Superconducting Nanowire Single photon detector (SNSPD) for Quantum Information

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In the beginning of this century, a new type of detector, superconducting nanowire single photon detector (SNSPD or SSPD) joined the family of superconducting sensors and detectors. Soon, it has been turning to be one of the most important players in this family since it surpasses the semiconducting single photon detectors (APD: avalanche photodiode and PMT: photo multiplier tube) with many advantages, such as high detection efficiency, low dark count rate, low timing jitter and higher counting speed. Now you may buy the commercial SNSPDs including the cryogenic system from a few start-up companies in the world. Many interesting applications and demonstrations of SNSPDs has been demonstrated in past a few years.

In this talk, I will introduce our work on SNSPD and its applications for quantum information in SIMIT, CAS.

(i) High detection efficiency SNSPD for the fiber communication wavelength of 1550 nm;
(ii) High detection efficiency SNSPD for wavelengths from the visible to near infrared;
(iii) How to reduce the dark count rate of SNSPD by the on-chip film narrow-bandpass filter;
(iv) Applications of SNSPD in quantum information and others.

Of course, the principle and the technical progress of SNSPD will also be reviewed.


Figure 1. DEs of SNSPDs vs other SPDs for different wavelengths.
Low-temperature detectors for dark matter investigation and neutrino studies

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Low-temperature detectors (LTDs) have become a useful technology in many aspects of science that requires extreme detector performance in energy resolution and threshold better than conventional detectors (e.g., semiconductor-based detectors). The use of superconducting materials and electronics at ultra-low temperatures made the detector performance reaching intrinsic detection limits. As their applications in nuclear and particle physics, these detectors play a major role in dark matter searches and neutrino studies in particular. In this presentation, I will review LTD sensor technologies such as transition edge sensors and metallic magnetic calorimeters that are developed based on as superconducting electronics. I will also introduce several science projects for direct detection of a dark matter candidate, neutrinoless double beta decay search, and precision end-point-measurement of electron capture decay process.
TES X-ray Microcalorimeters for X-ray Astronomy and Material Analysis

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An X-ray microcalorimeter detects individual X-ray photons as a heat input and determines the X-ray energy from the increase of temperature. The ideal energy resolution is limited by the thermal fluctuation. When it is operated at a cryogenic temperature of ~100 mK, an FWHM (full width half maximum) resolution of a few eV can be obtained for soft X-rays of several keV with a realistic size of detector. This is by a factor of ~50 better than the energy resolution of semiconductor detectors. The first generation X-ray microcalorimeters uses a thermistor to sense the temperature increase, while the second generation, i.e. TES (transition edge sensor) microcalorimeter utilize superconducting transition edge as thermometer. Advantages of TES micro calorimeters over thermistor-type calorimeters are two folds. Firstly, a large format array of a few k pixels becomes possible even for space missions where the cooling power is very limited (typically a few µW at 100 mK). Utilizing the low impedance of TES device, a few mΩ while it is ~1 MΩ for thermistors, different methods for signal multiplexing at cryogenic temperature are extensively studied in order to reduce number of wire harnesses between room temperature electronics and the detector. A large format array is essential for the focal plane detectors of future X-ray astronomy missions. Secondly, the time constant of TES microcalorimeter signals is by an order of magnitude shorter than that of thermistor calorimeters due to the strong electro-thermal feedback (ETF). After absorbing an X-ray photon, the device returns its equilibrium temperature with a certain time constant. When the ETF is strong, the heat from the X-ray photon is compensated by the decrease of heat dissipation from the thermometer (TES). As a result the time constant becomes much shorter, and an order of magnitude larger high counting rates are available. High counting rate is essential for ground applications, such as material analysis. We can increase the maximum counting rate by using multiple pixels at the same time.

Our group at ISAS, JAXA is developing TES microcalorimeters for two purposes in collaboration with Kyushu University, NIMS, Hitachi HiTech Science, and Tokyo Metropolitan University. For X-ray astronomy space missions, our goal is 16x16 format array or larger. We are presently focusing on two developments; frequency division signal multiplexing and a pixel with a large (400 µm) X-ray absorber. For the former purpose we bias the TES microcalorimeter with a few MHz RF current. We developed FPGA based SQUID feedback system and so far we successfully read signals from two pixels simultaneously. For the latter purpose we are developing Bi/Cu bilayer as an X-ray absorber (see Noda et al. in this conference).

For material analysis, we are developing an sensor system for a scanning transmission electron microscope (STEM). It includes 6x6 format microcalorimeter array, SQUID array amplifiers to read the signals form 6x6 array, and the cold head on which all those device are mounted together. In Figure 1, we show photographs of the devices and some results. We plan to install this sensor system as the EDS for STEM in 2016.

