Proceedings of the Korean Superconductivity Society Meeting 1999
(KSS 99), YongPyung, Kangwondo, Korea, Aug. 18-20, 1999

Junction, Circuit and System Developments for a High-Tc Superconductor Sampler

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Abstract

A Josephson sampler circuit using high-Tc superconductor (HTS) ramp-edge junctions has been designed, fabricated, and experimentally tested. It consists of five ramp-edge junctions with a stacked groundplane and is based on single-flux-quantum (SFQ) operations. The sampler was used to measure current waveforms at picosecond and microampere resolutions. We are developing a system based on the sampler for measuring the current waveform in a room-temperature sample. And measuring current flowing through wiring in a semiconductor large-scale integrated circuit is a promising application for the HTS sampler system.

Keywords: YBCO, Sampler, SFQ, Ramp-edge junction, Current measurement

1. Introduction

A sampler measures a repeated electric-signal waveform with high time resolution. The Josephson sampler was one of the most popular devices for low-Tc superconductor (LTS) applications throughout the 1980s [1], [2] because it is able to effectively utilize the characteristics of Josephson junctions, such as high speed and high sensitivity. Hypres Inc. produced a commercial Josephson sampler system from 1987 to 1990 [2]. This product performed well, but, the user had to transfer liquid helium into a dewar and the need to handle the liquid helium limited the market acceptance. However, if it had been made using high-Tc superconductor (HTS) materials and a compact single-stage cryocooler had been available, the sampler would have been more successful. Moreover, the sampler circuit has a simple configuration. We therefore think that the Josephson sampler is a suitable first target for our development of HTS integrated circuits.

In this article, we begin by describing the circuit design of a single-flux-quantum (SFQ) sampler compatible with HTS over-damped junctions. Next, we briefly explain the fabrication process, which includes that of the junction, and a multilayer structure for the stacked groundplane. And the sampler is used to measure current waveform at picosecond resolutions. Finally, we describe a system based on the sampler in which the current flowing through a room-temperature sample can be measured without direct contact.

2. Circuit design

Figure 1 shows the circuit diagram of the HTS sampler circuit [3]. The circuit consists of five ramp-edge junctions and inductance elements. The circuit operation is described in detail in Ref. [4]. The moment the trigger current I_{tr} rises, an SFQ pulse is generated by JJ1 and JJ2 and propagates to JJ3. A stored SFQ in Loop3 by the JJ3 switching is read out using a readout SQUID which includes JJ4 and JJ5.

Since the sampling points are accurately determined by the picosecond-width SFQ pulses and an outer delay line, the waveform of signal current I_s is measured at picosecond resolution in spite the sampling frequency of several-tens-kHz. It is one of the advantages of the sampler that the high-resolution measurements can be performed at low frequency.

3. Fabrication process

The fabrication process of the sampler circuit is

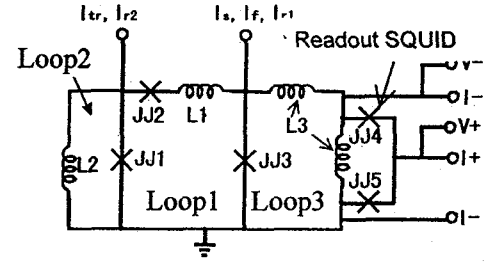

Fig. 1 Circuit diagram of the HTS sampler. The design parameters are I_C(JJ1)=I_C(JJ3)=0.5 mA, I_C(JJ2)=I_C(JJ4)=I_C(JJ5)=0.25mA, L1=3.7 pH and L2=L3=5.0 pH. V+, V- and I+, I- are voltage and current terminal of the readout SQUID.

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described in detail in Ref. [4]. $YBa_2Cu_3O_7$ (YBCO), $SrTiO_3$ (STO), and $PrBa_2Cu_3O_7$ (PBCO) were used as the superconductor, insulator, and tunnel barrier layer, respectively. An in-situ fabrication process for the ramp-edge junctions [5] and a new multilayer structure called a HUG (HTS circuit with an upper-layer groundplane) structure [6] have been added. In the in-situ process, the barrier and the counter electrode layer were deposited immediately after the edge formation without breaking the vacuum in order to obtain a clean junction interface. An HTS groundplane was placed on the junctions in the HUG structure to prevent junction quality degrading because of surface roughness of the lower layer groundplane. The typical junction I_cR_n product was 1.6 mV at 4.2 K and 0.2 mV at 50 K. The critical current spread of the junctions 1σ was as low as 10% in twelve 4-μm-width junctions with a critical current density J_c of 5×10^4 A/cm^2. The line inductance was around 1.0 pH per square and no superconductivity deterioration was observed in any of the YBCO multilayers. This inductance value is low enough to allow implementation of the sampler circuit inductance within its parameter margin.

