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Recent research trends for superconducting detectors: Introduction on the focus of the special issue

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The combination of unique characteristics in superconducting materials and the extremely low thermal noise conditions available in cryogenic environments have led to the demonstration of various types of superconducting detectors with unmatched performance. In this editorial, we briefly introduce these detectors, which are the topic of this special issue.

A Josephson junction (JJ) consists of a thin insulator sandwiched by two superconducting layers. JJs have unique features, such as the Josephson tunnelling effect, flux quantization, and photon assisted tunnelling, which are at the core of the operation of superconducting tunnel junction (STJ) detectors, superconductor-insulator-superconductor (SIS) mixers, and superconducting quantum interference device (SQUID) sensors. Non-equilibrium states induced in thin superconducting films or strip lines have also been utilized in various sensitive and ultra-fast detectors such as the transition edge sensor (TES), the hot electron bolometer (HEB), the superconducting nanowire single photon detector (SNSPD or SSPD), the superconducting strip line detector (SSLD, SNSPD, or SSPD), and the microwave kinetic inductance detector (MKID).

Superconducting Tunnel Junction (STJ) detectors

An STJ detector consists of a JJ designed to efficiently detect incident radiation (with wavelength varying in the range from X ray to THz) by measuring the induced tunnelling current of excited quasi particles through the insulating thin layer. In this issue, Du et al. report on a cryogen-free STJ detector system for terahertz radiation based on a high-critical-temperature superconductor (HTS) [1]. The use of an HTS and user-friendly cryogenics is a crucial step for the success in commercialization of such sophisticated high-performances detectors. Furthermore, in this issue, Fujii et al. report on the development of a new fabrication process for three-dimensional STJs for X-ray absorption fine structure (XAFS) spectrometry. Fujii's process enables high operational yield and high mean energy resolution [2].

Superconductor-Insulator-Superconductor (SIS) mixers

Applying an external magnetic field to a JJ irradiated by electromagnetic radiation causes a strong non-linearity in the I-V characteristic of the JJ (this effect is known as the photon-assisted tunnelling effect), making quantum mixing possible. The SIS mixer has already been utilized as the heart of the heterodyne receiver system for THz electromagnetic waves. The Atacama Large Millimeter/submillimeter Array (ALMA) project is one of largest international projects to develop a ground-based radio telescope in the Atacama Desert in the Republic of Chile [3]. ALMA allows sensitive observations over the frequency range from 31 GHz to 0.95 THz – divided into 10 bands. Several groups within the ALMA project have carried out development and production of the receivers for each band. In this issue, Kojima et al. report the design and development of SIS mixers for ALMA band 4, over the frequency range of 125–163 GHz [4].

Superconducting Quantum Interference Device (SQUID) sensors

A SQUID is a highly sensitive magnetic sensor, which relies on the combination of flux quantization and Josephson tunnelling. SQUID-based sensors have been widely applied in commercial products such as magnetocardiography (MCG) and magnetic resonance imaging (MRI). Recently, there has been a requirement for very small SQUID devices, able to observe nanoscale targets. Gallop et al. report a new approach using Dayem bridge SQUIDs for energy-resolved single photon detection [9].

Transition Edge Sensors (TESs)

A TES is a calorimeter that utilizes the steep superconducting to normal transition of a superconducting film close to the critical temperature (T_C) to measure the energy of incident particles or radiation with high resolution [10]. Depending on its design, a TES can be used to efficiently detect X-rays, gamma rays, THz waves, or single photons from visible to near infrared wavelengths. In this issue, Ullom et al. report a detailed review of TES sensors for X-ray and gamma-ray spectroscopy [11]. Posada et al. report the fabrication of multi-chroic TES bolometer arrays for the observation of the cosmic microwave background [12].

Hot Electron Bolometers (HEBs)

A HEB utilizes non-equilibrium superconductivity in an ultra-thin film and can act as either a mixer or a direct detector. Since the energy relaxation of the excited quasi-particles in a HEB can happen trough phonon cooling (phonon-cooled HEB [13]) or diffusion cooling (diffusion-cooled HEB [14]), fast recovery times (< 30 ps) can be obtained. HEBs have been successfully used as mixers at frequencies above 1 THz, at which the SIS mixer is difficult to operate due to the limit set by of the energy gap frequency. In this special issue, Shurakov et al. report an historical, theoretical, and experimental review of HEBs [16]. Guruswamy et al. report the theoretical calculation of non-equilibrium quasi-particle and phonon distribution, which are crucial phenomena for understanding the operation mechanism of HEBs, as well as other superconducting detectors [17]

Superconducting Nanowire Single Photon Detectors (SNSPD or SSPD)

An SNSPD consists of a thin and narrow superconducting nanowire [18] and is sensitive to single photons from X-ray [19] to mid-infrared wavelengths [20]. SNSPDs have attracted a lot of attention as promising single photon detectors, since they offer high sensitivity, low dark count rate, high counting rate, and short timing jitter. Since the successful demonstration of a QKD experiment over 200 km with SNSPD [21], they have risen to fame outside of the superconducting community. Intensive experimental and theoretical studies are performed in many institutes over the world [22-23].

In this issue, Engel et al. review recent theoretical studies of the detection mechanism of SNSPDs [24]. Mattioli et al. report the development of a new type of SNSPD, which can resolve the number of detected photons by means of a new device architecture [25].

Superconducting Strip Line Detectors (SSLD, SNSPD, or SSPD)

SSLDs have a similar geometry to SNSPDs, however SSLDs use thicker and wider strip-lines to efficiently detect particles having energy of about 20 keV (much higher than the energy of optical photons, which is as low as a few eV). An SSLD was successfully used for the first time in 2008 to detect biological molecules in time-of-flight mass spectrometers (TOF-MSs) [26]. Since then, intensive investigation on the detection mechanism and on design optimization to improve the performances in the detection of high-energy ions [27-29] and low-energy neutral particles / light ions were carried out [30-31].

In this issue, Cristiano et al. review all progress in the development and investigation on the underpinning detection mechanism for this class of detectors [32]. Sano et al. also report the demonstration of single-flux-quantum (SFQ) readout circuits for TOF-MSs with SSLD, which would be a crucial technology for intelligent processing from large-scale SSLD array systems [33].

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