![Figure 1](image.png)

(a) 6x6 format TES X-ray microcalorimeter array developed for STEM EDS. (b) close up photo of a pixel. from the device (a). Gold X-ray absorber and Ti/Au bilayer TES are located at the center surrounded by the thin Silicon Nitride membrane for thermal link (dark part). (c) SQUID array amplifier device developed to read 8 TES pixels simultaneously. (d) The energy spectrum of Fe$^{55}$ radioisotope obtained use (a)(c). With an energy resolution of 7.8eV, the fine structure of the Mn K$_\alpha$ line is partly resolved.
Fabrication and Characterization of Nb and NbN Microwave Resonators for Multiplexed Readout of Superconducting Detector Arrays


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Superconducting detectors have exhibited much lower noise than semiconductor detectors ranging from millimeter wave to γ-ray. To develop practical spectrometers and sensing systems with compact and low-power consumed cryocoolers, multiplexing readout circuits capable of large-format detector arrays are key devices. Recently, frequency domain multiplexers (FDM) in microwave region attracted much attention to increase the multiplexing number [1]. Microwave FDM consists of high-\(Q\) thin-film resonators with unique resonant frequencies (\(f_R\)) where each \(f_R\) depends on each pixel. To increase the resonant \(Q\)-factor, we have fabricated and characterized Nb and NbN resonators. The Nb and NbN film were optimized with respect to the critical temperature and the resistivity. The multiplexers were characterized at 4 K and NbN resonators’ \(Q\)-factors were confirmed to be larger than those of Nb ones. The measured noise of the readout circuits, i.e., the square root of spectral density of current noise referred to the input of a superconducting quantum interference device (SQUID) for connection to a detector, was 31 pA/√Hz that is factor-of-seven improvement from our Nb resonators-based circuits [2]. They were also measured at down to < 100 mK using an adiabatic demagnetization refrigerator cryostat, and unloaded \(Q\)-factor larger than \(10^3\) was obtained at 100 mK, which is about ten times larger than the value obtained at 4K [3]. An FPGA(field programmable gate array)-based room temperature back-end circuit for the multiplexed readout of transition edge sensor (TES) photon counters is currently developed.

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Figure 1. Microwave SQUID multiplexer consisting of 16 resonators at around 5 GHz with 20 MHz spacing. The chip size is 5 mm x 5 mm.

Figure 2. Amplitude of transmission component of scattering matrix \(S_{21}\) vs. frequency for resonators based on NbN at 4K (black) and 100mK (red).
Pulse Shape Simulations of TES Microcalorimeter with Multi-Layer Absorber by Thermal Desktop/SINDA

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For precision X-ray spectroscopy by detectors onboard future X-ray astronomical satellites, Transition Edge Sensor (TES) microcalorimeters [1] with high spatial covering factors are powerful. In order to realize high photon detection efficiency keeping energy resolution high enough, we are now developing a TES microcalorimeter with a double-layer absorber. The first layer is made from Bi (~120 × 120 × 1 μm³) having low specific heat and high X-ray stopping power, while the second is Cu (~120 × 120 × 1 μm³) with high thermal conductivity set via electrocrystallization (Fig. 1a). By X-ray irradiating tests, we obtained the energy resolution of 19.79 eV at 5.9 keV, and found that pulse time constants varied by ~0.1 μs from the average of ~0.2 μs for photon by photon [2]. Because the baseline resolution was 14.63 eV [2], the derived energy resolution was presumably degraded by the time constant variations.

In order to identify the origin of the time constant dispersion, we constructed a thermal mathematical model of the TES microcalorimeter by using the finite element method software, Thermal Desktop/SINDA [3] (Fig. 1b). When contact thermal conductance (CTC) was set to 50 W/K/m² between Bi and Cu, and between the Cu and TES (hence, the combined CTC is 25 W/K/m²), the simulation successfully reproduced the averaged pulse shape in the experiment (Fig. 2 black). However, the time constant variability was not reproduced, even though we changed photon incident positions for photon by photon. Then, we changed the combined CTC into 27.5 W/K/m² (10% higher) at some parts, while kept 25 W/K/m² at the other parts in the model. As a result, the simulated time constant varied by ~0.1 μs, depending on photon incident positions (Fig. 2 red). This shows a possibility that the time constant variations are resulted by the CTC non-uniformity, which may occur in the Cu electrocrystallization.

![Figure 1: A schematic structure and an actual picture (panel a) and a thermal mathematical model (panel b) of the TES microcalorimeter with the multi-layer absorber.](image)

![Figure 2: Simulated pulse profiles of the TES microcalorimeter with the multi-layer absorber, which includes CTC non-uniformity. Black and red show the pulse shapes, when a photon enters at position 1 and 2 in Fig. 1(b), respectively.](image)