High-resolution Measurement by a High-T_c Superconductor Sampler

M. Hidaka, T. Satoh, M. Koike and S. Tahara
Fundamental Research Laboratories, NEC Corporation, Tsukuba, Ibaraki 305-8501, Japan

***Abstract*—We measured a signal current waveform by using a high-T_c superconductor (HTS) sampler with a 1-ps delay between every sampling point. The maximum time differential obtained in the measured waveform was 12 μA/ps with 2.5-μA current sensitivity at 25 K. This result guarantees that the sampler is able to measure current waveforms correctly when their maximum time differential is less than 12 μA/ps. The superior time resolution was achieved by using high-speed single-flux-quantum pulses generated in the HTS circuit. A unique feature of the sampler is that it directly measures the current with picosecond time-resolution and microampere current- resolution. Current measurement flowing through wiring in a semiconductor large-scale integrated circuits is a promising application for the HTS sampler.**

I. Introduction

In general, even though a sensor of an electric measurement system is relatively small component, it must have high performance. Considering high potential of high-T_c superconductor (HTS) circuits and their immature fabrication process, it seems that the sensor is a suitable item for an HTS circuit application. We are developing a sampler circuit for a circuit application of HTS. The sampler is a sensor for measuring repeated waveforms with high-time-resolution. High-speed switching and the well-defined current threshold of Josephson junctions are effectively utilized in the sampler. The Josephson sampler using low-Tc superconductor (LTS) latching circuit had been investigated throughout 1980s [1],[2]. In 1987, Hypres Inc. introduced a Josephson sampler system into the commercial market-place [3]. These LTS samplers, however, were not widely used, because liquid helium was needed to cool the sampler to its required operating temperature. We think, however, that the HTS sampler, which can be cooled by a compact cryocooler, has a chance to spread through the general market.

We designed a new circuit for implementing the sampler with HTS materials. This circuit consists of five Josephson junctions and four superconducting loops, and it is based on single-flux-quantum (SFQ) operations [4]. $YBa_2Cu_3O_x$ (YBCO)/$PrBa_2Cu_3O_x$ (PBCO)/YBCO ramp-edge junctions with an integrated groundplane were adopted for fabricating the sampler circuit. An in-situ process, in which the PBCO barrier and the YBCO counter-electrode layer are deposited immediately after edge etching without breaking the vacuum, was developed [5]. The in-situ process improved the critical current uniformity of the junctions to 1σ=10% in twelve 4-μm-wide junctions [6]. An YBCO groundplane was placed on the junctions in the multilayer structure. We call this structure a HUG (HTS circuit with an upper-layer groundplane) structure. The inductance of YBCO lines was reduced to 1 pH per square without degrading the junction quality in the HUG structure [7].

The successful operation of the sampler circuit was confirmed by comparing an input-signal current waveform with a measured waveform by the sampler operated at 50 K [8]. However, since the operation carried out for a function test, the delay between every sampling point was 1 μs. This delay was insufficient for deriving the time resolution of the HTS sampler. We therefore measured current waveforms to the order of picoseconds.

II. Setup for High-resolution Measurement

Fig. 1 is a block diagram of the experimental arrangement for the automatic-sampler measurement system. The HTS sampler chip is cooled in a magnetically shielded temperature-controlled cryostat. A feedback current I_f and a reset current I_{r1} are supplied by a personal computer (PC) via 12-bit digital-to-analog converters (D/A). A trigger current I_{tr} is generated by a high-speed-pulse generator (Picosecond Pulse Labs. 4015C) and I_{tr} is delayed by a trombone delay line (Colby Instruments PDL 10A), whose delay times are controlled by PC via a general-purpose information bus (GPIB). Signal trigger current I_{str} is also generated by the pulse generator and propagates to the sampler chip via a manual delay line. The readout SQUID of the sampler is biased by a battery. After 500-times amplification, the output voltage V_{out} of the sampler circuit is digitized using a 12-bit analog-to-digital converter (A/D). Then the digitized V_{out} is sent to the PC and an *n*-times averaging value is calculated. And the averaged V_{out} is compared with the expected value. When the averaged V_{out} is smaller than the expected value, I_f is increased in the next cycle. When the average V_{out} is larger than the expected value, the V_{out} is measured with the same I_f in the next cycle. If V_{out} is exceeded in *m* continuous cycles, the I_f value and the I_{tr} delay time are memorized and the next measurement is

