Neutron signal features of Nb-based kinetic inductance detector with $^{10}$B convertor

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Abstract. In our preceding works, we demonstrated successful neutron detection using a superconducting current-biased kinetic inductance detector (CB-KID), which is composed of two Nb-based superconducting meanderlines and the $^{10}$B neutron absorption layer. The CB-KID with a $^{10}$B absorption layer outputs the voltage pulses when it is irradiated by pulsed neutrons. We expected that the voltage $V$ is proportional to a product of the bias current $I_b$ and a time derivative of the local kinetic inductance $\Delta L_k/dt$, and a pair of signals propagate along the Nb stripline as an electromagnetic wave at a certain fraction of the light velocity $c$ toward end electrodes. It still remains to be revealed why the signal voltage shows such a continuum in the histogram of the signal height even if the incident energy of the light ion is apparently monochromatic. In the present work, we investigated the distribution of the height and width of the signal. We found a clear correlation between height and width, which might be a key of understanding the operating principle of our detector. We consider that the origin of the signal distribution is due to the positional dependence of the light ion bombardment with respect to the meandering Nb nanowire.

1. Introduction
Neutron beam has attracted a great deal of interests in view of fundamental researches and various useful applications in recent years. For example, neutron diffraction is a standard technique to determine the atomic or magnetic structure of new materials. It serves as a powerful tool in examining crystal structures in drug-development research and material sciences [1]. We can also observe the dynamics of carbons and water molecules in operating fuel cell and hydrocarbons in operating engine [2]. However,
spatial resolution is still not satisfactory enough to satisfy various needs. It typically remains on the sub-millimetre scale with the use of conventional neutron detectors such as a miniaturized gas counter [3] although it becomes on the scale of several tens µm in high-end neutron detectors such as a detector using a micro channel plate and optical readout [4]. Much faster response time is desired for counting high-intensity neutron beam for more effective use of neutrons. We developed a superconducting detector for sensing neutrons with high-spatial resolution and fast response time, and first succeeded in detecting the neutrons using an MgB2 thin film in our preceding works [4-6]. We also developed a superconducting neutron detector using a Nb-based current-biased kinetic inductance detector (CB-KID) with a 10B conversion layer [7-10]. Choosing Nb has an advantage in a fabrication process because it has been established well in the long history of superconductive electronics. Hence, Nb devices have merits to build them rather reproducibly using a service from a superconductive foundry. There is the reason why the response time of a CB-KID is very fast compared to other superconducting detectors. It depends on an excitation time from Cooper-pairs to quasi-particles in a superconductor, but is not sensitive to the recombination processes from quasiparticles to the Cooper pairs. The latter process includes the phonon-mediated electronic processes, and could be rather time consuming to complete the recombination. The electronic relaxation time of Nb is not so fast compared to other superconductors, but it would not be demerits of using Nb to fabricate the CB-KID since it does only see the earlier process of the Cooper-pair breaking.

Our detector is rather new and under development, and the details of the operating mechanism of CB-KID are not elucidated thoroughly to date. In this paper, we show the systematic investigation of the characteristic features of the signals from a neutron detector CB-KID to understand the operation.

2. Delay-Line Current-Biased Kinetic Inductance Detector

2.1. Operation Principle of CB-KID
A CB-KID consists of superconducting Nb-based meanderline. Figure 1 is a schematic diagram of CB-KID structure for providing imaging function. The CB-KID of an effective area 15 mm × 15 mm on a single Si chip (22 mm × 22 mm) is cooled to a temperature below a critical temperature $T_c$, and is usually operated at 4 K under a constant DC bias current $I_b$. When a mesoscopic portion of the meanderline exhibits an abrupt reduction in the density of the Cooper pairs, a transient change occurs in the local kinetic inductance $\Delta L_k = \frac{m_s \Delta \rho}{n_s q^2}$ of a hot spot candidate, where $m_s$ is the effective mass of a Cooper pair, $q_s$ is the effective electric charge of a Cooper pair, $n_s$ is the Cooper pair density, $\Delta \rho$ is the length of the local hot spot candidate, and $S$ is the cross-sectional area of the Nb wire. A temporary change in $L_k$ generates a voltage $V$ across the Nb nanowire expressed as follows:

$$V = R I_b + \frac{d(L_m + L_k + \Delta L_k) I_b}{dt} \approx I_b \frac{d(\Delta L_k)}{dt}$$

Since the magnetic inductance $L_m$ is described as $L_m = \mu l / 4 \pi$, $L_m$ does not alter with time. The factor $dl/db/dt = 0$ is kept as far as the detector is kept in the superconducting state. The kinetic inductance $L_k$ of the entire nanowire of length $l$ is $L_k = m_s \rho / n_s q^2$, where we intend to exclude a tiny portion from the total length $l$ to estimate the kinetic inductance $L_k$ as a candidate of a possible hot spot. The response signal of CB-KID is supposed to be very fast because it depends on the time differentiation of Cooper pair density. The output voltage of CB-KID is proportional to $I_b$, and the output voltage can be tuned at a desired level by adjusting $I_b$. We produced a neutron detector using Nb-based CB-KID coated with 10B absorption layer.
Figure 1. Schematic diagram of a CB-KID structure for imaging. The $^{10}$B absorption layer is deposited on top of double Nb meanderlines.

Figure 2. Diagram of signal generation and propagation along the stripline of CB-KID with a pitch $p$. A positive signal propagates toward the upstream of the DC bias current while it is reversed toward the downstream of the current.

