Noise Properties of Serial SQUID Array Amplifiers for Transition Edge Sensor

Toshimitsu Morooka [a,1], Keiichi Tanaka [a], Atsushi Nagata [a], Satoshi Nakayama [a], Kazuo Chinone [a]

[a] *Seiko Instruments Inc., 563 Takatsuka-Shinden, Matsudo-shi, 270-2222 Chiba, Japan*

Abstract

We report on the noise properties of serial SQUID arrays (SSAs). We have developed current amplifiers using SSAs for transition edge sensor microcalorimeters with high current resolution and large dynamic range. Some SSAs changing the number of DC-SQUIDs were fabricated. Distortions on the Φ-V curves did not occur for all SSAs. Current resolution better than 10 pA/$\sqrt{\text{Hz}}$ was obtained by SSA amplifiers composed of 200 DC-SQUIDs or more. For SSAs composed of DC-SQUIDs having same device parameters, the current resolution is improved as the number of the DC-SQUIDs is increased. However, it is limited by a certain number, which does not only depend on the voltage noise of RT electronics but also on the noise generated in SSA itself.

Key words: SQUID current amplifier; serial SQUID array; transition edge sensor; current resolution

1. Introduction

We have developed SQUID current amplifiers for transition edge sensor (TES) microcalorimeters with a high current resolution of 10 pA/$\sqrt{\text{Hz}}$, a large dynamic range of 60 dB, and a bandwidth of 100 kHz [1,2]. Since the large voltage of Serial SQUID array (SSA), which consists of many DC-SQUIDs connected in series, allows the noise contribution of room temperature (RT) electronics to be reduced effectively, and gives a very high flux resolution less than 1 $\mu\Phi_0/\sqrt{\text{Hz}}$. When an N-SSA amplifier having an input coil magnetically coupled to the SQUID loop is driven using RT electronics, the current resolution (I_{n}) is given by [3],

$$I_n = \frac{\Phi_{\text{n}}}{M_{\text{in}}} = \frac{\sqrt{NS_{\text{V(SQ)}} + S_{\text{V(RT)}}}}{G_{\text{in}}} \quad (1)$$

$$G_{\text{in}} = NM_{\text{in}}V_{\Phi(\text{SQ})} \quad (2)$$

N is the number of DC-SQUIDs. Φ_{n} is the flux resolution. $S_{\text{V(SQ)}}$ and $V_{\Phi(\text{SQ})}$ are the voltage noise spectral densities caused by Johnson noise on the shunt resistors (R_{s}) and the Φ-V coefficient of each DC-SQUID. $S_{\text{V(SQ)}}$ is given by $\sim 16k_BTR_s$ [4]. $S_{\text{V(RT)}}$ is the voltage noise spectral densities of the RT electronics ($\gg S_{\text{V(SQ)}}$). M_{in} is the mutual inductance between the input coil and the SQUID loop. The current resolution can be improved by reducing Φ_{n} and enlarging G_{in}. While a large M_{in} improves the current resolution, it decreases the dynamic range. Hence, to be satisfied both the high current resolution and the large dynamic range, noise reduction of the SSA are very important. We have fabricated some SSAs changing the number of DC-SQUIDs, which have M_{in} of 100 pH or less, and investigated the noise properties.

2. Preparation of SSAs

Four types of SSAs; 25-SSA, 50-SSA, 100-SSA, and 200-SSA, were designed and fabricated on separate

[1] E-mail:toshimitsu.morooka@sii.co.jp

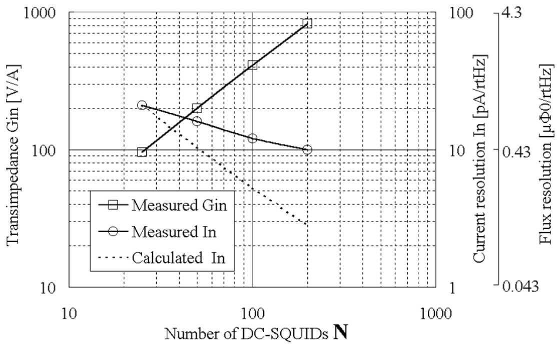

Fig. 1. Dependences of the transimpedance and the current resolution on the number of DC-SQUIDs. These were measured at the bias points where the amplitude of modulated voltage was $\frac{2}{3}$ of the maximum value.

3mm×3mm Si chips using Nb thin film fabrication technology [2]. All SSAs were composed of same DC-SQUID in shape. A single-turn input coil and a single-turn modulation coil were formed on the washer coil of each DC-SQUID to avoid distortions on the Φ-V curves. The device parameters of the DC-SQUIDs were similar for all SSAs. The SQUID inductance (L_s) of the washer coil was designed to be 120 pH. All SSAs had $\beta_L(2L_sI_c/\Phi_0) = 1.5$, $\beta_c(2\pi I_cR_s{}^2C_j/\Phi_0) = 0.6$, and $M_{in} = 90pH$, where I_c and C_j were the critical current and the capacitance of the Josephson junction.

