Extended Abstracts of the 1991 International Conference on Solid State Devices and Materials, Yokohama, 1991, pp. 453-455 **S-F-12**

Fabrication and Noise Properties of NbN Nanobridge dc SQUIDs

A. IRIE, H. ABE, K. MORI, M. HATLE and K. HAMASAKI

Nagaoka University of technology, Department of Electronics

1603-1 Kamitomioka-machi, Nagaoka-shi, Niigata 940-21

We have fabricated various-type NbN nanobridge dc SQUIDs. From the analyses of the response to magnetic field, it is found that the current-phase relationship for the planar type nanobridge and the nanobridge fabricated by field evaporation is close to sinusoidal. For $V \gtrsim 1mV$, we found that the spectral densities of the voltage noise show linear dependence on the voltage for the SQUIDs with nanobridges of which the length is about coherence length. While the SQUIDs with nanobridge which is several times coherence length have the parabolic voltage dependence. Also, the field-evaporated NbN nanobridge dc SQUIDs have low telegraph-like noise.

INTRODUCTION

To obtain ultra-low noise dc SQUIDs various approches have been made by a number of workers. The dc SQUIDs with the low noise limited by uncertainty principle have been reported.[1-3] Almost dc SQUIDs consist of two tunnel junction which had been progressed in the fabrication process developed for Josephson computer.

J. Clarke et al. predicted the energy sensitivity of dc SQUID by $\varepsilon = 16k_BT\sqrt{LsC_J}$,[4] where k_B is Boltzmann's constant, T is temperature, Ls is SQUID inductance and C_J is capacitance of each junction. To reduce SQUID noise, it is desirable to reduce Ls and C_J. However, low values of Ls are not permissible for practical SQUIDs because the appropriate value of Ls is required to obtain the coupling to the external field. For practical devices, in order to improve the sensitivity of SQUID, C_J must be reduced.

From this point of view, bridge type junctions and small tunnel junctions with smaller C_J are more suitable for low noise SQUIDs. Recently, some workers have report the tunnel junction with submicron size,[5,6] which has small capacitance, for mixer devices and SQUIDs. It is, however, not easy to prepare such junctions because the nanometer technology is required to fabricate the submicron size junction.

On the other hand, for bridge type junction, it is also required that the bridge size is satisfied Likharev's condition of $\ell \lesssim (3\text{~}5)\xi$,[7] where ξ is the coherence length and that of NbN is 40~70Å.[8] Therefore, to obtain the devices which show the excellent Josepson effect the nanobridge length must be less than ~350Å. We have fabricated three type nanobridge which are satisfied such condition.[9,10]

In this paper we present the fabrication process and noise properties of NbN nanobridge dc SQUIDs.

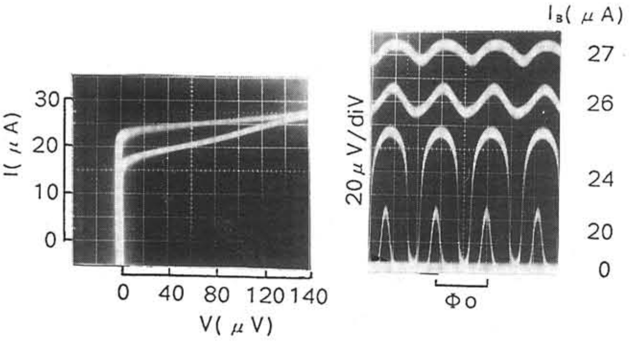
DEVICE FABRICATION

NbN nanobridges were chosen as Josephson elements because of their small capacitance and high critical temperature (~15K).

Type A nanobridge is planar type nanobridge and fabricated by photolithography (PL), reactive ion etching (RIE) and lift-off technique. First, MgO and NbN films are sequentially deposited on Si substrates. After the formation of first electrode by PL and RIE, to fabricate second electrode MgO(200Å)/NbN(1500Å) films are deposited and patterned by PL and RIE. The co-planar edge structure consisted of NbN/MgO/NbN is made by lifting off the photoresist on NbN film. Then NbN nanobridge SQUID is finished by deposition of Al film using as shunt resistor on NbN nanobridge to eliminate the hysteresis of I-V characteristics. The bridge length of this type device may be less than 200Å, which corresponds to $(2\text{~}3)\xi$. This length is sufficiently short to obtain the good Josephson junction.

