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Absorber-coupled lumped element kinetic inductance detectors for gamma-rays

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ABSTRACT

We propose gamma-ray detectors based on superconducting resonators that can be largely multiplexed and show potential for quick response time, high spatial resolution, and high energy resolution. The resonators were fabricated with a niobium film on a silicon wafer. Eight out of ten detectors could be operated at 0.3 K. The detectors were coupled to a 2-mm-thick lead absorber and examined with a cesium 137 source. The pulse decay time was 3.6 µs and energy resolution was 3.8 keV at 662 keV. We also describe the resonant properties of each detector. The proposed detectors are suitable for use as food-screening systems.

1. Introduction

Many types of systems for monitoring the level of radioactive substances, such as cesium 137 (^{137}Cs) and cesium 134, in food have been developed to ascertain whether food is safe for consumption [1]. Such a system is required to determine, as quickly as possible, whether the quantity of radioactive materials contained in food is less than 100 Bq/kg. For quick detection, wide-area and high-efficiency detectors are needed. In addition to a quantitative test, array detectors are also required to determine the spatial distribution of radioactive substances. The data of the spatial distribution with high energy resolution are applied to examine the half-life of the radioactive substance in vivo for food items such as fish. It is also important to distinguish which radioactive materials exist, for the high energy resolution. Scintillation detectors have the advantages of large area and good efficiency, but they usually have low spatial resolution. On the other hand, semiconductor-based detectors show high energy resolution but with small detection areas. Absorber-coupled superconducting detector arrays are useful for high-spatial-resolution, high-energy-resolution, and large-area gamma-ray cameras, which can be applied as food-screening systems. There exist several types of gamma-ray cameras based on superconductors, such as superconducting tunnel junctions [2], transition edge sensors [3,4], and detectors based on superconducting resonators called microwave kinetic inductance detectors (MKIDs) [5]. To develop a high-spatial-resolution gamma-ray camera, we decided to take advantage of the MKIDfs features that are suitable for a large format array, such that the resonators are easily fabricated with a few photolithographic processes, the yield of the resonators is more than 90%, and hundreds of superconducting resonators can be biased with a single readout line to be read out together with frequency multiplexing. Furthermore, the MKIDs have a potentially high energy resolution of 0.55 keV at 30 keV [6]. MKIDs are widely used in various applications, particularly astronomical observations [7]. An X-ray MKID camera has been proposed in Ref. [8]. Furthermore, phonon-mediated lumped-element kinetic inductance detectors (LEKIDs) are good candidates for particle detection and neutrino experiments [9]. Between the two types of MKIDs we selected, LEKIDs [10] are chosen as the sensors of our gamma-ray camera because LEKIDs have a wide inductance area that is easily coupled to an absorber. Although the equivalent circuit of the resonator is composed of an inductor and a capacitor, only the inductance part is sensitive to signals. When the Cooper pairs in the inductor are broken by a photon, phonon, or heat, the surface inductance of the resonator changes and the resonant frequency of the resonator decreases. Therefore, we perceive signal events by monitoring the resonant frequency shifts. In our camera, gamma rays first excite phonons in a lead absorber; subsequently, the phonons reach the detector and break Cooper pairs in the resonator. In other words, our LEKIDs work as phonon-mediated detectors. We developed niobium (Nb)-based LEKIDs coupled to an absorber. As an initial test, the proposed camera was measured

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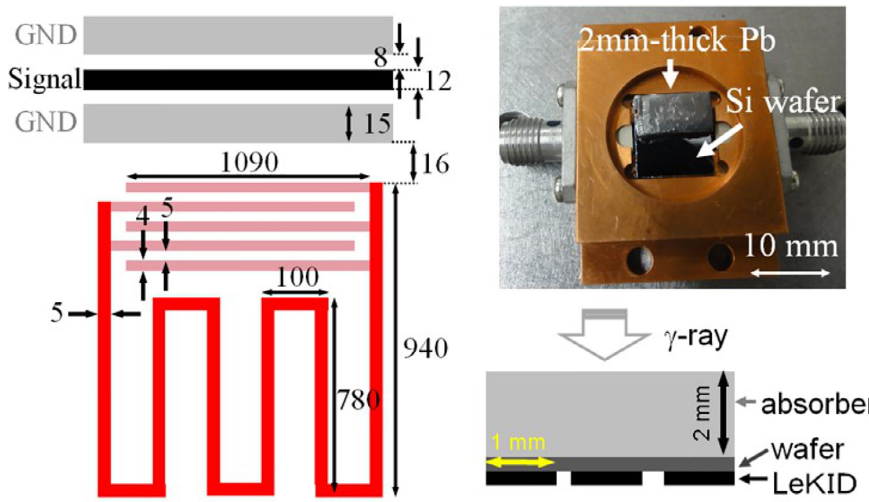