3. Results and discussion

Distortions on the Φ-V curves for four types of SSAs did not occur without damping resistors on the input coils and the modulation coils. Noise power spectral densities were measured by using RT electronics having $S_{\rm V(RT)} = 2\ {\rm nV}/\sqrt{\rm Hz}$. The dependences of $G_{\rm in}$ and $I_{\rm n}$ on the number (N) of DC-SQUIDs are shown in Fig. 1. The current resolution was improved as the number was increased, and $I_{\rm n} = 10\ {\rm pA}/\sqrt{\rm Hz}$ was achieved by 200-SSA. While the transimpedance showed a proportional increase to N, the current resolution was limited around N = 100. It means that the current resolution did not depend on only $S_{\rm V(RT)}$. Additionally, a large difference between the measured and calculated results appeared.

In order to investigate the noise properties in detail, bias current ($I_{\rm b}$) dependences of $G_{\rm in}$ and $I_{\rm n}$ were measured using a 420-SSA. It consisted of different DC-SQUIDs from the DC-SQUIDs composed four types of SSAs mentioned above. It had $\beta_{\rm L} = 1.4$, $\beta_{\rm c} = 0.5$, $L_{\rm s} = 80$ pH, and $M_{\rm in} = 52$ pH. The I-V and Φ-V characteristics are shown in Fig. 2. The measurement results are shown in Fig. 3. The bias point ($I_{\rm b} = 24\ \mu$A) where the minimum current resolution was obtained was not in agreement with the bias point ($I_{\rm b} = 30\ \mu$A)

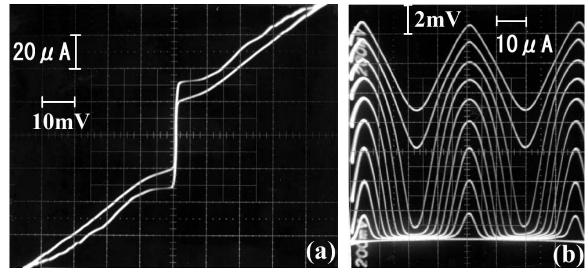

Fig. 2. (a) I-V characteristic and (b) $\Phi - $V characteristic of 420-SSA.

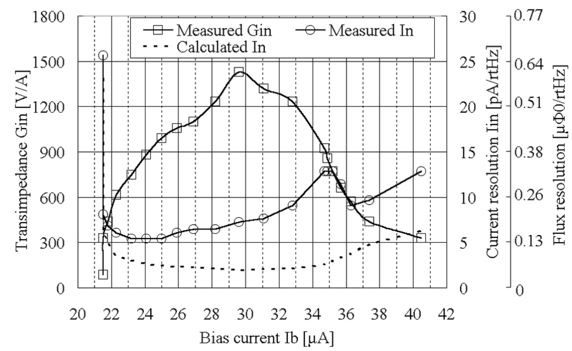

Fig. 3. Bias current dependences of the transimpedance and the current resolution.

where the maximum transimpedance was given. While the 200-SSA gave $I_n = 10\ {\rm pA}/\sqrt{\rm Hz}$ at $G_{\rm in} = 820$ V/A, the 420-SSA gave $I_n = 5\ {\rm pA}/\sqrt{\rm Hz}$ at $G_{\rm in} = 900$ V/A. The improvement in $I_{\rm n}$ was attributed to changing the device parameters rather than increasing N. In spite of the smooth Φ-V curves, the SSAs generated a much larger excess noise than $NS_{\rm V(SQ)}$ or $S_{\rm V(RT)}$. Figure 3 shows that the excess noise depended on I_b and that the rate of increase of the excess noise for I_b was larger than that of $G_{\rm in}$ between $I_{\rm b} = 24\ \mu$A and 30 μA. The excess noise is seemed to be caused by the dynamic resistance at bias point [5]. To raise the current resolution, not only $G_{\rm in}$ and $S_{\rm V(RT)}$ but also the noise of SSA itself must be considered.

References

[1] K. Tanaka, *atel.*, Appl. Phys. Lett. **77** (2000) 1677.

[2] T. Morooka, *atel.*, IEEE Trans. Appl. Supercond. **11** (2001) 751.

[3] F. Hirayama, *atel.*, IEEE Tran. Appl. Supercond. **9** (1999) 2923.

[4] J. Clarke, Proceedings of the IEEE **77** (1989) 1208.

[5] D. Drung, *atel.*, IEEE Trans. Appl. Supercond. **3** (1993) 2594.