus on Low and High- $T_c$ Superconducting Sensors and Detectors’

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Sensors and detectors are fundamental in all areas of modern science and technology. Superconductivity is playing an important role in realizing innovative performance in measurement and analysis, and contributes to the advancement of human knowledge and life. There is also hope for it to be more widespread in society so as to be applied in a various range of fields such as medicine, resource exploration, and information technology.

The word ‘sensor’ is normally used for measuring stationary or slowly changing electromagnetic fields, and physical quantities such as current and temperature in a coherent manner. The word ‘detector’ is normally used for detecting single quantum particles such as photons from infrared light to  $\gamma$ -rays and ions directly. However, the boundary between ‘sensor’ and ‘detector’ is ambiguous. Referring to an international standard published on 27 July 2017 [1], the words sensor and detector are explained in this manner. Therefore, both words are used in this preface and the title of this special issue ‘Focus on Low and High- $T_c$  Superconducting Sensors and Detectors.’ [2] The special issue ‘Focus on Superconducting Detectors’ was completed in 2016 [3], and it collected the latest achievements in this area. To succeed this collection, a new special issue was planned at the occasion of the International Workshop on Superconducting Sensors and Detectors (IWSSD) in 2016. This special issue collected some distinguished papers from the workshop and other latest achievements in the field. The selected presentations from IWSSD2016 are available in [4]. The IWSSD covers sensors and detectors with low and high- $T_c$  superconductors and provides a forum to discuss international standards for terminology, graphical symbols, and measurement methods through the cooperation between the International Electrotechnical Commission (IEC) and Institute of Electrical and Electronic Engineers (IEEE). We believe that the standardization enhances the advancement of superconductor science and technology, and its widespread use.

The papers in this special issue report the forefront of many R&D disciplines from routine use to new device development in superconducting sensors and detectors. The sensors and detectors were mainly classified into coherent detection for fields and direct detection for quantum particles, respectively [1]. In addition, direct detection is divided into quantum detection and thermal detection. New device categories are also added in this preface.

## Coherent detection

Magnetocardiography (MCG) with superconducting quantum interference device (SQUID) type sensors has a long history, but widespread use has not been realized



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regardless of the initial expectation. Nevertheless, there are a few examples for successful routine clinical use at hospitals. Inaba *et al* [5] reported the imaging power of a Nb SQUID array sensor and software system compared with simple wave forms in electrocardiography. They examined 10 085 fetal and adult patients at the University of Tsukuba Hospital in the period from 2008–2016. The medical doctors ordered about 100 examinations per month, which shows that the SQUID MCG system is indispensable.

Another Nb SQUID application is geomagnetic field measurement. Kawai *et al* [6] reported the status of their three-axis system with a system noise of about  $0.2 \text{ pT}/\text{Hz}^{-1/2}$  in a frequency range of 1–50 Hz. They observed very weak geomagnetic activities of the Schumann resonance and the ionospheric Alfvén resonance.

When SQUIDs are made in a nano-scale dimension, they can be used for an analytical instrument of mesoscopic and microscopic magnetic imaging of materials. Wu *et al* [7] reported their NbN nano-SQUID results on the observation of the Meissner effect in small superconductors like Nb and FeSe crystals with a dimension range of 25–120  $\mu\text{m}$ .

### Quantum direct detection

Neutrons can be measured by superconducting nanostrip type particle detectors (SSPDs) with a  $^{10}\text{B}$  neutron absorber in which neutron capture emits a  $^7\text{Li}$  and an  $\alpha$  particle with their total kinetic energies over 2 MeV. Shishido *et al* [8] reported that the product particles create pulse signals on the nanostrip, and neutron imaging is possible. The time difference at both ends was used to determine the incident position at an accuracy of 1.3 mm.

The SSPD type was originally used for detecting infrared photons at a telecommunication wave length of 1150 nm. You *et al* [9] reported an optimum design of dielectric mirror to achieve a system detection efficiency (SDE) of near 90%. Huang *et al* [10] also described polarization-insensitive SSPD with an SDE over 50% using a spiral nanostrip configuration.

Only one paper in this special issue, by Shibata *et al* [11], reported on a high- $T_c$  superconductor. They fabricated an SSPD with a 100 nm wide and 5 nm thick LaSrCuO nanostrip. LaSrCuO was the first oxide high- $T_c$  superconductor and the Nobel prize was given to J G Bednorz and K A Müller. They observed a signal for an irradiation of  $10^5$  photons. Although it is far from single photon detection, it is a promising result for high temperature operation in addition to successful single photon detection with  $\text{MgB}_2$ . There are many trials using YBaCuO that have a higher  $T_c$ , but no one has succeeded in SSPD operation.