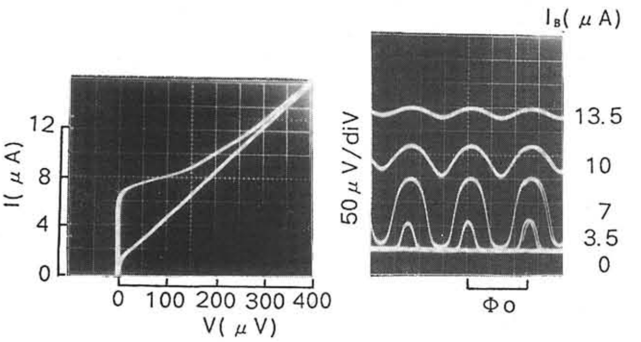
Type B nanobridge is fabricated by appling the voltage pulse to NbN(1200Å)/MgO(70Å)/NbN(1200Å) edge junctions with ~0.2 μm^2 area which had no supercurrent and high resistance of $R \gtrsim 1M\Omega$. In this configuration the length of the nanobridge is determined by the thickness of MgO insulator and therefore approximately 70Å, which is close to ξ. It is the advantage of this device that the critical current can be easily adjusted at the operation temperature by an amplitude and number of applied voltage pulse.

Type C nanobridge is step-edge junction. In this device a single film deposition used to form both the bridges and banks. The step is made by SiNx film deposited on Si substrate. Since the step hight is about 1000Å and the thickness of NbN film is 1500Å, the geometical bridge-length is about 500Å and somewhat longer than maximum length 5ξ of Likharev's condition. The effective bridge-length for Josephson junction is, however, unknown.



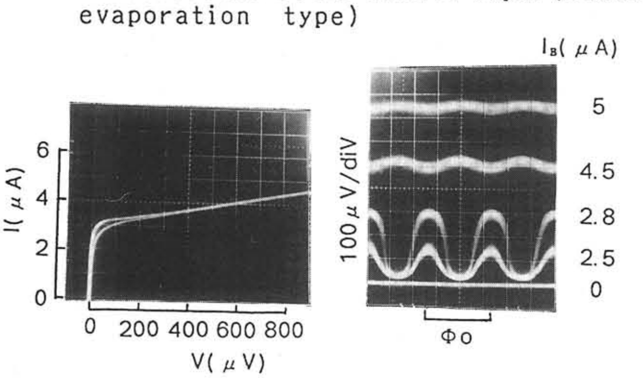
(a) (b)

Fig.1 I-V and V-Φ characteristics for type A nanobridge SQUID with L=180pH. (planar type)



(a) (b)

Fig.2 I-V and V-Φ characteristics for type B nanobridge SQUID with L=14pH. (field evaporation type)



(a) (b)

Fig.3 I-V and V-Φ characteristics for type C nanobridge SQUID with L=300pH. (step-edge type)

PERFORMANCE OF THREE NANOBRIDGE SQUIDS

The typical I-V and V-Φ characteristics for each SQUID are shown in Fig.1(a) to 3(b).

Type A nanobridge SQUID has an inductance of ~180pH. The critical current 2Io is 23μA and the output voltage across the SQUID is 110μV. The maximum value of transfer function, $\partial V/\partial\Phi$, and the energy sensitivity are ~1mV and 20h (h is Plank's constant), respectively.

Type B SQUID has small inductance of 14pH. The SQUID hole can be extended by the etching-out of the electrode by RIE. From the result of magnetic field dependence of the critical current, we have found that the critical current of each junction is almost equal.

The quality of nanobridge in type C SQUID which has the inductance of ~300pH is not so good as compared with that of other type nanobridges because the flux modulation depth of the critical current is little and the output voltage is thus low. This may be due to the longer effective bridge-length.

NOISE PROPERTIES

Figure 4 shows the spectral densities Sv of voltage noise at 4.2K for three type SQUIDs. The dashed lines are theoretical values.[11]

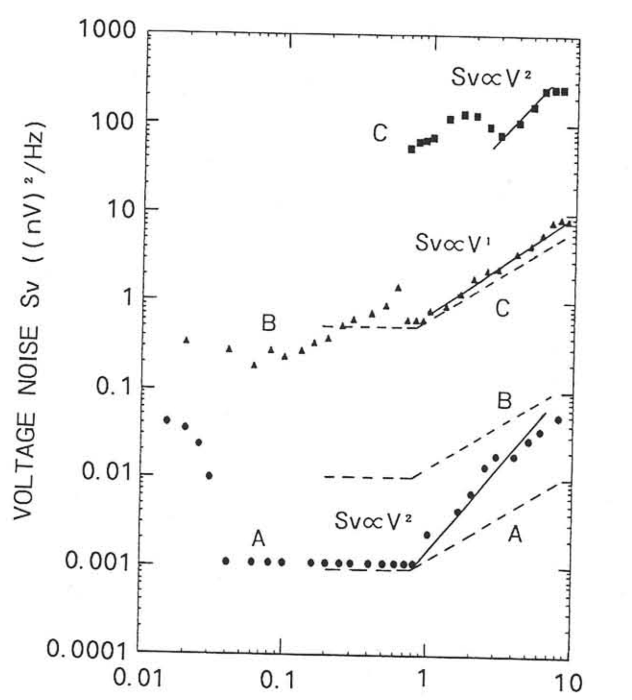


Fig.4 The voltage noise power spectral density Sv vs bias voltage for various type nanobridge dc SQUIDs.