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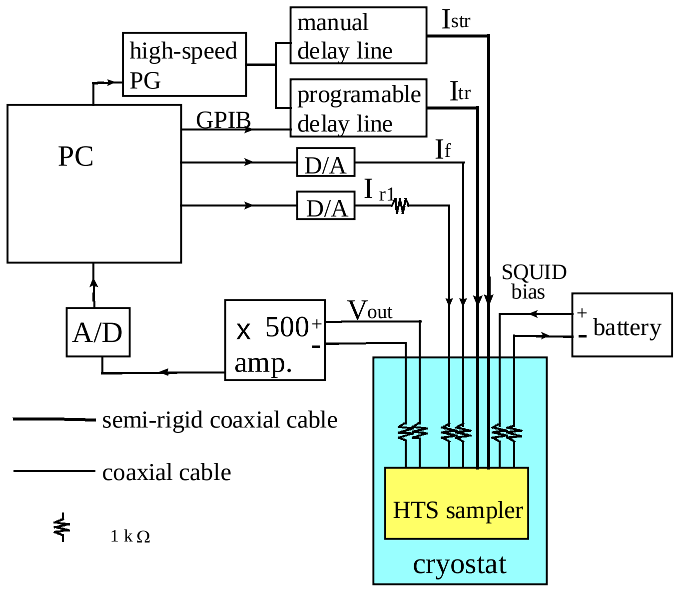

Fig. 1 Block diagram of the experimental arrangement for the automatic sampler measurement system.

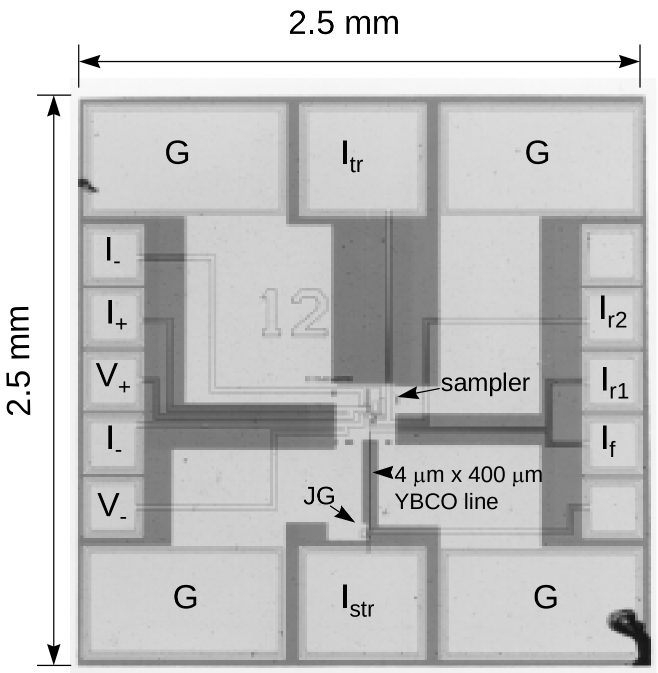

Fig. 2 Optical closeup of the HTS sampler chip. The sampler circuit is placed in the center and the Josephson signal generator JG is below the sampler.

started with a larger delay time and a decreased I_f value. The current sensitivity of the measurement strongly depends on *n*, *m*, and the expected voltage. We optimized these values experimentally. In order to reduce current noise, 1-kΩ chip resisters were inserted in the input lines (except the I_{tr} and I_{str} lines) near the sampler chip in the cryostat. Semi-rigid coaxial cables were used for the high-speed I_{tr} and I_{str} lines. And the sampling frequency was 15 kHz.

Fig.2 shows a sampler chip for high-time-resolution measurement. The chip size is relatively small (2.5 mm square) in order to decrease the length of the high-speed current lines on a $SrTiO_3$ substrate (which has a huge dielectric constant). For reducing cross-talk between current lines, ground pads are placed on both sides of the high-speed current pads.