Fig. 1. (left) Schematic illustration of a resonator. Dimensions are not equally scaled in width and height. The number of meanders of the inductor has been reduced for clarity. (right top) Gamma-ray camera installed to a copper sample box. A lead absorber is glued on the top half of the wafer. (right bottom) Cross section of the camera. Gamma rays are incident from the absorber side. Phonons created in the absorber change the resonant frequency of the LEKID.

in a 0.3 K sorption cryostat to improve the detectorsf performance, although niobium-based LEKIDs have been reported to operate at 4.2 K [11]. To demonstrate proof-of principle of the proposed detectors, we report on both the resonator properties and responses against gamma-ray photons at 662 keV, such as pulse signals and an energy spectrum.

The design and fabrications are described in Section 2, and measurement set-ups and results are presented in Section 3.

2. Design and fabrications

2.1. Design of microresonators

We adopted a standard type of LEKID. The resonator was divided into a capacitor part and an inductor part. The capacitor was made from lines 4-µm wide and 1090-µm long. The capacitor lines were positioned at 5-µm intervals. The length and width of the inductor lines of the reference pixel were 940 µm and 5 µm, respectively. The number of meanders was 11. A schematic view of the reference pixel is shown in Fig. 1. Ten LEKIDs were allocated to a chip. To change the designed resonant frequency, the length of the inductor was changed for every pixel in 5 of the 10 resonators. In the other resonators, the capacitance length was varied. The feed line of microwave signals for the detectors was made of a coplanar waveguide (CPW) line. The CPW was designed to match a 50-Ω line, and the widths of a center conductor and ground planes were 12 µm and 15 µm, respectively. The gaps between the center line and grounds were 8 µm. Microresonators were capacitively coupled to the feed line. The distance from the edge of the ground to a capacitor, fixed at 16 µm, determined the coupling quality factor.

2.2. Fabrication of a gamma-ray camera

The microresonators were made of a Nb film with a thickness of 100 nm in the Advanced Technology Center, the National Astronomical Observatory of Japan. The film was sputtered on a high-resistivity (> 10 kΩ cm) silicon wafer that was hydrogen-passivated by a HF solution before the deposition. This process is crucial to reduce two-level system noise caused by silicon-oxide layers [12]. The superconducting transition temperature of the Nb film was 8.6 K. The detectors were patterned with standard photolithography processes and a dry etching process. After the patterning, a 2 mm-thick lead absorber with a purity of 99.9% was manually glued to the other side of the wafer. The width and height of the absorber were approximately 10 mm and 5 mm, respectively, as shown in Fig. 1. The absorber covered the top half of the wafer and was located behind 5 of the 10 detectors. Gamma rays entered the camera from the absorber side. The phonons generated in the absorber changed the resonant frequency of the resonators.

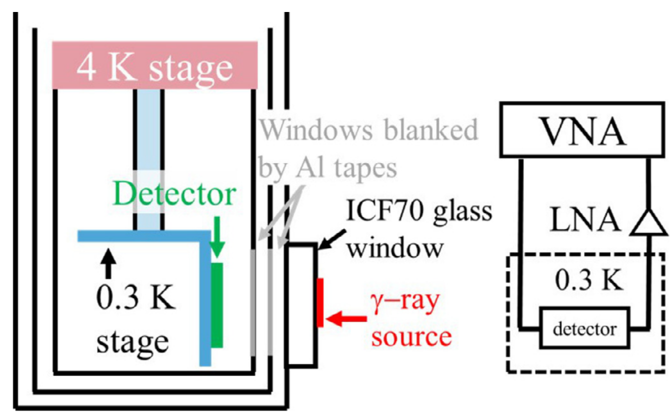

Fig. 2. (left) Schematic view of the measurement setup. A gamma-ray camera was installed to a 0.3 K stage. Gamma rays (662 keV) were irradiated from a 137Cs source. The gamma rays passed through windows blocked by aluminum tape and finally reached a lead absorber. (right) Block diagram of the resonators f properties. Transmission losses (S21) were measured with a vector network analyzer.

3. Experiments

3.1. Measurement systems

We used a combination of a 4 K pulse tube refrigerator and a 0.3 K sorption cooler. The camera was installed on the 0.3 K stage of the cryostat. The cryostat had three optical windows, each of which had a size equaling the diameter of the ICF 70 port. The room temperature window was made from Sapphire. The windows at a 30 K shield and 4 K shield were blocked with aluminum tape to prevent infrared radiation entering the cold stage, as shown in Fig. 2. A microwave signal generated by a vector network analyzer (VNA; Rohde & Schwarz ZNB8) was introduced via coaxial cables