Energy-Resolved Neutron Imaging using a Delay Line Current-Biased Kinetic-Inductance Detector

Hiroaki Shishido, Kazuma Nishimura, The Dang Vu, Kenji M. Kojima, Tomio Koyama, Kenichi Oikawa, Masahide Harada, Shigeyuki Miyajima, Mutsuo Hidaka, Takayuki Oku, Kazuhiko Soyama, Kazuya Aizawa, Soh Y. Suzuki and Takekazu Ishida

1Department of Physics and Electronics, Graduate School of Engineering, Osaka Prefecture University, Sakai, Osaka 599-8531, Japan
2NanoSquare Research Institute, Osaka Prefecture University, Sakai, Osaka 599-8570, Japan
3Materials and Life Science Division, J-PARC Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
4Center for Molecular and Materials Science, TRIUMF and Stewart Blusson Quantum Matter Institute, University of British Columbia, Vancouver, BC, V6T 2A3 and V6T 1Z4, Canada
5Division of Quantum and Radiation Engineering, Osaka Prefecture University, Sakai, Osaka 599-8570, Japan
6Advanced ICT Research Institute, National Institute of Information and Communications Technology, 588-2 Iwao-k, Nishi-ku, Kobe, Hyogo 651-2492, Japan
7Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305-8168, Japan
8Computing Research Center, Applied Research Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

E-mail: shishido@pe.osakafu-u.ac.jp

Abstract. We demonstrate the development of an energy resolved neutron transmission imaging system via a solid-state superconducting detector, called current-biased kinetic-inductance detector (CB-KID). CB-KIDs comprise X and Y superconducting Nb meanderlines with Nb ground plane and a 10B conversion layer, which converts a neutron to two charged particles. High-energy charged particles are able to create quasi-particle hot spots simultaneously in the X and Y meander lines, and thus, the local Cooper pair density in meander lines is reduced temporarily. When DC-bias currents are fed into the meander lines, double pairs of voltage pulses are generated at the hot spots and propagate toward both ends of the meander lines as electromagnetic waves. The position of the original hot spot is determined by a difference in arrival times of the two pulses at the two ends for X and Y meander lines, independently. This is so-called the delay-line method, and allows us to reconstruct the two-dimensional neutron transmission image of a test sample with four signal readout lines. We examined the capability of high spatial and energy (wavelength) resolved neutron transmission imaging over the sensor active area of 15 x 15 mm$^2$ for various samples, including biological and metal ones. We also demonstrated the capability for the Bragg edge transmission and an energy-resolved neutron image in which stainless-steel specimens were discriminating from other specimens.

1. Introduction

Superconducting detectors are one of the most successful applications of superconducting devices because of their advantages of high sensitivity and fast response [1, 2, 3, 4]. Transition edge
sensors (TES) and microwave kinetic conductance detectors (MKID) are widely applied to the detection of cosmic ray. TES is a kind of bolometer, in which a finite temperature increase of the detector induced by the X-ray irradiation is detected by the instantaneous rise of resistance at the superconducting transition edge [1]. In the MKID, multiple superconducting resonators electromagnetically couple with a single readout line, and the kinetic inductance change induced by Cooper pair breaking in a resonator is detected as a change of the resonance frequency [2, 3]. Superconducting nanowire single photon detectors (SNSPD) are efficiently able to sense a single photon detector. In the SNSPD, the meanderline of the superconducting nanowire, in which a bias current is fed just below the critical current, becomes the normal state with the aid of the Joule heating when a normal core is induced by an incident photon; thus, the photon incident event is detected [4]. Recently, some efforts were made to apply a superconducting detector for detecting neutron beam. A TES with a B neutron absorption layer [5] and two superconducting tunnel junctions (STJs) on a single crystal of Li$_2$B$_4$O$_7$ with a neutron-converter layer $^6$Li or $^{10}$B [6, 7] were proposed to be used as a neutron detector.

