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Development of Meander-shaped Metallic Magnetic Calorimeters

W. S. Yoon[a,b], Y. S. Jang[a], G. B. Kim[a], H. J. Lee[a,b], J. Y . Lee[a], M. K. Lee[a], Y. H. Kim[a,b*]

[a] *Korea Research Institute of Standard and Science, Daejeon, Korea*

[b] *University of Science and Technology, Daejeon, Korea*

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Abstract

We are developing meander-shaped metallic magnetic calorimeters using micro-fabrication methods. A planar Nb coil in a meander shape was fabricated on a Si substrate. The coil was designed to have a persistent current using a metal heater evaporated on a part of the coil. A paramagnetic sensor, 5 μm thick Au:Er foil, was glued on top of the meander structure with epoxy. The magnetization and heat capacity were measured at different temperatures, and applied field currents matched well with expected values. The detector showed an energy resolution of 4 keV FWHM for the 5.5 MeV alpha particles.

Keywords : metallic magnetic calorimeters, low temperature detectors, microfabrication

I. Introduction

Metallic magnetic calorimeters (MMCs) have demonstrated their high energy resolution in many applications over a wide energy range of particle detection [1-4]. A paramagnetic alloy, Au:Er (i.e. gold doped with a small concentration of erbium) was used as the sensor material of the MMCs. The magnetization and heat capacity of Au:Er keep the temperature dependent properties well below 100 mK under a magnetic field.

The early stage MMCs were hand-constructed with a SQUID susceptometer [5]. The magnetization change of an Au:Er sensor was directly measured with a dc-SQUID. The Au:Er sensor was hand-positioned inside the SQUID pick-up loop. In spite of their high performances, the handmade setups were difficult to use for a detector requiring for many pixels. The requirement of using special SQUIDs was another limit of the early setups.

Using micro fabrication methods, a new type of MMC was developed. A few micron thick Au:Er was fabricated on top of a planar pickup coil in a meander-shaped geometry. The pickup coil was connected to the input coil of a current-sensing SQUID, forming a superconducting loop. A simplified circuit diagram of the meander-shaped MMC is illustrated in Fig. 1. The micro fabrication capability makes it easy to vary the size of an MMC for given experimental requirements and is advantageous for wide detection areas and multiple array structures.

The present experimental research focuses on the development of fabrication and characterization of meander-shaped MMCs, particularly for detectors that need an absorber with a large heat capacity. We describe the micro fabrication process to make a planar pickup coil. The measurements of the magnetization and the heat capacity of a MMC setup are introduced in different experimental conditions.

*Corresponding author: Yong-Hamb Kim Tel : +82 42 868 5975
e-mail : yhkim@kriss.re.kr

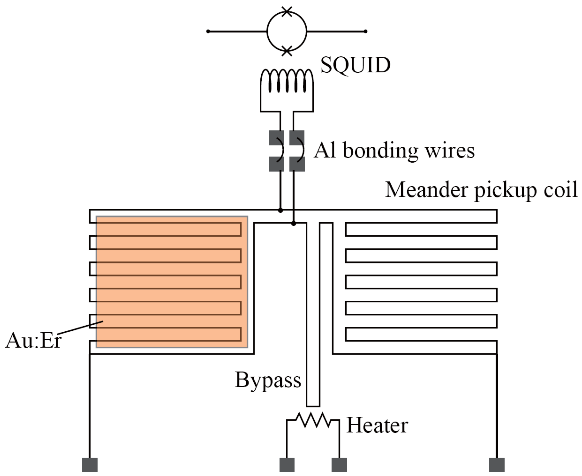

Fig. 1. A simplified measurement circuit of a meander-type MMC. The heater is fabricated above the bypass of the meander coil to break superconductivity of local area. Au:Er sensor of 1 mm×1 mm is glued on one side of the meander pickup coil.

II. MMC fabrication and experimental setup

A magnetic field is required to magnetize the erbium ions in an MMC sensor. In a meander-shaped geometry, a field current applied in the meander coil generates the magnetic field. The meander coil is connected to a SQUID input coil to measure the induced current in the pickup loop, as shown in Fig. 1. This coil has a bypass passing near the heater. The setup is able to store a persistent current in a meander loop more than 100 mA. The meander coil is composed of two sides to make a gradiometric configuration with respect to the current-sensing SQUID canceling external field noise.

The micro fabrication used to make a meander coil with a heater involved several steps: sputtering, etching, anodizing, photolithography, electron beam deposition, and electroplating procedures. First, a 400 nm Nb layer was sputtered on a 3-inch Si wafer covered with 200 nm of SiO_2. The desired Nb pattern with a 5 µm width and a 10 µm pitch was made by using photolithography and reactive ion-etching processes. After making an insulating layer with niobium anodization [6] and SiO_2 deposition on top of the niobium surface, a Cr/AuPd heater with a thickness of 10/50 nm was evaporated using a photolithographic method. The resistance of the heater was about 20 Ω below 4 K. The critical current of the 5 µm wide Nb line was found to be 190 mA.

After the fabrication of the meander structure with the heater, an Au:Er sensor and a gold absorber were attached to form a complete MMC setup. A piece of 5 µm thick Au:Er foil was rolled from a bulk piece which had an 800 ppm erbium concentration, and was cut by 1 mm×1 mm with a laser cutting machine. Then, the Au:Er foil was glued onto the top of the meander structure with a stycast1266 epoxy. In an ideal case, the Au:Er layer should be as close as possible to the meander coil. Non-negligible thickness of the epoxy layer may affect the effective magnetic field on the Au:Er layer.