2.2. Delay-line CB-KID

We describe the principle of delay-line CB-KID. In the delay-line CB-KID, the position of neutron nuclear reaction is detected from a time difference of the travelling signal caused by irradiating pulse neutrons on the $^{10}$B layer. Figure 2 shows a hot spot on the Nb nanowire (stripline) and the signal transmission along the stripline. The signal is caused by the hot spot when the stripline is biased by the DC current while the hot spot is caused by the nuclear reaction between $^{10}$B and neutron. The nuclear reaction $^{10}$B(n, $^4$He)$^7$Li mostly releases a $^4$He particle of 1.47 MeV and a $^7$Li particle of 0.88 MeV, and the local energy dissipation of each projectile is used to create a hot spot on the Nb nanowire stripline of the detector. When energy is added to the superconducting Nb meanderline, the Cooper pair density decreases locally. This leads to a generation of a pair of pulsed voltage signals according to equation (1), of which the sign (polarity) is dependent on the current direction. Each voltage signal propagates to both ends of the meander line as a pair of electromagnetic wave packets. Since the fractional lengths of the striplines, on which the signals move, are different from each other, the arrival timestamps of the signals at both ends are also different from each other. From the difference in the arrival timestamps of the signals at both ends of the meander line, we can calculate the position of the hot spot as

$$\chi = \frac{\Delta t \cdot p}{2 \cdot L} \cdot \frac{v_x}{v_x},$$

on the basis of the ceiling function of $x$ in units of the segment length $L$ and a pitch $p$ of line and space. Our system is able to identify a position of a local meso-excitation from a difference in arrival timestamps of the two signals of opposite polarities. This means that only four readout channels are enough to conduct a large area imaging, and is in marked contrast with the exiting other techniques.

3. Experimental principle and setup

Our neutron detector was cooled down to a temperature below $T_c$ of Nb using a 4K Gifford–McMahon (GM) refrigerator. The signal was amplified by an ultra-low-noise amplifier (NF SA-430 F5) and was detected by a 2.5GHz sampling digital oscilloscope (Teledyne LeCroy HDO4104-MS). Neutron irradiation experiments were performed with the pulsed neutrons at the beam line BL10 in J-PARC. Figure 3 shows a schematic diagram of experimental setup. The cryostat has an anti-vibration mechanism to prevent the detector from mechanical displacements to ensure high resolution measurements. The whole system is controlled by the LabVIEW program on the windows OS. We store the whole waveform signals to perform data analyses after completing the data acquisition.
Figure 3. Schematic diagram of the experiment setup of neutron irradiation using CB-KID. The voltage across the sensor is amplified by a low-noise amplifier, and is observed by a digital oscilloscope.

4. Experimental Results
Figure 4 shows the typical output waveforms from detectors when the nuclear reaction event occurs by an incident neutron under the conditions of $T = 4$ K and $I_b = 150 \mu$A. Figure 4(a) is a typical quartet set of output waveforms from the $XY$ detectors. The negative polarity signal is inverted by a differential amplifier. Fig. 4(b) is an enlargement of one of the signals of Fig. 4(a), where the peak voltage is 41.2 mV, and the full width at half maximum is 12.4 ns.

To clarify the signal characteristics of CB-KID, we focus on the peak voltage of the signal and full width at half maximum (FWHM). We investigated the distribution of the peak voltage and full width at half maximum of signals. Figure 5(a) shows the histogram of the peak voltage and Figure 5(b) shows the histogram of FWHM. These results are obtained by analysing 3,792,600 event signals. Despite of the energy for generating the mesoscopic excitation in the stripline is monochromatic determined by the $Q$ value of the nuclear reaction, distribution of signal height and width is rather continuum. We consider that the origin of the signal distribution is due to the positional dependence of the meso-excitations with respect to the Nb stripline and the time-derivative dependent feature on the kinetic inductance. Especially, the logarithmic representation of the number of signals follows the linear relation, remarkably. This is a key to explain the origin of distribution in signal amplitude. However, the full width at half maximum seems to show the double components in the semi-logarithmic representation. The origin of the double components are not clear yet at this moment. We consider that it might be relevant to the fact whether a hot spot extends to the multiple Nb nanowires or not. If it were relevant to the multiple wires, the phonon processes must be involved in transferring the local excitations to the next. This may results in a prolonged elementary process of generating signal in addition to a short-time component. Detailed measurements of scanning a focused pulsed laser spot on the delay-line CB-KID would be useful to judge the validity of the present tentative explanations. The correlation between the height and width of the pulsed signals might be useful to discriminate the signals from noises while the detailed mechanism remains to be explored in our future work.
Figure 4. The typical output waveforms of detectors in detecting neutrons. These output signals are amplified by the amplifier with the gain of 46 dB. (a) A typical quartet set of output waveforms from the XY detectors. (b) One of the signals of Fig. 4(a) shows a pulse width of 12 ns and a pulse height of 41 mV.

Figure 5. (a) The histogram of the peak voltage of signals. The bin width of voltage $\Delta V_p$ is 1 mV. (b) The histogram of the full width at half maximum of signals. The bin width of FWHM $\Delta \tau_p$ is 0.8 ns.
5. Conclusion
We investigated the characteristic features of a novel imaging system [6-10] proposed by our group on the basis of delay-line CB-KID method. Experimental observations of pulsed neutron signals from CB-KID with 10B conversion layer were conducted systematically at the beam line (BL10) of Materials and Life Science Experimental Facility (MLF) of J-PARC. The CB-KID detects a neutron, and the response time of the signal is very fast on the order of tens of nanoseconds, and is much faster than other existing neutron detectors. We investigated the distribution of height and width of the output signals from neutron irradiation. The height and width of the signal formed continuum distribution in histograms and have a clear correlation between signal height and signal width. The correlation of signal might be a key of understanding the operating principle of our detector. Detailed origin of the observed profiles is not clear yet at this moment, but we plan to investigate a positional dependence of mesoscopic excitations with respect to nanowire stripline in our future work.

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