Signal current I_s which is measured using the sampler, is generated by the signal trigger current I_{str} input at an on-chip Josephson signal generator (JG) and is propagated to the sampler through a 4-μm-wide and 400-μm-long YBCO line without any matching resistance. Two junctions are used in JG as shown in Fig. 3(a). Fig. 3(b) and (c) show simulation results of the I_s waveform at the end of the YBCO line for I_{str}=0.4 mA and I_{str}=0.7 mA, respectively. When I_{str} is 0.4 mA, junction JG2 does not switch after junction JG1 switches and SFQs do not enter the superconducting loop including JG2, the YBCO line, and the comparator junction of the sampler. In this case, the waveform modulates on a hundred picosecond time scale due to reflections. Another feature is that the waveform crosses the zero level corresponding because no SFQs enter the loop. Larger I_{str}, for instance 0.7 mA, causes JG2 to switch after JG1 switches and many SFQs enter the loop. A more complicated waveform including steeper slopes than that in Fig. 3(b), which is due to the reflections and the JG2 switches, is observed. Its current level is increased by an offset of a few hundred microamperes which is owing to the stored SFQs in the loop, and the waveform does not cross the zero level.

Since the YBCO line does not have an integrated groundplane, it is difficult to estimate its inductance and capacitance. Moreover, spreads of junction characteristics [6] makes construction of an accurate simulation model difficult. As these results, the simulation model was insufficient. Therefore, we cannot expect the simulation results coincident with the experimental results in detail, but their features described above should be reflected in the experimental results describe next.

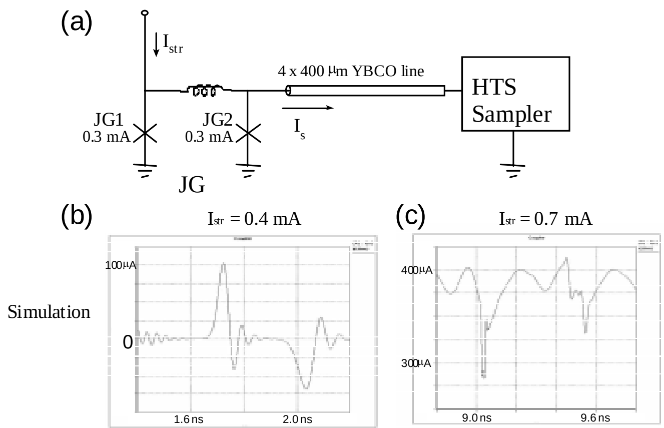

Fig. 3 (a) Schematic diagram of the Josephson signal generator. Simulation results of output current at the end of the YBCO transmission line for I_{str} = 0.4 mA (b) and I_{str} = 0.7 mA (c).

III. Experimental Results

Fig. 4 shows an I_s waveform measured by the HTS sampler at relatively small I_{str}. The value of I_{str} flowing into the JG in the sampler chip cannot measure, but its relative amplitude is able to control by a variable attenuator. Delay time between every sampling point was set up at 2 ps and measuring temperature was 25 K. A comparator junction with a smaller critical current results in lower operation temperature and the sample used in this measurement had a smaller critical current than that of the sample used in [8]. I_s waveforms modulated on a hundred-picosecond time scale and crossed the current zero level. These features agree with the simulation result in Fig. 3(b). In Figs. 4(b), 4(c) and 4(d), by using the manual delay line, I_{str} input was delayed by 175, 350, and 525 ps, respectively, compared to I_{str} in Fig. 4(a). Similar waveforms as that in Fig. 4(a) but delayed by 175, 350, and 525 ps were observed in Figs. 4(b), 4(c) and 4(d), respectively. It is confirmed from this experiment that the measured current waveform was generated by JG.

By inputting a larger I_{str}, a more complicated waveform was observed. Fig. 5 shows one of the results with a 1-ps delay time between every sampling point. The waveform in Fig. 5 had an offset of about 150μA. The dip structure around 160 ps of Fig. 5(a) was remeasured in detail as shown in Fig. 5(b). In Fig. 5(b), the maximum time differential of the measured waveform was 12 μA/ps, which fell down 60 μA with a 5 ps time interval.

Fig. 6 shows a measurement result for I_s=0 which indicates no I_{str} entered into the JG. As the measured current spread in Fig. 6 is less than 2.5 μA, we determined that the current sensitivity of the measurement was 2.5 μA.

IV. Discussions

A. Time Resolution

In this section, we discuss what the 12-μA/ps time differential means when input signal current waveform is unknown.