Another gold foil with a thickness of 56 µm served as a particle absorber was connected to the Au:Er foil. It was thick enough to stop alpha particles completely with the absorber. The gold absorber and the Au:Er sensor were connected with 8 bonding wires with a 25 µm diameter. The annealed gold wires with a resistivity of 80 nΩcm provide a strong thermal contact between the absorber and the sensor. The measurement setup was attached to an adiabatic demagnetization refrigerator.

III. Experimental results

The present MMC setup was inductively coupled to a measurement SQUID. The induced current measured with this setup depends upon the inductance of the coils in the circuit, as shown in Fig. 1. A series of Johnson noise measurements was made in a helium storage dewar to determine the inductance of each component of the circuit. The SQUID current sensor used in the experiment had an input coil of 30 nH self-inductance and 6 $\mu A/\Phi_0$ mutual-inductance to the SQUID. The total inductance of the meander coil was 16 nH. The inductance from the bonding wires was found to be relatively negligible. The measurement circuit can be

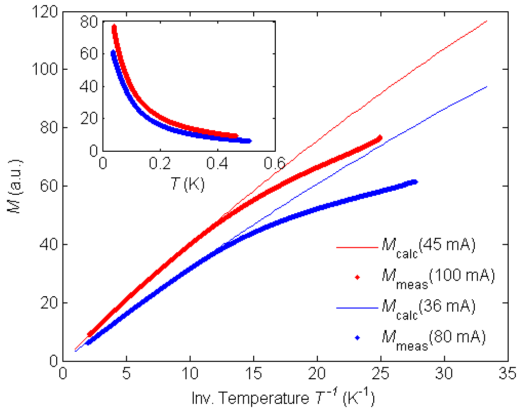

Fig. 2. Magnetization vs. temperature (*M*-*T*) curves.

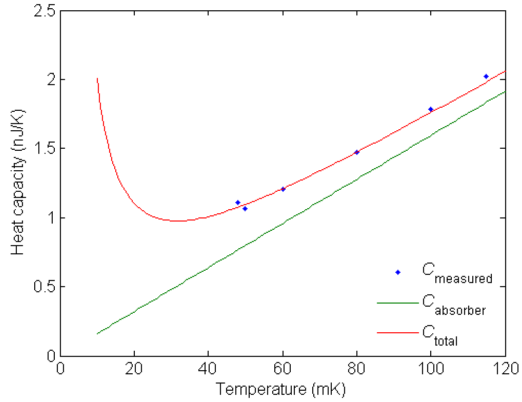

Fig. 3. Heat capacity of the detector. The curved line is calculated for the whole MMC setup while the straight-line is for the gold absorber only.

improved more efficiently if the SQUID inductance better matches with that of the meander coil.

The temperature dependence of the magnetization (*M*-*T* curve) was measured for the MMC setup. A field current was applied in the meander coil with a few mA of a current pulse in the heater. This method allows the meander loop to run a persistent current. As the temperature varies, the SQUID reads the magnetization change of the Au:Er sensor below the transition temperature of Al bonding wires.

Fig. 2 shows the measured *M*-*T* curves with a persistent current of 80 mA and 100 mA. The inset plots the magnetization on a temperature scale. The two lines are the calculated *M*-*T* curves of the Au:Er sensor taking into account the inductance values of the circuit. It is noticeable that the measured and calculated curves are consistent and the effective field is smaller than that applied to the epoxy layer. The calculation assumes an Au:Er layer is fabricated on top of the 250 nm thick oxide layer. The effective magnetic field in the Au:Er sensor applied by the field current was found to be 45% of the calculation value. The measured values start to deviate from the calculation at temperatures lower than 80 mK. We attribute this to the non-uniform distribution of erbium ions in Au:Er. The exchange interactions of neighboring erbium ions became stronger than expected, weakening the polarization of the spins.

For a preliminary investigation of the fabricated MMC setup, an ^{241}Am alpha source is introduced to the absorber. The heat capacity of the detector can easily be measured. The energy input from alpha particles is well known, and the pulse size can be calibrated by the *M*-*T* curve. The measured values of the heat capacity at different temperatures are in a good agreement with the expected values as shown in Fig. 3.

IV. Conclusion

The MMC setup with a meander-type pickup loop with the heater has been successfully fabricated. The *M*-*T* curves measured with the current-sensing SQUID with a persistent current showed a reasonable result for the glued Au:Er sensor. The heat capacity measurement agrees well with the calculation. Although only half of the magnetization was measured due to the gap between the Au:Er layer and the Nb coil, this fabrication method and measurement setup can be employed for an optimal MMC setup. For the next step, an Au:Er layer will be sputtered on top of an oxidized Nb layer.

We obtained 4.0 keV FWHM energy resolution for the 5.5 MeV alpha particles. It is somewhat a worse result than that of our previous work, which showed 2.8 keV FWHM with the same source in a dilution refrigerator [3]. However, the resolution in the present work can be improved further with a specialized Au:Er fabrication and an optimal choice of an absorber and a sensor SQUID for purposed applications.

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