We have been developing a unique superconducting neutron detector, called current-biased kinetic-inductance-detector (CB-KID) [8, 9, 10, 11, 12, 13, 14]. The CB-KID has superconducting meander microstrip lines and a $^{10}$B neutron conversion layer, and can operate in a wide region of the superconducting phase. High-resolution imaging in two dimensions with four signal readout lines was recently achieved using a combination of CB-KID and delay-line method (delay-line CB-KID). We succeeded in achieving the spatial resolution of 16.2 μm with a delay-line CB-KID [14]. Recently, the delay-line method was applied to a single photon imager based on the SNSPD [15]. Energy resolved imaging also successfully realized thanks to high temporal resolution of delay-line CB-KID via the the time-of-flight (TOF) method in the pulsed neutron source. In the energy (wavelength) dependence of the neutron transmission, the characteristic sawtooth structures, which are called the Bragg edges, appear at wavelengths where the Bragg conditions are satisfied because of a transient change of the coherent scattering. The analysis of the Bragg edges gives unique information of the samples such as the crystal structure and crystalline quality, and is an important technique in material sciences [16, 17]. A pulsed neutron source, which generates neutrons with a wide energy range, is suitable to conduct observing the Bragg edge. Thus, a combination of the high temporal resolution of a neutron detector and TOF technique in a pulsed neutron source is promising for the Bragg edge analysis. The delay-line CB-KID has a potential for application in the Bragg edge method with a high spatial resolution.

High spatial resolved neutron imaging system without a superconducting detector have been developing in various approaches [18, 19, 20, 21]. A gadolinium-oxysulphide scintillator with a cooled complementary metal-oxide semiconductor (CMOS) camera has reached a spatial resolution of 2 μm by using the center of mass calculation of the scintillation events for a reactor neutron source [18]. A high spatial and temporal resolved neutron imager has been developed using a $^{10}$B-doped microchannel plate (MCP) [19] combined with a Timepix readout [20, 21, 22]. It achieves a high spatial resolution of 55 μm with a high time resolution of 10 ns.

In the present work we demonstrate herein a clear imaging of various test specimens, including biological and metal samples over the whole sensor active area of 15 x 15 mm$^2$. A successful energy resolved neutron imaging and observation of a stainless-steel Bragg edge in the neutron transmission are also discussed.

2. Delay-line current-biased kinetic inductance detector

The transient reduction of the Cooper pair density $n_s$ on the superconducting wire can be locally induced at a hot spot by phonon irradiation or collision of the charged particle, and consequently the kinetic inductance in the superconductor exhibits a transient change. When a DC bias current $I_b$ is fed into the superconducting wire, a pair of voltage pulses is generated at the hot spot within a tiny segment of the superconducting wire, and each pulse propagates toward both
Figure 1. (a) Block diagram of the experimental setup for the delay-line CB-KID. X-meanderline and Y-meanderline are orthogonal to each other. The $^{10}$B conversion layer is deposited on the two meanderlines. Bias currents $I_x^b$ and $I_y^b$ are fed to X and Y meanderlines independently by constant voltage sources through 3 kΩ resistors. Pulse signals are detected by a Kalliope-DC readout circuit. (b) A schematic overview of the Gifford–McMahon (GM) refrigerator, detector and test samples setup. The pulsed neutrons were irradiated to the detector through the test samples after traveling the 14 m length neutron beam-line at BL10 of the MLF of J-PARC.

ends of the wire with opposite polarities as electromagnetic waves. We point out that the signal amplitude is not only a function of $n_s$ but also that of $dn_s/dt$. This is a crucial difference with the MKID. Because of ultra fast quasi-particle excitation, $dn_s/dt$ can be sufficiently large, and thus the signal becomes finite even if the superconducting wire remains in the superconducting zero-resistance state at a hot spot. It is in sharp contrast with TES and SNSPD.

Figure 1 (a) shows a schematic of the delay-line CB-KID system. The delay-line CB-KID has two mutually orthogonal meanderlines of the superconducting Nb nanowires on the superconducting Nb ground plane. The meanderlines with the ground plane can be regarded as the superconductor-insulator-superconductor (S-I-S) coplanar waveguides. Therefore, a lower attenuation of the high-frequency traveling waves is expected even in a 151 m-length superconducting waveguide [23]. The signal propagation velocity can be suppressed by placing the superconducting meanderline closer to the ground plane [24]. Therefore, the propagation velocities for orthogonal meanderlines are different from each other. Signal propagation velocities for X and Y meanderlines in the present CB-KID were $v_x = 6.290 \times 10^7$ m/s and $v_y = 5.746 \times 10^7$ m/s, respectively, and thus, the signal transmission time was around 2.5 $\mu$s at most. If we consider the meanderlines as a delay-line, the delay-line CB-KID can image the hot spot distribution on the detector with only four signal leads. The hot spot positions $x$ and $y$ are determined as follows:

$$x = \text{ceil} \left[ \frac{(t_{Ch4} - t_{Ch3})v_x}{2h} \right] p, \quad (1)$$

$$y = \text{ceil} \left[ \frac{(t_{Ch2} - t_{Ch1})v_y}{2h} \right] p, \quad (2)$$

where $h$ is the length of each segment of the meanderline, $p$ is a repetition pitch for the meanderline, $t_{Ch1}$, $t_{Ch2}$, $t_{Ch3}$, and $t_{Ch4}$ are the corresponding time stamps of the signals received at Ch1, Ch2, Ch3, and Ch4, which correspond to the signals propagated toward both ends of the
X (Ch3, Ch4) and Y (Ch1, Ch2) meanderlines [13]. We can estimate a signal generation time from the combination of $t_{Ch1}$ and $t_{Ch2}$ or that of $t_{Ch3}$ and $t_{Ch4}$. If the signal quartet originating from a single event, estimated signal generation times should coincide with each other. By using this criterion, we can identify signal quartet originating from a single event, even though several signals are simultaneously present on the meanderlines [13]. Therefore, the CB-KID has a high multi-hit tolerance up to the temporal resolution limit, where the signals can be discriminated.

Present CB-KID was fabricated on a thermally oxidized Si substrate by depositing six layers, which were sequentially stacked from bottom to top as follows: (1) a 300 nm-thick superconducting Nb ground plane, (2) a 350 nm-thick insulating SiO$_2$ layer, (3) a superconducting 40 nm-thick Nb Y meanderline, (4) a 50 nm-thick insulating SiO$_2$ layer, (5) a superconducting 40 nm-thick Nb X meanderline and (6) a 50 nm-thick passivation SiO$_2$ layer. The X and Y meanderlines of 0.9 $\mu$m width and 15.1 mm segment length were folded 10,000 times with 0.6 $\mu$m spacing ($\rho$=1.5 $\mu$m). The Nb meanderline with two end electrodes was fabricated in the Clean Room for Analog-Digital Superconductivity (CRAVITY) at the National Institute of Advanced Industrial Science and Technology (AIST).

On the top of CB-KID, a $^{10}$B neutron conversion layer was made by painting a mixture solution of GE7031 varnish and $^{10}$B powder with a brush. The nuclear reaction $^{10}$B(n, $^4$He)$^7$Li mainly emitted a $^4$He ion of 1.47 MeV and a $^7$Li ion of 0.88 MeV. Then, one of the projectile ions provides the local energy dissipation to the meanderlines. This method intends to achieve sufficient thickness of the neutron capture layer, but causes the influence of inhomogeneity in the $^{10}$B density in the conversion layer because of the segregation of the GE7031 varnish.

3. Experimental apparatus

The DC bias currents $I^x_b$ and $I^y_b$ were applied by two constant voltage sources through the 3 k$\Omega$ resistors for both meanderlines. The signals from Ch1, Ch2, Ch3, and Ch4 were amplified by a differential ultralow-noise amplifier (SA-430 F5 by NF Corporation), while the negative signals from Ch1 and Ch3 were inverted. The Kalliope-DC readout circuit, which is a 1 ns-sampling multichannel (16 Ch $\times$ 2) time-to-digital converter (TDC), and a 2.5 GHz sampling digital oscilloscope (Teledyne LeCroy HDO4104-MS) simultaneously received positive signals because the positive thresholds for the counting signals in the Kalliope-DC circuit were configured for convenience. The Kalliope-DC was originally developed by Kojima et al for the muon-spin relaxation ($\mu$SR) measurements at the J-PARC facility [25], and was improved to fit CB-KID readout [13].