Fig. 7 shows the circuit design of the HTS sampler circuit [4]. The moment the trigger current I_{tr} rises, an SFQ current

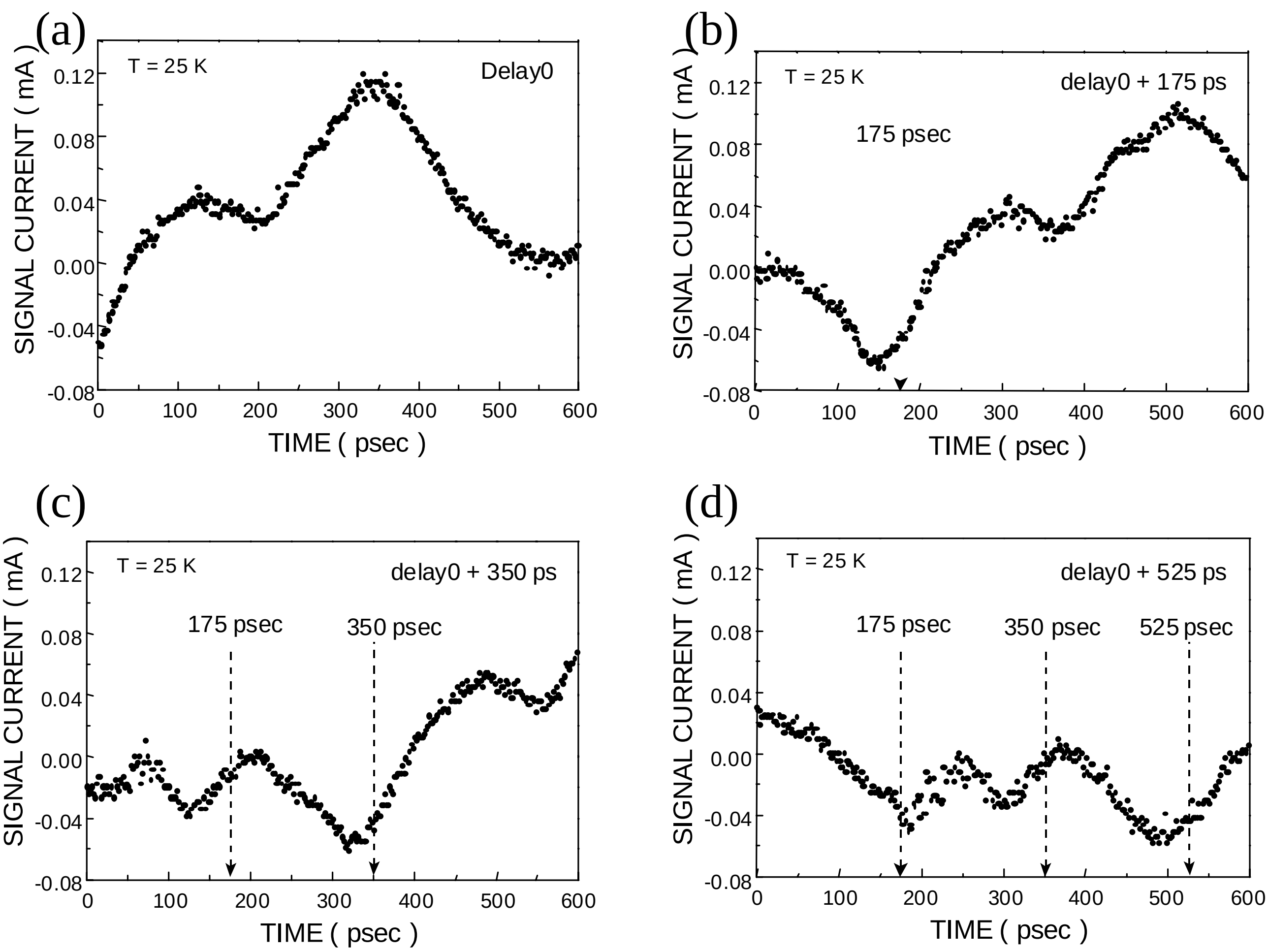

Fig. 4 Measured signal current waveform by the HTS sampler, n=100 and m=10. The supply current I_{str} to the Josephson generator was relatively small. (b), (c) and (d), by using a manual delay line, I_{str} input was delayed by 175, 350, and 525 ps, respectively, compared to I_{str} in (a).