### Thermal direct detection

Transition edge sensors (TES) with a SQUID readout rely on a detection mechanism of temperature measurement using a superconducting film biased at the middle of the normal–superconducting transition with electrothermal feedback. The counting rate of this type of detector is normally limited even though an electrothermal feedback may shorten the decay time of quantum-particle-induced pulses. Lee *et al* introduced an event grade method [12] in which they call for an optimal filtering scheme to overcome a pulse pile-up problem. They achieved 5 eV FWHM energy resolution at 1000 counts  $\text{s}^{-1}$  per pixel for the 6 keV x-ray photons, which is over ten times faster than the conventional TES operation.

The TES operation and optimization of detector structure are still an active research area. Harwin *et al* of the Cavendish Laboratory [13] numerically examined the typical TES detector structures such as bars and dots on

superconductor films. They demonstrated a good agreement with experimental results on proximity effects in lateral metal structures.

Another thermal type that also uses a SQUID readout is a metallic magnetic calorimetric (MMC) detector with a paramagnetic absorber. Kim *et al* and Kang *et al* [14, 15] reported the status of simultaneous detection of heat and light for so-called rare events in particle physics. A way to maximize the light signal in MMC was also proposed by Oh *et al* [16]. The thermal direct detection method with MMCs is applied to a large particle physics project to answer the fundamental physics questions of the neutrinoless double beta decay.

### New devices

Kornev *et al* [17] reported broadband active electrically small antennas (ESAs) with superconducting quantum arrays (SQAs) of Josephson junctions. They reviewed SQAs and ESAs.

Signal readout is an important area. Yamanashi *et al* [18] reported a possibility of quantum flux parametron or superconducting sensors and detectors, and later signal processing circuits at a low temperature.

A new electrothermal feedback scheme was introduced for a microwave kinetic inductance type detector by Guruswamy *et al* of the Cavendish Laboratory [19]. They built a model for absorption and heating of microwave readout power with quasiparticles, which may cause positive or negative feedbacks. The effects on responsivity and noise were reported in detail.

### International standardization

Although there is no paper on standardization in this special issue, we would like to mention it because of its importance in a series of IWSSD Workshops. A special IEC–IEEE joint standardization session was held at every IWSSD in addition to the occasions of other major conferences on applied superconductivity. The report of the IWSSD2016 standardization session is available at [20]. After the final discussion on 14 November 2016 at IWSSD2016, the first international standard was officially published on 27 July 2017: ‘Superconducting electronic devices—Generic specification for sensors and detectors (IEC 61788-22-1)’ [1]. The generic specification, which is the starting point of succeeding standards for measurement methods, covers the classification of device types and measurands, nomenclature, graphical symbols and the descriptions of major device types.

One of the topics arising after publication is that the Josephson junction (JJ) symbol in IEC 61788-22-1 was officially registered in the IEC graphical symbol databases through approval of the responsible technical committee: IEC60417/ISO7000 [21] on 17 September 2016 and IEC60617 [22] on 11 October 2017. These databases include the symbols for use on equipment and circuit diagrams: earth, transformer, resistor, diode, capacitor, transistor etc. There was previously the symbol of a tunnel diode that is also called an Esaki diode, but no official symbol for JJs existed, both of which received the Noble prize at the same time. A conflict of the widely used cross symbol with the IEC standard prompted us to propose the new JJ symbol. The scale of change was kept to a minimum so that users do not have to draw a complex symbol, and the new symbol reminds us of superconductivity, keeping the conventional cross that is assigned to the attribute for magnetic effect or magnetic dependence in the IEC standard.

The new symbol in IEC60617 was defined more precisely in size for circuit diagrams, and it can be viewed at IEC60417/ISO7000 [23]. Some related symbols were also registered with both databases so that the symbols have a structural logic as other IEC symbols have. We hope that the standards of the generic specification

and future measurement methods for various device parameters contribute to the R&D and diffusion of superconducting devices in order to make our society better.