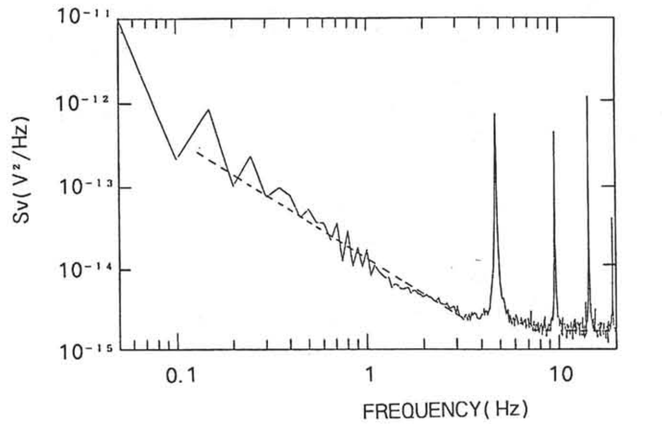


Fig.5 Low frequency noise of a field evaporataed dc SQUID.

In the type A SQUID, for the voltage range from $200\mu V$ to $800\mu V$, the spectral density of voltage noise is constant and agreement with the predicted value since the noise is dominated by thermal noise of resistance of the SQUID. At $V \lesssim 40\mu V$, Sv increases with decreasing of bias voltage due to the increase of dynamic resistance of the SQUID. For the type B and type C SQUID, at $V \lesssim 1mV$, Sv is also dramatically change due to the dynamic resistance. The amplitude of voltage noise is, however, not agreement with theoretical value. The origin of this excess Sv is not still understood.

On the other hand, for $V \gtrsim 1mV$, the spectral density increases with the slope of V^r. Sv shows the approximate parabolic (V^2) voltage dependence for type A and C SQUIDs and linear (V^1) voltage dependence which predicted for shot noise for type B SQUID.[11] The bridge length for type A and C SQUIDs is apparently longer than that of type B SQUID. The V^2 dependence of Sv may be caused by Joul heating due to hot spot occured in the bridge by biasing high voltage.

Typical low frequency noise of the field-evaporated SQUID is shown in Fig. 5. The onset of 1/f noise is about 3Hz. Also, it is found that NbN nanobridge dc SQUID has low telegraph-like noise. This result is useful for SQUID magnetometer application measuring the low frequency signal such as biomagnetism.

SUMMARY

Various type NbN nanobridge SQUIDs have fabricated and their noise properties were discussed. The NbN nanobridge SQUIDs have the current-phase relationship which is close to sinusoidal. In high-bias voltages it is found that in shorter bridge case, such as $\ell \sim \xi$, the spectral density of the voltage noise showed the linear voltage dependence. For the long bridge, such as $\ell \sim (3\sim5)\xi$, the spectral density of the voltage noise showed the parabolic voltage dependence. From the present results, the effective length and nonequilibrium effect of nanobridge may be evaluated by measuring the shot noise in high-bias voltages. The field-evaporated NbN nanobridges with submicron area junctions have low telegraph-like noise. The field-evaporated SQUIDs may be useful as magnetic sensors for measurement of biomagnetism.

ACKNOWLEDGEMENT

We are grateful to Mr. T. Kondo for his help in the fabrication process of the step-edge junction.

Financial support of the work was provided by the SECOM Foundatation's Research Grant.

REFFERENCE

1) P. Carelli and V. Foglietti, J. Appl. Phys., 53 (1982) 7592.
2) M. B. Kectchen and J. M. Jaycox, Appl. Phys. Lett., 40 (1982) 736.
3) R. F.Voss, R. B. Laibowitz, A. N. Broers, S. I. Raider, C. M. Knoedler and J. M. Viggiano, IEEE Trans. Magn., Mag-17 (1981) 395.
4) C. D. Tesche and J. Clarke, J. Low Temp. Phys., 30 (1979) 397.
5) H. Dang and M. Radparvar, IEEE Trans. Magn., MAG-27 (1991) 3157.
6) S. E. Huq, M. G. Blamire, J. E. Evetts, D. G. Hasko and H. Ahmed, IEEE Trans. Magn., MAG-27 (1991) 3161.
7) K. K. Likharev, Rev. Mod. Phys., 51 (1979) 101.
8) A. I. Braginski, J. R. Gavaler, M. A. Janocko and J. Talvachio, in SQUID '85, edited by H. D. Hahlbohm and H. Lubbig, Walter de Gruyter & Co., Berlin (1985) 591.
9) A. Irie, K. Hamasaki, T. Yamashita, T. Matsui and B. Komiyama, IEEE Trans. Magn., MAG-27 (1991) 2967
10) K. Hamasaki, Y. Misaki, T. Yamashita, S. Nagaoka and T. Komata, Proc. ICEC-11, G. Klipping and I. Klipping, eds., (1986) 508.
11) K. R. Carroll and H. J. Paik, J. Appl. Phys., 65 (1989) 4333.