We have recently developed a new process for fabricating uniform HTS ramp-edge junctions with modified interface barriers. Though no intentional barrier deposition is included in this process, the fabricated junctions showed resistively and capacitively shunted junction-like current-voltage characteristics and excellent uniformity. The critical current spreads of 100 junctions at 4.2 K were as small as 1σ=8% [7].

4. Measurement results

First, because no other suitable method can measure the original current waveform in the picosecond resolution regime, we confirmed that the measured signal current waveform by the sampler was coincident with the original one with a 1-μs delay time between every sampling point. Then, we measured the signal current waveform generated by the on-chip Josephson signal generator in the picosecond-resolution regime. Figure 2 shows the measured current waveform with a 1-ps delay time between every sampling point. In Fig. 2, the maximum time differential of the measured waveform is 12 μA/ps and current sensitivity is 2.5-μA at 25 K [8]. The observed time differential indicates that the sampler can correctly measure a signal current waveform whose time differential is less than 12 μA/ps.

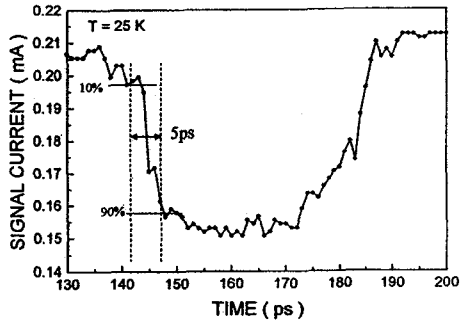

Fig. 2 Measured signal current waveform by the HTS sampler.

5. System application

We are developing a current measurement system based on the HTS sampler [9]. Figure 3 shows the measurement principle of this system. Current I_1 flowing through a sample generates a magnetic field. The magnetic field induces a shielding current I_2 in a superconducting closed loop, which includes the comparator junction of an HTS sampler. Since I_2 is in proportion to I_1, I_1 can be measured by the HTS sampler without direct contact. Moreover, the HTS sampler can measure I_1 from DC to extreme high frequency, for instance several tens gigahertz, because the relation of I_1 and I_2 does not depend on frequency.

In this system, the sampler chip is housed in a vacuum chamber and is cooled down to its operating temperature by a single stage GM-pulse-tube cryocooler. The distance between the sampler chip and a sample at room temperature can be reduced up to 2 mm because 0.7-mm-thick AFRP is used for the bottom wall of the chamber. As a preliminary test of the system, voltage modulations of a direct-injection HTS SQUID were successfully measured at around 40 K.

Semiconductor samplers and electro-optic (E-O) samplers are well known for characterizing temporal shape of high-speed electrical signals. However, the semiconductor samplers measure voltage and the E-O samplers observe electrical field. In order to measure current by using these samplers, the electrical impedance of the measured part has to be known. As the operation frequency of semiconductor large-scale integrated circuits (LSIs) increases towards the gigahertz frequency regime, the demand for current measurements increases from the viewpoints of circuit

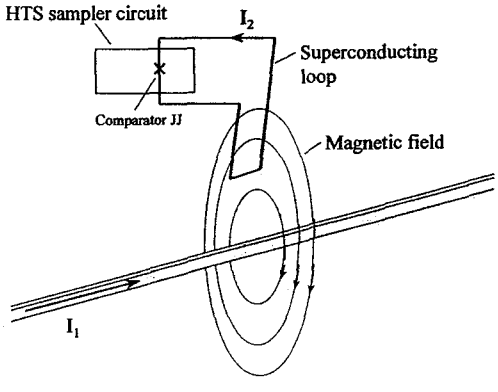

Fig. 3 Measurement principle using the HTS sampler and a superconducting loop.

design and electromagnetic compatibility (EMC) technology. However, since the impedance of a wiring in LSI under test is generally unknown because of its complex layered structures and via holes, current flowing through the wiring cannot be measured by using the semiconductor or E-O samplers. The HTS sampler can observe the current waveform in the LSI with high resolution. We expect the HTS sampler system to be very useful for studying transient phenomena, cross-talk, and EMC in high-speed LSI circuits.

6. Summary

We have designed, fabricated, and experimentally tested a Josephson sampler circuit based on HTS ramp-edge junctions. The sampler circuit consists of five ramp-edge junctions with a stacked groundplane and is based on SFQ operations. Current waveforms have been successfully measured at picosecond and microampere resolutions at 25 K. This superconductor sampler is the only device that can measure current waveforms with such high resolutions.

We are developing a high-resolution current-measurement system based on an HTS sampler circuit. In the system, the sampler circuit is cooled down to around 40 K by a single-stage GM-pulse tube cryocooler and is housed in a vacuum chamber whose bottom wall thickness is only 0.7 mm. Current flowing through a room-temperature sample, which is placed just below the vacuum chamber, is measured by the sampler without direct contact.

Acknowledgements

This work was supported by New Energy and Industrial Technology Development Organization (NEDO) through International Superconductivity Technology Center (ISTEC).

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