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## References

- [1] 2017 First international standard in superconducting electronics ([https://webstore.iec.ch/preview/info\\_iec61788-22-1%7Bed1.0%7Den.pdf](https://webstore.iec.ch/preview/info_iec61788-22-1%7Bed1.0%7Den.pdf))
- [2] Focus on Low and High- $T_c$  Superconducting Sensors and Detectors (<http://iopscience.iop.org/journal/0953-2048/page/Focus-on-Low-and-High-Tc-Superconducting-Sensors-and-Detectors>)
- [3] Focus on Superconducting Detectors (<http://iopscience.iop.org/journal/0953-2048/page/Focus-on-Superconducting-Detectors>)
- [4] Selected presentations from the IWSSD2016 Workshop (<http://snf.ieeeecsc.org/issues/snf-issue-no-40-april-2017>)
- [5] Inaba T *et al* 2017 Routine clinical heart examinations using SQUID magnetocardiography at University of Tsukuba Hospital *Supercond. Sci. Technol.* **30** 114003
- [6] Kawai J, Miyamoto M, Kawabata M, Nosé M, Haruta Y and Uehara G 2017 Characterization and demonstration results of a SQUID magnetometer system developed for geomagnetic field measurements *Supercond. Sci. Technol.* **30** 084002
- [7] Wu L, Chen L, Wang H, Wang Q, Wo H, Zhao J, Liu X, Wu X and Wang Z 2017 Measurement of Meissner effect in micro-sized Nb and FeSe crystals using an NbN nano-SQUID *Supercond. Sci. Technol.* **30** 074011
- [8] Shishido H *et al* 2017 Neutron detection using the superconducting Nb-based current-biased kinetic inductance detector *Supercond. Sci. Technol.* **30** 094003
- [9] You L, Li H, Zhang W, Yang X, Zhang L, Chen S, Zhou H, Wang Z and Xie X 2017 Superconducting nanowire single-photon detector on dielectric optical films for visible and near infrared wavelengths *Supercond. Sci. Technol.* **30** 084008
- [10] Huang J *et al* 2017 Spiral superconducting nanowire single-photon detector with efficiency over 50% at 1550 nm wavelength *Supercond. Sci. Technol.* **30** 074004
- [11] Shibata H, Kirigane N, Fukao K, Sakai D, Karimoto S and Yamamoto H 2017 Photoresponse of a  $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$  nanostrip *Supercond. Sci. Technol.* **30** 074001
- [12] Lee S-J *et al* 2017 High count-rate study of two TES x-ray microcalorimeters with different transition temperatures *Supercond. Sci. Technol.* **30** 104005
- [13] Harwin R C, Goldie D J and Withington S 2017 Modelling proximity effects in transition edge sensors to investigate the influence of lateral metal structures *Supercond. Sci. Technol.* **30** 084001
- [14] Kim I *et al* 2017 Application of metallic magnetic calorimeter in rare event search *Supercond. Sci. Technol.* **30** 094005
- [15] Kang C S 2017 MMC-based low-temperature detector system of the AMoRE-Pilot experiment *Supercond. Sci. Technol.* **30** 084011
- [16] Oh S Y, Kim G B, Kim H L, Kim I, Kim S R, Lee H J, Lee M K and Kim Y H 2017 Protocol for maximising light signal of metallic magnetic calorimeters for neutrinoless double beta decay search *Supercond. Sci. Technol.* **30** 084005
- [17] Kornev V K, Kolotinskiy N V, Sharafiev A V, Soloviev I I and Mukhanov O A 2017 Broadband active electrically small superconductor antennas *Supercond. Sci. Technol.* **30** 103001
- [18] Yamanashi Y, Matsushima T, Takeuchi N, Yoshikawa N and Ortlepp T 2017 Evaluation of current sensitivity of quantum flux parametron *Supercond. Sci. Technol.* **30** 084004
- [19] Guruswamy T, Thomas C N, Withington S and Goldie D J 2017 Electrothermal feedback in kinetic inductance detectors *Supercond. Sci. Technol.* **30** 064006
- [20] Ohkubo M 2016 Standardization Session at IWSSD2016 Report [http://snf.ieeeecsc.org/sites/ieeecsc.org/files/documents/snf/abstracts/edOhkuboM\\_Report\\_of\\_IEC-IEEE\\_joint\\_std\\_IWSSD20160129-final-4\\_040617.pdf](http://snf.ieeeecsc.org/sites/ieeecsc.org/files/documents/snf/abstracts/edOhkuboM_Report_of_IEC-IEEE_joint_std_IWSSD20160129-final-4_040617.pdf)
- [21] International Electrotechnical Commission IEC60417/ISO7000 database ([www.graphical-symbols.info](http://www.graphical-symbols.info))
- [22] International Electrotechnical Commission IEC60617 database (<http://std.iec.ch/iec60617>)
- [23] IEC 60417 2016 New Josephson Junction symbol (International Organisation for Standardization) <https://iso.org/obp/ui#iec:grs:60417:6371>