The experimental apparatus is schematically shown in Fig. 1 (b). The detector and test samples were mounted on the detector stage in the cryostat, and cooled down to 4 K by using a Gifford–McMahon (GM) refrigerator in which the cold head is suspended by silicone rubber feet for vibration isolation. To ensure transparency for the neutron beam, the vacuum can and the main parts of the sample holder were made from Al alloy. The neutron beam was irradiated to the detector from the substrate side through the test samples placed at a distance of 0.8 mm from the detector. Electrical contact springs were used to connect the detector. Neutron-irradiation experiments were performed with pulsed neutrons with the collimator ratio $L/D = 14$ m/0.1 m = 140 at BL10 of the Material and Life science experimental Facility (MLF), J-PARC [26]. The measurement of the neutron flight time to travel the known neutron beam-line length provides the neutron velocity, which proportional to the neutron wave length. This is so-called TOF method. The neutron wave length $\lambda$ is proportional to the TOF and the neutron energy $E$ as $\lambda (\text{nm}) = 28.2556 \times t (\text{sec}) = 0.9044/\sqrt{E} (\text{eV})$ at BL10. The energy resolution was produced by the TOF method through the 14 m flight path with 33 $\mu$s full width at half maximum (FWHM) at 10 meV.
Figure 2. (a) Neutron image without the test samples with a wavelength from 0.052 to 1.13 nm and (b) that after removing the diagonal line of Fig. 2 (a) by image processing. (c) Photograph of the imaging samples of (#1) a spider, (#2) a titanium screw, (#3) a screw of stainless-steel, (#4) a screw of stainless-steel, (#5) a Japanese beautyberry (plant), and (#6) a circuit board. (d) Optical photograph of a neutron absorber of $^{10}$B-dots as a test pattern. It comprises a 50 $\mu$m-thick stainless-steel mesh in which each hole is tightly filled by very fine $^{10}$B particles. (e) Neutron transmission image after correcting for background by dividing the neutron image with test samples by the image of Fig. 2 (b).

4. Results and discussion

4.1. Neutron transmission image of the test samples

The neutron image without the test samples are shown in Fig. 2 (a). The color scale indicates the number of events (NOE). Here, the NOEs from $10 \times 10$ pixels were combined to obtain a high-contrast image. The image was obtained by summing the NOEs with an incident neutron wavelength $\lambda$ ranging from 0.052 to 1.13 nm up to 17.9 h with 395 kW beam power under the detector conditions of $T = 4.0$ K and $I_x = I_y = 0.15$ mA. As discussed above, the neutron conversion layer was not homogeneous enough in the present CB-KID sensor, as evidenced by the irregular pattern seen in Fig. 2 (a). Additionally, a white diagonal line from the upper left to lower right can be seen. We consider this line to be caused by the signal leaks or cross-talks between X and Y meanderlines, as discussed in Ref. [13]. Because of an extrinsic origin, we tried to remove the diagonal line via imaging processing as shown in Fig. 2 (b).

Figure 2 (c) shows a photograph of the test samples of (#1) a spider, (#2) a titanium screw, (#3) a screw of stainless-steel, (#4) a screw of stainless-steel, (#5) a Japanese beautyberry (plant), and (#6) a circuit board. In addition, we superimposed well-shaped $^{10}$B-dot square pattern as a neutron absorber, as shown in Fig. 2 (d). The test absorber comprised a 50 $\mu$m thick stainless-steel mesh, wherein $100 \times 100 \mu m^2$ rounded square holes were arrayed in every 250 $\mu$m. Each hole was tightly filled by very fine $^{10}$B particles.

Figure 2 (e) represents the neutron transmission image with test samples at $0.052 < \lambda < 1.13$ nm after background correction by dividing the neutron image with the test samples by that without samples of Fig. 2 (b). In this image, the NOEs from $10 \times 10$ pixels were combined. Notably, the neutron imaging with test samples was performed about two months before the measurement without samples and had no diagonal line, implying that the diagonal line appeared because of the degradation of the Nb meanderlines of the detector. As shown in Fig. 2 (e),
Figure 3. (a) The histogram of the number of events (NOE) as a function of time of flight (TOF) or wavelength $\lambda$. Blue dashed lines correspond to the imaging wavelengths of $\lambda = 0.3\,\text{nm}$, $0.5\,\text{nm}$, $0.7\,\text{nm}$, $0.9\,\text{nm}$, and $1.1\,\text{nm}$. Neutron transmission images for several different wavelengths (b) $0.294\,\text{nm} < \lambda < 0.300\,\text{nm}$, (c) $0.492\,\text{nm} < \lambda < 0.503\,\text{nm}$, (d) $0.689\,\text{nm} < \lambda < 0.704\,\text{nm}$, (e) $0.887\,\text{nm} < \lambda < 0.907\,\text{nm}$ and (f) $1.085\,\text{nm} < \lambda < 1.108\,\text{nm}$.