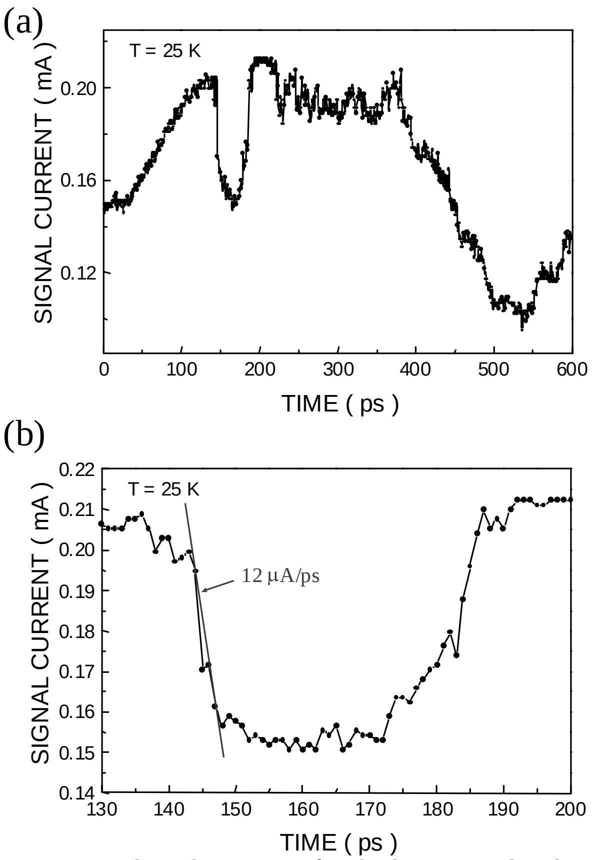

Fig. 5 Measured signal current waveform by the HTS sampler. The supply current to the Josephson signal generator was larger than in Fig. 4. (a) Measurement result from 0 to 600 ps, n=100 and m=10. (b) Remeasured waveform between 130 ps and 200 ps, n=1000, m=3.

pulse I_p is generated by JJ1 and JJ2 and this pulse propagates to JJ3. Here, it combines with a signal current I_s, at a given sampling point determined by the I_p generation, and a feedback current I_f. When the sum of the three currents exceeds a threshold value, an SFQ is stored in the superconducting loop, Loop 3. Then an output voltage V_{out} is induced by the stored SFQ at the readout SQUID, which consists of JJ4 and JJ5. The stored SFQ in the Loop 3 is reset using negative reset currents I_{r1} at the end of each sampling cycle.

The value of $I_{fmin}(I_s)$, which is defined as the minimum I_f required to store an SFQ in Loop 3 for I_s at the sampling point, can be determined by repeating the above operation with various I_f values. Comparing $I_{fmin}(I_s)$ with $I_{fmin}(0)$, which is the I_{fmin} for I_s=0, we can obtain I_s at the sampling point. The whole I_s waveform is measured by detecting I_s for various I_p generation times. In this measurement, dynamic range of the measurable I_s amplitude is limited by the I_p amplitude.

The principle for measuring a sampling point is simply illustrated in Fig. 8. In this measurement, only the maximum point of the I_s and I_p sums is detected. When the I_s time differential $|dI_s/dt|$ is less than the I_p time differential $|dI_p/dt|$, the maximum point appears at the top of I_p. In this case, the I_s

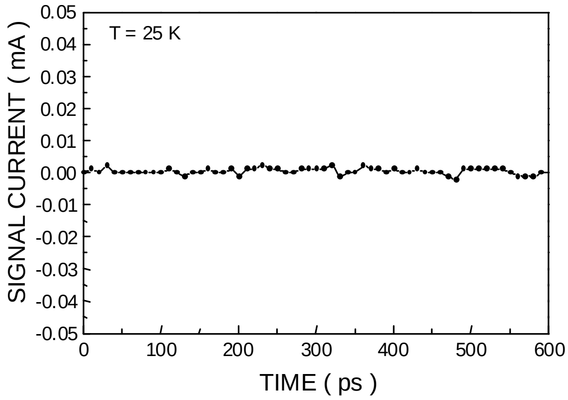

Fig. 6 Measurement result with no signal current, n=100, m=10. The measured current spread was less than 2.5 μA.

slope is measured correctly, as shown in Fig. 9(a), because the I_p top pushes up every part of I_s waveform to the maximum point by scanning I_p position. In Fig. 9, we suppose that the amplitude of I_s is equal to that of I_p. On the other hand, when $|dI_s/dt|$ is larger than $|dI_p/dt|$, the maximum point is not at the I_p top and every part of the I_p waveform is pushed up to the maximum point by I_s. As a result, the I_p slope itself is observed as shown in Fig. 9(b). Thus, either I_s slope or I_p slope is reconstituted in the measurement and the time differential of the I_p slope is equal to the maximum time differential, which can be measured using the sampler.

