Neutron Imaging for Intermetallic Alloy using a Delay Line Current-Biased Kinetic-Inductance Detector

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Abstract. The current-biased kinetic-inductance detector (CB-KID) is a solid-state superconducting neutron detector with high spatial and temporal resolutions, and multi-hit tolerance. We demonstrate high temperature operation of CB-KID at 7.9 K with the delay-line method. High temperature operation reduces imaging pixel size by suppressing signal propagation velocity. High spatial neutron transmission image for a mixed metal alloy consisting of heavy elements Sm and Sn is successfully constructed. We also examine the capability of element discrimination imaging based on the resonance dip analysis.

1. Introduction
Superconducting detectors have been recognized as the most important and successful applications in the superconducting devices [1, 2, 3, 4]. The kinetic inductance of superconducting resonators can be probed through a readout line coupled electromagnetically to a microwave resonator. Therefore, the kinetic inductance change induced by the Cooper pair...
breaking by radio wave irradiation in a resonator is detected by a resonance frequency change. This is the operating principle of microwave kinetic conductance detectors (MKID) [2, 3].

Superconducting nanowire single photon detectors (SNSPD) have been known as high-performance single photon detectors [4]. The SNSPD, consisting of a meanderline of the superconducting nanowire, is biased by a DC current just below the critical current $I_C$. When the Cooper pairs are destroyed by an irradiated photon, a normal region is induced in the meanderline with the aid of the Joule heating. This transient change induced by the photon incident event is detected as a voltage signal at the end of meanderline.

Applicabilities of superconducting detectors are not only for electromagnetic waves but also for other particle beams such as neutrons. Transition edge sensors (TES) are a kind of bolometer [1], and can be applied to a neutron detector by combining a B neutron absorption layer [5]. Two superconducting tunnel junctions on a single crystal of Li$_2$B$_4$O$_7$ with a neutron-converter layer $^6$Li or $^{10}\text{B}$ were also proposed as a neutron detector [6, 7].

The current-biased kinetic-inductance detector (CB-KID) is a unique superconducting neutron detector [8, 9, 10, 11, 12, 13, 14]. The CB-KID has meanderlines of the superconducting microstriplines and a $^{10}$B neutron conversion layer. DC bias currents are fed to meanderlines to detect a transient change of the kinetic inductance induced by Cooper pair breaking as voltage pulses. While the device structure of the CB-KID is very similar to that of SNSPD, there is a crucial difference in the magnitude of the DC bias current: that for CB-KID is quite lower than that for SNSPD. We mention a notable difference between the MKID and CB-KID. The MKID measures the total kinetic inductance of superconducting resonators, but the CB-KID senses the time derivative of local kinetic inductance. This difference allows the CB-KID to operate at high frequency.

We succeeded in achieving the spatial resolution of 16 $\mu$m with a pulsed neutron source by the combination of delay-line method (delay-line CB-KID) [12]. Concomitantly, neutron energy resolved imaging via the the time-of-flight (TOF) method in the pulsed neutron source also demonstrated. Energy resolved imaging provides further internal information of materials, such as nuclide distributions, crystal structures, and single crystallinity. Recent developments of intense pulsed neutron sources stimulate demand for high spatial and temporal resolution neutron imagers.

Although the center of mass correction for distribution of photon counts was applied, the highest spatial resolution of 2 $\mu$m was achieved with a reactor source using a gadolinium-oxy sulfide scintillator [15]. It is, however, difficult to applied the energy resolved imaging with a pulsed neutron source due to the lack of temporal resolution. A $^{10}$B-doped microchannel plate was reported to act as a high spatial resolution and a high energy resolution neutron imager [16, 17]. A high spatial resolution of 55 $\mu$m with a high time resolution of 10 ns was achieved without the center of mass correction in a pulsed neutron source. The delay-line CB-KID achieved higher spatial resolution without conducting center of mass correction. Therefore, the resulting image does not contain any uncertainty due to the numerical calculation of the center of mass correction.

In the delay-line CB-KID, meanderlines function not only as a detector but also as a delay-line for signals, so that two dimensional high-resolution imaging can be performed by reading only four signals. The delay-line method was also applied to a single photon imager based on the SNSPD [18].