The plant fruit, three screws, spider, and $^{10}$B-dot pattern are well identified, demonstrating the capability of neutron transmission imaging for organic and metal samples by the CB-KID. Moreover, an internal structure of the two stainless-steel screws (#3 and #4) and the seeds of berry (#6) can be seen. No such additional structure appears in the Ti screw (#2) even though these screws have a similar shape. Therefore, the additional structure observed in stainless-steel screws may reflect a difference of the microstructure of stainless-steel between the inside and surface of screws.

As mentioned earlier, we succeeded in imaging the test objects of interests over the $15\times15\,\text{mm}^2$ size using the CB-KID. While irregular patterns which come from the inhomogeneity in the neutron conversion layer still remained visible.

4.2. Energy-resolved neutron transmission imaging

The TOF or $\lambda$ distribution of NOEs corrected at the detector area without sample is shown in Fig. 3 (a), and is in good agreement with that of the neutron flux [27]. Figures 3 (b)–(f) present the neutron transmission imaging of the test patterns corresponding to each $\lambda$ as discriminated by the dashed lines in Fig. 3 (a) with the width of $\Delta\lambda/\lambda \simeq \pm 1\%$. In these images, the NOEs from $10\times10$ pixels were combined for clarity. Even in limited neutron energy range, samples can be confirmed in wide $\lambda$ range, demonstrating the capability for energy resolved neutorn imaging by the combination of the delay-line CB-KID and Kalliope-DC readout circuit.
Figure 4. (a) Neutron transmission image for the stainless-steel screw (sample #3) and (b) corresponding transmission in the area surrounded by a solid line on an image, together with a simulation curve with the Miller indices. (c) Stainless-steel enhanced image obtained by dividing the neutron transmission image with wavelengths shorter than 111 Bragg edge by those longer than 111 Bragg edge.

4.3. Material analysis using Bragg edge
Figure 4 (a) shows the superimposed image of the stainless-steel screw (sample #3). The neutron wavelength dependence of the transmission was computed by summing NOEs in the area surrounded by a solid line on Fig. 4 (a), and is represented in Fig. 4 (b) together with the simulation curve with the Miller indices. Notably, the metal mesh of the stainless-steel was not attached during neutron imaging measurements without sample; however, it was installed during neutron imaging measurements with the test samples. The 111 stainless-steel Bragg edge was clearly observed, as shown by arrow in Fig. 4 (a). A finite, but distinct 200 Bragg edge also arises. Figure 4 (c) shows the image which was obtained by dividing the neutron transmission image with a wavelength shorter than 111 Bragg edge (0.390 nm < λ < 0.401 nm) by that with a wavelength longer than 111 Bragg edge (0.423 nm < λ < 0.434 nm). As shown in Fig. 4 (c), only stainless-steel screws are clearly observed, because the steep dip on the transmission by the 111 Bragg edge reinforces the stainless-steel sample images whereas images of other samples with no distinct change at around λ = 0.41 nm weaken by division.

5. Summary
In this study, we demonstrated that the delay-line CB-KIDs combined with the Kalliope-DC readout circuit can be used for not only high spatial resolution neutron imaging for various shapes and materials with wide wavelength range beam but also wavelength (energy) resolved neutron imaging and Bragg edge analysis in combination with the TOF method in the pulsed neutrons from the MLF facility of J-PARC. Neutron transmission images were clearly observed over the whole sensor area of 15 × 15 mm², thanks to successful fabrication of 151 m-length 0.9 μm width X and Y meanderlines without any disconnection. Further improvement of the fabrication method of the homogeneous 10B-conversion layer is required. Nonetheless, the CB-KID has potential as a unique two-dimensional superconducting imager.

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