The I_p time differential as a function of the I_cR_n products of junctions JJ1 and JJ2 was calculated by computer simulations using the parameters in the Fig. 7 caption. Here, I_c and R_n are the critical current and the normal resistance of the junctions, respectively. Fig. 10 shows the results for the rising and falling parts of the I_p slope. It is clear that larger I_cR_n products result in larger $|dI_p/dt|$. The reason why $|dI_p/dt|$ at the falling slope was larger than that at the rising one is that the falling slope is caused by junction JJ2 switching and the load inductance when JJ2 switches is smaller than that when JJ1 switches, and this causes the I_p rising slope. The falling and rising parts of $|dI_p/dt|$ determine the measurable maximum

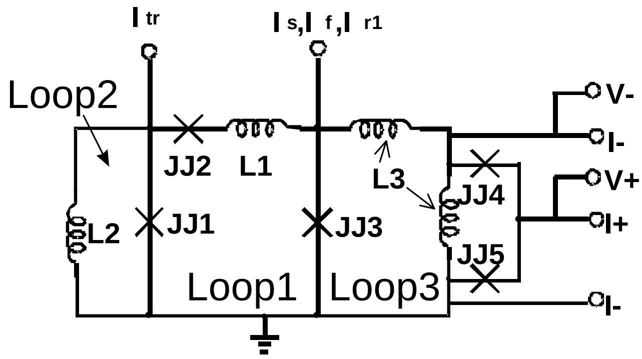

Fig. 7 Circuit diagram of the HTS sampler. The design parameters are I_c(JJ1)=I_c(JJ3)=0.5 mA, I_c(JJ2)=I_c(JJ4)=I_c(JJ5)=0.25mA, L1=3.7 pH and L2=L3=5.0 pH. V+, V- and I+, I- are voltage and current terminal of the readout SQUID.

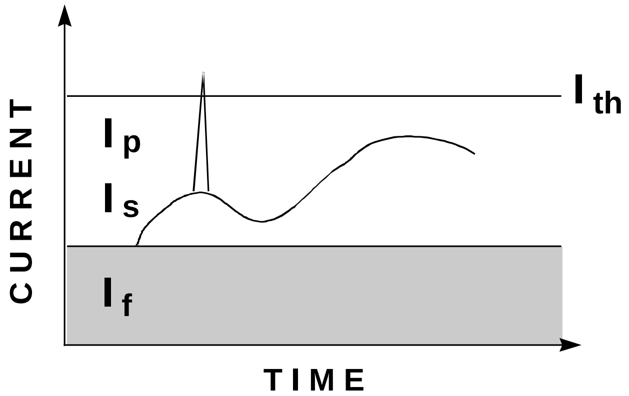

Fig. 8 Schematic representation for explanation of HTS sampler operational principle in a sampling point.

$|dI_s/dt|$ for the rising and falling parts of I_s, respectively.

From above discussion, it is obvious that almost all the measured waveform in Fig. 5 was that of the signal current (except the falling part in which a maximum falling-time differential of 12 μA/ps was observed). The falling part shows either the slope of I_s or I_p. Even if it shows the latter, we can confirm that our HTS sampler is able to correctly measure current waveforms whose maximum time differential is within 12 μA/ps.

Since the I_cR_n products of junction JJ1 and JJ2 cannot be observed directly, we measured the I_cR_n products of junctions JJ4 and JJ5. The experimentally obtained I_cR_n product for JJ4 and JJ5 was 0.7 mV at 25 K. Because the I_cR_n products in our junctions seldom differ more tan 50% in each other even on a 5 mm x 5 mm area [6], we consider that the I_cR_n products of JJ1 and JJ2 were around 0.7 mV, and a $|dI_p/dt|$ of about 50 μA/ps is expected according to Fig. 10. The measured waveform in Fig. 5 was therefore probably that of the signal current in all sampling points.