A resonance dip, which denotes a dip structure caused by the resonance structure in the neutron-induced reaction cross sections, appears in the neutron transmissions as a fingerprint of an isotope through a resonance absorption of neutrons. An elemental imaging technique based on resonance dip named neutron resonance transmission imaging (NRTI) has been applied to mainly historical heritages [19, 20]. For the NRTI, a combination of a pulsed neutron source and high energy resolved, namely high temporal resolved neutron imager is required.
It was demonstrated that the neutron detection efficiency of the CB-KID was improved with increasing the operating temperature [13]. In addition, signal propagation velocities along meanderlines of the CB-KID are suppressed from $v_x = 8.778 \times 10^7$ m/s ($v_y = 7.278 \times 10^7$ m/s) at 4 K to $5.981 \times 10^7$ m/s ($4.544 \times 10^7$ m/s) at 7.9 K. Suppressing the signal propagation velocity reduces the maximum pixel size of the neutron transmission image from $4.5 \mu m \times 4.5 \mu m$ to $3 \mu m \times 3 \mu m$. Despite these advantages, the neutron imaging by the delay-line CB-KID was previously performed at 4.0 K [11, 12, 14].

In the present work, signal properties of CB-KID at high temperature of 7.9 K are discussed. We also demonstrate high spatial resolution neutron transmission imaging, resonance dips in the transmission and element discriminative imaging of a mixed metal alloy consisting of heavy elements Sm and Sn.

2. Experimental methods

2.1. Delay-line current-biased kinetic inductance detector

The delay-line CB-KID consists of the superconducting Nb ground plane, two mutually orthogonal superconducting Nb meanderlines and a $^{10}$B neutron conversion 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. Therefore, a repetition pitch $p$ and the total length $l$ for the meanderline are $p=1.5 \mu m$ and $l=151 \mu m$, respectively. This device was fabricated in the Clean Room for Analog-Digital Superconductivity (CRAVITY) at the National Institute of Advanced Industrial Science and Technology (AIST). A $^{10}$B layer with 70 nm thick was deposited by an electron beam deposition technique under ultra high vacuum.

Nuclear reaction between a $^{10}$B nuclei and an incident neutron at the neutron conversion layer creates charged particles ($^7$Li-particle and $\alpha$-particle). One of them may hit $x$ and $y$ superconducting meanderlines, and thus a transient reduction of the Cooper pair density $n_s$ occurs locally at the hot spot. A local transient reduction of $n_s$ induces a transient change in local kinetic inductance. When a DC bias current $I_b$ is fed into the meanderline, a pair of voltage pulses is generated at the hot spot, and each pulse propagates toward both ends of the meanderline as electromagnetic waves. A voltage $V$ across the hot spot is expressed as follows:

$$ V = I_b \frac{dL_0}{dt} \approx I_b \frac{dL_k}{dt} = - \frac{m_s \Delta l I_b}{n_s q_s^2 S} \frac{dn_s}{dt}, $$

where, $L_0$ is the total inductance; $L_k$ is the kinetic inductance; $\Delta l$ and $S$ are the hot spot length and cross-sectional area of the superconducting wire, respectively; and $m_s$ and $q_s$ are the effective mass and electric charge of the Cooper pair, respectively.

The meanderlines with the ground plane can be regarded as the superconductor-insulator-superconductor (S-I-S) coplanar waveguides, and thus can transmit the high frequency waves with lower attenuation even after 151 m-long traveling [21]. The meanderlines act as not only a superconductor (S-I-S) coplanar waveguides, and thus can transmit the high frequency waves effective mass and electric charge of the Cooper pair, respectively.

The meanderlines and the corresponding time stamps of the signals received at Ch1, Ch2, Ch3, and Ch4; and $v_x = 5.981 \times 10^7$ m/s and $v_y = 4.544 \times 10^7$ m/s are signal propagation velocities for X and Y meanderlines, respectively at $T=7.9$ K in the present CB-KID. Because the Y meanderline was placed closer to the ground plane, $v_y$ was slower than $v_x$, as predicted [22].

$$ x = \text{ceil} \left[ \frac{(t_{Ch4} - t_{Ch3})v_x}{2h} \right] p, \quad y = \text{ceil} \left[ \frac{(t_{Ch3} - t_{Ch1})v_y}{2h} \right] p, $$

where $h$ is the length of each segment of 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; and $v_x = 5.981 \times 10^7$ m/s and $v_y = 4.544 \times 10^7$ m/s are signal propagation velocities for X and Y meanderlines, respectively at $T=7.9$ K in the present CB-KID. Because the Y meanderline was placed closer to the ground plane, $v_y$ was slower than $v_x$, as predicted [22].
We can estimate a hot spot emerging time $t_0$ from the combination of pair channels ($t_{Ch1}$ and $t_{Ch2}$ for Y meanderline, and $t_{Ch3}$ and $t_{Ch4}$ for X meanderline) as follows:

$$t_0 = \frac{t_{ch4} + t_{ch3}}{2} - \frac{l}{2v_x} = \frac{t_{ch2} + t_{ch1}}{2} - \frac{l}{2v_y}.$$  \hspace{1cm} (3)

If $t_0$ coincides with each other in the X and Y meanderlines, we reasonably conclude that the selected signal quartet originates from a single event. Coincidence of $t_0$ in both meanderlines is a powerful criterion to identify signal quartet originating from a single event even when several different-event signals simultaneously present on the meanderline. Therefore, the delay-line CB-KID has a high multi-hit tolerance in contrast with other sorts of detectors. More detailed detector structure and principle were described elsewhere [11].

