International Standards for Superconducting Electronic Devices

- Superconducting Sensors and Detectors -

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***Abstract* - International standardization for superconducting electronic devices - generic specification for sensors and detectors is in progress. The working group 14 (WG14) was established under IEC-TC90 (superconductivity) in May 2014 to standardize terms and definitions, graphical symbols for diagrams, measurands, nomenclature, categorization of the device types for superconducting sensors and detectors on the basis of *the guide to IEC/IEEE cooperation*. The users of superconducting device products require generic specification first. In a following series of standards, we will consider measurement methods for fair comparison of device performance.**

***Keywords* – IEC-IEEE collaboration, International standards, Superconducting electronics, Superconducting sensors, Superconducting detectors**

I. INTRODUCTION

Practical use and commercial products of superconducting sensors and detectors (SCSDs) have been around in the field of superconducting electronics for some decades. In particular, measurement systems based on superconducting quantum interference devices (SQUIDs) represent a market sized in the low hundred millions of US dollars. They emerged as products around 1970 while their market, mainly of laboratory systems for materials characterization, experienced rapid growth in the late 1980s to early 1990s. Moreover, large medical research and diagnostics systems have been manufactured, in much lesser volume, since the early 1990s. SQUIDs provide the highest magnetic field sensitivity in the low-frequency bandwidth, from near 0 Hz up to the kHz and even low MHz range. They are presently used as enabling sensors in minerals exploration, food contamination inspection, integrated circuit testing, etc. In communication and many fields of science they increasingly serve as both sensors and amplifiers.

Other SCSDs have also been applied to detect electromagnetic radiation, in the wide spectrum from microwaves to X-rays, and particles such as photons, electrons, ions, *etc*. Most of such detectors has been investigated, developed, and theoretically understood in the past 20-30 years, with intense development continuing. For example, at radio frequencies and in the microwave frequency range, coherent sensors are Josephson junctions used as frequency mixers. Beginning in the past decade theuse of superconducting detectors is developing rapidly, mainly in radio telescopes for astronomy and cosmology, air pollution monitors, materials analysis, *etc*. To date, a variety of SCSDs detectors, have been fabricated in very large numbers within scientific projects. Currently there exist also commercial products, but the market is rather limited. It is likely that in foreseeable future larger scale manufacture of these devices will be gradually taken over by industry.

The start of the standardization activity goes back to 2005 [1]. We started to consider the standardization of superconducting electronics in addition to that of superconducting wires and cables, already in progress. Since then, we have considered the possibilities of standardization for Josephson junctions as fundamental elements of superconducting electronics, and also of superconducting digital circuits, cryogenics, and superconducting sensors and detectors. After the worldwide survey of the demand for standardization and a long-term discussion, the SCSDs came to the front of standardization candidates. The increase of the scientific paper number and the emergence of commercial products suggest that it is now the appropriate timing for standardization.

We proposed a new ad hoc group on the occasion of the IEC general meeting at Seattle in 2010. After the approval during the meeting, the members of the ad hoc group were nominated from the IEC-TC90 participating member (P-member) countries of China, Germany, Japan, Korea, and USA: M. Ohkubo (rapporteur, JP), B. Mazin (US), Z. Wang (JP), D. Fukuda (JP), S. Tanaka (JP), J. Kohlmann (DE), Y. Lee (KR), Y. Chong (KR), Y-H. Kin (KR), R. Cristiano (IT), and L. You (CN). In the course of survey and discussion in the ad hoc group, we learned that a party of IEEE led by Dr. Catherine Foley of CSIRO is also interested in standardization in superconducting electronics. We contacted her and Dr. Lance Cooley, and the first IEEE-IEC joint meeting on standardization of superconducting electronics took place during ISEC2013 in Cambridge, US, in July 2013. One of the fruitful outcomes of this joint meeting was the agreement to the IEEE-IEC joint standardization on the basis of the *guide to IEC/IEEE cooperation* [2]. Our continuous activity resulted in the submission of New Work Item Proposal (NP) to the IEC office in Jan. 2014. The NP was approved by international votes of IEC P-memebers: China, Germany, Italy, Japan, Korea, and US, with the participation of 9 experts in May 2014. Accordingly, new Working Group 14 (WG14) was established. The current expert members of WG14 are M. Ohkubo (JP, Convenor), L. Cooley (US), Y-H. Kim (KR), S. Adachi (JP), R. Cristiano (IT), J. Kohlmann (DE), T. May (DE), J. Chen (CN), and L. You (CN), who were nominated by the IEC P-member countries [3]. The experts of Australia are negotiating with the national IEC committee about participation.

In April 2015, an IEC Committee Draft (CD) will be distributed to national IEC committees in order to collect their opinions for one year as the longest deadline. We also welcome opinions of the readers of Superconductivity News Forum (SNF) (please mail to: m.ohkubo@aist.go.jp). Finally, the International Standard (IS) for the generic specification of terms and definitions, graphical symbols for diagrams, measurands, nomenclature, categorization of the device types for superconducting sensors and detectors will be published by Apr. 2017. A submission of Project Authorization Request (PAR) of the IEEE party is under consideration on the basis of the guide to IEC/IEEE cooperation. The IS for generic specification will be followed by NPs for the several types of sensors and detectors, which is necessary for defining measurement methods of, for example, magnetic field sensitivity, energy resolution for X-rays, dark-count rate for telecommunication, etc.