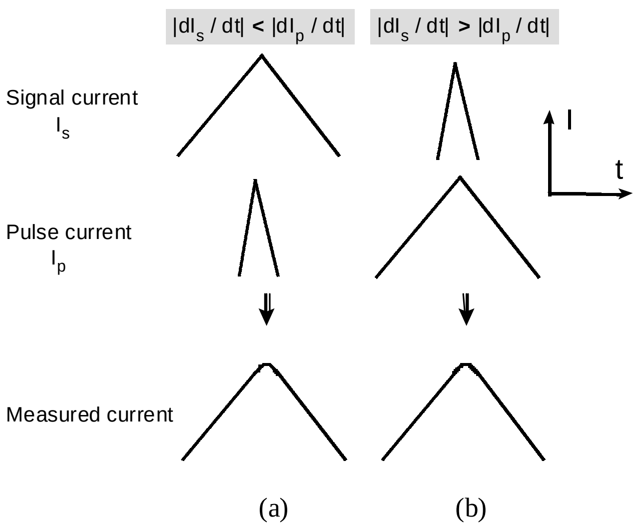

Fig. 9 Dependence of measured current waveform on signal current and pulse current time differential. (a) $|dI_s/dt| < |dI_p/dt|$, (b) $|dI_s/dt| > |dI_p/dt|$.

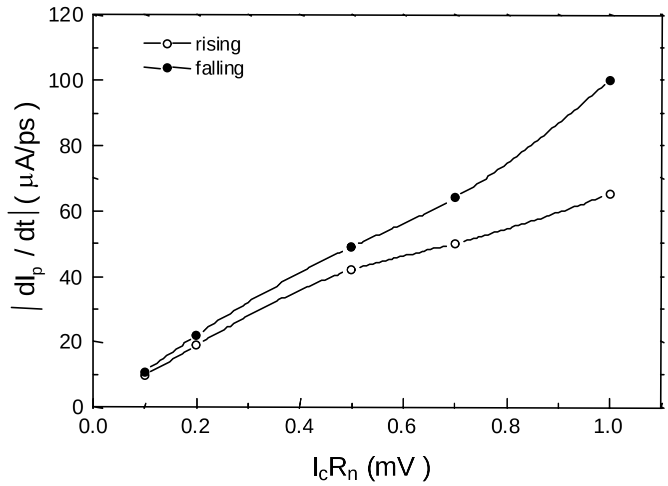

Fig. 10 Simulation results for pulse current time differential versus junction I_cR_n products.

B. A Promising Application

The HTS sampler is able to measure current waveforms directly with picosecond and microampere resolutions. To our knowledge, no other method for measuring current waveforms with such high resolutions have been reported to date, except the LTS Josephson samplers [1]-[3]. Semiconductor samplers [9] and electro-optic (E-O) samplers [10] 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 using these samplers, the electrical impedance of the measured part has to be known. Current waveforms were recently measured with 4-ps time-resolution by using a magnet-optic (M-O) sampler, which utilizes the Kerr or Faraday effect in the ferromagnetic film [11]. Its current-resolution, however, is about 1 mA. This resolution is considerably inferior to that of the HTS sampler. Moreover, a strong magnetic field, for instance 28.8 kOe, is necessary to prevent high-frequency oscillation superimposed on the current waveform, and the magnetic field possibly affects signal currents.

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 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 is able to observe the current in the LSI with high resolution. We expect the HTS sampler to be very useful for studying some transient phenomena, cross-talk, and EMC in high-speed LSI circuits.

V. SUMMARY

We have succeeded in measuring a signal current with a 12-μA/ps time resolution and a 2.5-μA current sensitivity at 25 K by using an HTS sampler consisting of five ramp-edge junctions with a stacked HTS groundplane. The observed time resolution indicates that the sampler is able to correctly measure a signal current waveform whose time differential is less than 12 μA/ps. The time resolution is expected to be around 50 μA/ps according to the measured junction I_cR_n product. As the minimum pulse width of external input currents is 10 ns, i.e. the trigger current, it is clear that picosecond time resolution was achieved by using a SFQ current pulse generated in the sampler circuit. We believe this is the first experiment in which high-speed characteristics of SFQ pulses in HTS circuits were extracted.

The HTS sampler has a unique function for measuring current. Current measurement is difficult with semiconductor devices because they are controlled by voltage. On the other hand, the Josephson junction has a well-defined current threshold. The HTS sampler utilizes this characteristic of Josephson junctions. Therefore, the HTS sampler has the chance of occupying a unique position in the field of measuring equipment.

An attractive application of the HTS sampler is measuring a current flowing through wiring in a semiconductor LSI. Increasing operation frequency in LSIs requires current measurement from the viewpoints of transient analysis, cross-talk, and EMC. These issues, however, have been neglected to date, since no suitable measurement equipment is available. We intend, therefore, to develop a current measurement system for LSIs by using the HTS sampler circuit.

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