### 2.2. Preparation for a Sm-Sn mixed metal
We prepared Sm-Sn mixed metal in which SmSn$_3$ single crystals were distributed in a Sn ingot. SmSn$_3$ is an antiferromagnet with the Néel temperature of 12 K [23, 24]. Single crystals of SmSn$_3$ were grown by the Sn-flux method. Starting materials of Sm and Sn with the atomic ratio of 1:9.2 were sealed in a quartz tube under Ar atmosphere. This tube was heated up to 950°C and cooled down to 200°C with the cooling rate of 10°C/h. The platelet specimen of thickness $\sim$0.5 mm for the neutron imaging experiments was cut from the ingot.

### 2.3. Cryogenic and signal measurement systems
The delay-line CB-KID was cooled down to 7.9 K with test samples by using a Gifford-McMahon (GM) refrigerator in which the cold head is suspended by silicone rubber feet for vibration isolation. Test samples were pasted on an Al plate by epoxy adhesive, which placed at a distance of 0.8 mm from the detector. The detector temperature was controlled by a temperature controller (Model 44 by Cryogenic Control Systems Inc.). The vacuum can and the main parts of the sample holder were made of Al alloy, which is almost transparent to neutron beams. Neutron beam was irradiated to the substrate side of the detector through the samples.

The DC bias currents for X and Y meanderlines were fed at $I_x^b=I_y^b=15$ μA. The signals from four channels were amplified by ultra-low-noise differential amplifiers (SA-430 F5 by NF Corporation), while the negative signals (Ch1 and Ch3) were inverted to positive polarity. Therefore, the Kalliope-DC readout circuit, which is a 1 ns-sampling multichannel (16 Ch $\times$ 2) time-to-digital converter [11], and a 2.5 GHz sampling digital oscilloscope (Teledyne LeCroy HDO4104-MS) simultaneously received a quartet of positive signals.

### 2.4. Neutron imaging
Neutron imaging experiments were performed with pulsed neutrons at BL10 of the Material and Life science experimental Facility (MLF), J-PARC [25]. Neutrons traveled from the moderator to the detector through the 14 m beam-line, where the time of flight (TOF) is proportional to the neutron wavelength $\lambda$ as $\lambda (\text{nm}) = 28.2556 \times t (\text{sec})$ at BL10. The neutron energy $E$ is represented as $E (\text{meV}) = 0.8179/\lambda^2$. The resolution of TOF is 33 μs full width at half maximum (FWHM) for 10 meV neutrons. Imaging experiments performed by choosing the collimator ratio $L/D=140$ under beam power of 589 kW. The neutron beams were irradiated to the detector from the substrate side through the test sample.

### 3. Results and discussion

#### 3.1. Detected voltage signals
A typical detected signal quartet is shown in Fig. 1(a). A sharp positive peak followed by a wider negative peak can be seen in each channel. Negative peaks gradually approach to zero with the
relaxation times of about 0.3 μs. Sharp positive peaks are induced by transient reductions of the Cooper pair density caused by neutron incident events. Negative peaks may correspond to a recovery of Cooper pairs by recombinations (see Eq. (1)).

The neutron incident event occurred at  \( t_0 \) and voltage pulses traveled to both ends through meanderlines. As discussed in Eqs. (2), one can estimate the hot spot position by differences of traveling times between paired channels (Ch1 and Ch2 for \( Y \)-meanderline, Ch3 and Ch4 for \( X \)-meanderline). For example, when voltage signals for Ch3 and Ch4 were detected almost at the same time, we recognize that the neutron incident position was almost at the center of \( X \)-meanderline.

![Figure 1](image1.png)

**Figure 1.** (a) A typical detected signal quartet at 7.9 K. The hot spot emerging time \( t_0 \) was calculated by Eq. (3) from the signal detection times \( t_{\text{Ch1}}, t_{\text{Ch2}}, t_{\text{Ch3}} \) and \( t_{\text{Ch4}} \). (b) The two dimensional histogram of signal peak voltages \( V_{\text{peak}} \) and full width at half maximum (FWHM) of signals for Ch1 at 7.9 K.