II. TERMINOLOGY AND CLASSIFICATION

It is very important for us to collect opinions of the members of IEEE Council on Superconductivity and other parties as well as the SCSD community. For this purpose, we present below the most pertinent part of the current IS draft.

Table I lists the measurands which are defined as the objects, input quantities, properties, or conditions that are to be sensed or detected by the superconducting sensors and detectors. The word "sensor" is normally used for measuring stationary or slowly changing electromagnetic fields, physical and chemical quantities such as current and temperature. On the other hand, the word "detector" is normally used for single quanta such as photons from infrared to γ-rays and individual particles. The boundary between "sensor" and "detector" is ambiguous. In this standard, therefore, both terms "sensor" and "detector" are used. The word "sensor" tends to be used for devices that measure fields and waves, while the word "detector" tends to be used for devices that measure single particles such as photons and ions. For example, if the measurand is a magnetic field, it is measured by a magnetic sensor; photon detector for photons, X-ray detector for X-ray photons. The measurands arranged in alphabetical order are: biological particles, elementary particles, magnetic quantities, physical and chemical particles, and radiations. Each entry in Table I represents not only the measurands themselves, but also their temporal or spatial distribution.

Table I. Measurands

1. Biological particles (count, energy, flux, spectrum, time)
1.1 Amino acids
1.2 Peptides
1.3 Proteins
2. Elementary particles (count, energy, flux, spectrum, time)
2.1 Dark matter
2.2 Electrons
2.3 Neutrinos
2.4 Neutrons
2.5 Protons
2.6 Positrons
3. Magnetic quantities (amplitude, count, density, distribution)
3.1 Magnetic fields
3.2 Magnetic flux
4. Physical and chemical quantities (amplitude, count, energy, flux, spectrum, time)
4.1 Current
4.2 Voltage
4.3 Displacement

4.4 Magnetic susceptibility

4.5 Polarization

4.6 Resistance

4.7 Spins

4.8 Atoms

4.9 Ions

4.10 Molecules

5. Radiations (amplitude, count, energy, flux, spectrum)

5.1 Alpha-rays

5.2 Beta-rays

5.3 Electromagnetic waves

5.4 Gamma-rays

5.5 Infrared-rays

5.6 Photons

5.7 X-rays

Table II lists the various types of sensors and detectors in alphabetical order. The sensors and detectors convert measurands to electronic signals. At this moment, there is confusion in nomenclature. In current version of the committee draft (CD), the nomenclature for the SCSDs should have the word order that is device structure or function, measurand, and then a word of detector, magnetometer, mixer, sensor, or other words. Examples of full names and corresponding abbreviations are also listed in Table II.

Table II. Types of Superconducting Sensors and Detectors, and Acronym Examples

The nomenclature has the word order of (device structure or function) – (a measurand) – (detector, magnetometer, mixer, sensor, other words).

1 Metallic Magnetic Calorimetric (MMC) type

Metallic Magnetic Calorimetric α-Ray Detector (MMCAD)

Metallic Magnetic Calorimetric γ-Ray Detector (MMCGD)

Metallic Magnetic Calorimeter X-Ray Detector (MMCXD)

2 Microwave Kinetic Inductance (MKI) type

Microwave Kinetic Inductance Photon Detector (MKIPD)

Microwave Kinetic Inductance X-Ray Detector (MKIXD)

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3 Superconducting Hot Electron Bolometric (SHEB) type

Superconducting Hot Electron Bolometric Photon Detector (SHEBPD)

Superconducting Hot Electron Bolometric Terahertz Mixer (SHEBTM)

4 Superconducting Quantum Interference Device (SQUID) type

Superconducting Quantum Interference Device amplifier (SQUID Amplifier)

Superconducting Quantum Interference Device current sensor (SQUID Current Sensor)

Superconducting Quantum Interference Device gradiometer (SQUID gradiometer)

Superconducting Quantum Interference Device magnetometer (SQUID magnetometer)

Superconducting Quantum Interference Filter magnetometer (SQIF magnetometer)

5 Superconducting Strip (SS) type

Superconducting Strip Electron Detector (SSED)

Superconducting Strip Ion Detector (SSID)

Superconducting Strip Photon Detector (SSPD)

6 Superconducting Tunnel Junction (STJ) type

Superconductor Normal-conductor Superconductor mixer (SNS mixer)

Superconducting Tunnel Junction Photon Detector (STJPD)

Superconducting Tunnel Junction Ion Detector (STJID)

Superconducting Tunnel Junction mixer (STJ mixer)

Superconductor Insulator Superconductor mixer (SIS mixer that is equivalent to STJ mixer)

Superconducting Tunnel Junction X-Ray Detector (STJXD)

7 Transition Edge Sensor (TES) type

Transition Edge Sensor X-Ray Detector (TESXD)

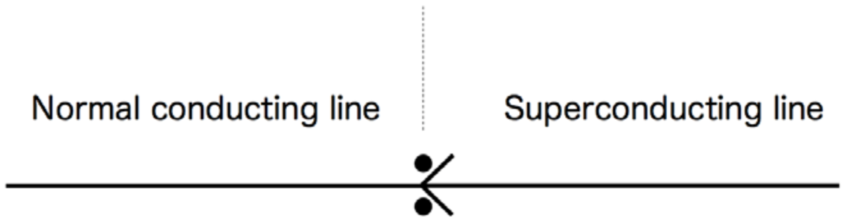
It is natural that inventors name the devices they invent. Successors often use different names to the same device type. This was one of the motivations to initiate our efforts of international standards. One of the requests from the SCSD community to us was to unify several names for so-called Superconducting Single Photon Detector (SSPD) originally named by Dr. Gol'tsman [4]. One problem of this name is that almost all types of superconducting sensors and detectors have the capability of single photon detection, so that the name of SSPD cannot be unique. In the community, several names appeared for single photon detection: Superconducting Nanowire Single Photon Detectors (SNSPD), Nanowire Superconducting Single Photon Detectors (NSSPD), Superconducting Nanowire Detector

(SND), Superconducting Meander Detector (SMD), Superconducting Nanostrip Detector (SND), Superconducting Nanostripe Detector, *etc*. Furthermore, this detector type was applied to detect electrons, ions, X-rays, and biomolecules. They used superconducting stripline detector (SSLD), superconducting nanowire single electron detector (SNSED), superconducting strip ion detector (SSID) *etc*. Some of them skipped the word "nanowire," since the size of superconductors is larger than nano-scale for ions and X-rays.

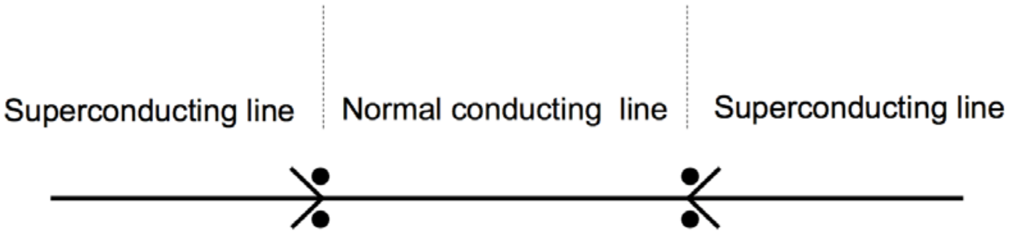
We believe that the IEC-IEEE standards should have consistency with other standards. The word "nanowire" is a matter for study in ISO/TS 27687 -Terminology and definitions for nano-objects [5]. The nanoscale means the size ranges from approximately 1 nm to 100 nm. "Nanowire" is defined as electrically conducting or semi-conducting nanofibre, "Nanofibre" must have two similar external dimensions in the nanoscale and the third dimension significantly large. The two similar external dimensions are considered to differ in size by less than three times, which may be somewhat understandable. One of the smallest superconducting lines of SSPDs is, for example, 7 nm-thick and 200 nm-wide. Since the dimension difference is more than three, the superconducting line cannot be called as nanowire. Consequently, the acronym of SNSPD seems not to be consistent with other standardization. A proposal from WG14 is Superconducting Strip Photon Detector (SSPD). For ion detection, we can use Superconducting Strip Ion Detector (SSID). In order to avoid confusion, the WG14 is proposing the nomenclature that has the following word order: (device structure or function) – (a measurand) – (detector, magnetometer, mixer, sensor, other words).

III. GRAPHICAL SYMBOLS

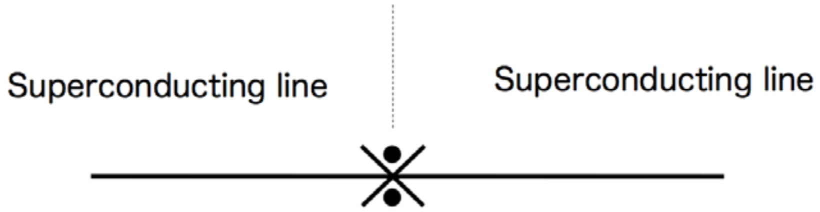
There are no international standards for graphical symbols in superconducting electronics. Therefore, the WG14 is proposing the graphical symbols for diagrams. First of all, it is necessary for distinguishing a superconducting line and a normal conducting line as shown in Fig. 1.The two dots symbolize a Cooper-pair. The analogy to the superconducting-normal-superconducting line leads to a Josephson junction symbol as shown in Fig. 1 (c). This kind of the graphical symbols should be considered together with other technical committees.



(a) Normal and superconducting line



(b) Superconducting-normal-superconducting line



(c) Josephson junction

Fig. 1. Graphical symbols for superconducting electronics.

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