![Figure 2](image2.png)

**Figure 2.** (a) The SEM image and (b) neutron transmission image of the Sm-Sn mixed metal sample.
Figure 1(b) shows the distribution of signal peak voltages $V_{\text{peak}}$ and FWHM of signals for Ch1 at 7.9 K. The number of events (NoE) increases abruptly with approaching $V_{\text{peak}}$ to zero, as reported previously [13]. FWHM slightly expands with increasing $V_{\text{peak}}$, while 95% of events range in between 17 and 50 ns. From the FWHM, we can estimate the theoretical limit of detection rate tolerance to be several tens of MHz. This is the same order of magnitude with that at 4 K [12] even though the temperature increased up to 7.9 K.

3.2. Neutron transmission image of SmSn$_3$

The SEM image of the Sm-Sn mixed metal sample is shown in Fig. 2(a). As shown in figure, SmSn$_3$ crystals are well identified by the color difference from Sn ingot (light gray in color), while only the morphology on the surface can be seen. The neutron transmission image of the sample at $0.052 < \lambda < 1.13 \text{ nm}$ is shown in Fig. 2(b). The NoE all over the sample was corrected for 72.6 hours, and is represented in color scale. The yellow colored areas, in which NoEs are much less than those in dark areas, correspond to the SmSn$_3$ single crystals. Facets of each single crystal of SmSn$_3$ as well as distribution of crystals in the specimen are clearly seen in Sn ingot thanks to large neutron absorption cross section of Sm nuclei. The strong permeability of neutron beams for many heavy metals is a significant advantage of neutron imaging, as demonstrated in Fig. 2(b).
Figure 3(a) shows the zoomed image for a part of Fig. 2(b). There are no SmSn₃ single crystals in the area surrounded by the solid line (area-1) in Fig. 3(a). The area surrounded by the broken line (area-2) in Fig. 3(a) is filled by a SmSn₃ single crystal. The neutron wavelength \( \lambda \) dependence of the number of transmitted neutrons calculated by summing NoEs in the area-1 was assumed as a background, which contains wavelength dependence of the neutron flux and absorption by the vacuum can, sample holder and Sn. The neutron transmission through the SmSn₃ single crystal was calculated by dividing the normalized number of transmitted neutrons of area-2 by those of area-1, and is represented in Fig. 3(b). The neutron transmittance shows a significant decrease above around \( \lambda = 0.06 \text{ nm} \), which is consistent with the steep increase of the neutron absorption cross section for \(^{149}\text{Sm}\). Moreover, resonance dips indicated by arrows in Fig. 3(b) distinctly indicate the absorption of neutrons by \(^{152}\text{Sm}\) and \(^{149}\text{Sm}\) in the SmSn₃ single crystal [26]. Figure 3(c) shows the neutron transmission obtained by dividing the number of transmitted neutrons of area-3 shown by the dot in Fig. 3(a), by that of area-1. As shown in Fig. 3(c), resonance dips shown by arrows (significant decrease) are clearly seen even though the size of area-3 is as small as 12 \( \mu \text{m} \times 9 \mu \text{m} \).

Figures 3(d) and (e) show neutron transmission images with a wavelength at the resonance dip of \( \lambda = 0.01 \text{ nm} \) and in between resonance dips of \( \lambda = 0.02 \text{ nm} \), respectively. In these images, the NoEs from 4 \times 4 pixels were combined over a wavelength range of 0.001 nm. Even in the limited wavelength range, SmSn₃ single crystals are clearly observed thanks to the resonance dip of \(^{152}\text{Sm}\). On the other hand, no SmSn₃ single crystals are identified in Fig. 3(e) because of a weak neutron absorption by Sm at \( \lambda = 0.02 \text{ nm} \). These results indicate the capability for NRTI with high spatial resolution by the delay-line CB-KID.

4. Summary
In conclusion, we demonstrated that the delay-line CB-KID can be used for high spatial resolution neutron transmission imaging in mixed metal Sm-Sn alloy which consists of heavy metals, at high operating temperature of 7.9 K. Moreover, element discriminative imaging by NRTI technique was demonstrated in combination with the TOF method with pulsed neutrons from the MLF facility of J-PARC. The delay-line CB-KID has a potential for applying the neutron non-destructive inspection of metal products with high spatial resolution, e.g. research of crystal growth process, crystallographic analysis, and corrosion of metals.

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