2 THz Hot Electron Bolometer Mixer using a Magnetic Thin Film

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***Abstract*— To expand the intermediate frequency (IF) band and improve the sensitivity of a hot electron bolometer mixer (HEBM), we have proposed and examined a new HEBM structure using a nickel (Ni) magnetic thin film (Ni-HEBM). We found that it was possible to suppress the superconductivity under the electrodes of the HEBM caused by the niobium nitride (NbN) thin film for construction of the superconducting strip by the addition of a Ni thin film. By using Ni-HEBM structure, superconductivity exists only in the region between both electrodes and we think that it is possible to further miniaturize the HEBM. The miniaturization acts to expand the IF band, improve the sensitivity and is expected to reduce the required LO power. By using the Au (100nm) / Ni (0.6 nm) bilayer for the electrodes, we fabricated Ni-HEBM with a NbN strip of 0.1 μm-length. The IF bandwidth of the fabricated Ni-HEBMs was evaluated at 1.9 THz. We confirmed that the IF bandwidth expands, and the evaluated bandwidths was about 6.9 GHz at 4 K.**

***Index Terms*—IF bandwidth, HEBM, NbN, Ni, THz.**

I. Introduction

In the terahertz band, there are plenty of emission lines from atmospheric constituents, that are applicable to observational studies of atmospheric dynamics and chemistry. For such applications, a heterodyne receiver with a high frequency resolution is necessary. Up to 1 THz, superconductor–insulator–superconductor (SIS) mixers show excellent performance and have already been used [1]-[3]. However, in the frequency region above 1.5 THz, it is difficult to realize, and superconducting hot-electron bolometer mixers (HEBMs) are expected as low-noise mixer elements. Several reports have already been made on the low noise operation of HEBMs with less than ten times the quantum noise limit in the terahertz frequency range [4]-[6]. However, the IF bandwidth of an HEBM is not sufficient when compared to that of an SIS mixer. Consequently, the usable IF band of receivers with an HEBM still remains limited to typically 3–5 GHz [7], [8]. Therefore, in recent years, several studies have focused on broadening the IF band. To broaden the IF band, efficient cooling of the hot electrons is required. In general, there are two cooling mechanisms of the HEBM, the heat dissipation process of excited electrons: lattice cooling and diffusion cooling. Lattice cooling releases the excitation energy to the substrate via the lattice, and diffusion cooling diffuses the excited electrons to the metal electrode directly [9]-[11]. In recent years, much research has focused on lattice cooling. However, we have proposed a new HEBM structure using a magnetic thin film that actively uses diffusion cooling to expand the IF band. Here, Ni thin films were used as the magnetic thin film; therefore, the new HEBM structure is denoted as Ni-HEBM. In this report, first, we influence of the Ni thin film on the superconductivity of the NbN thin film was investigated, and Ni-HEBMs with a strip length of 0.1 μm were fabricated and characterized.

II. Fabrication of Ni-HEBM

In Ni-HEBM proposed by this research, suppression of superconductivity by Ni is important. To suppress the superconductivity of NbN strip under the electrode, a Ni magnetic thin film places between the superconducting strip and the gold (Au) metal electrode. The details of the element structure and the manufacturing method are described in [12]. As a result, superconductivity exists only between both electrodes, and we think that it is desirable for further miniaturization of HEBM. To expand the IF band and improve the sensitivity, we tried to fabricate Ni-HEBMs with a strip length of 0.1 μm.

A. Optimization of the Ni thickness for Suppression of NbN Superconductivity

For miniaturization of Ni-HEBM, reducing the influence of the Ni addition is preferred. We have reported that superconductivity of the NbN strip near the electrodes was also suppressed by the Ni thin film and the region was to be series resistance of several Ω [12]. The resistance caused by Ni addition is expected to act as loss and reducing dR/dT of HEBM. Therefore, we tried to optimize the thickness of Ni for miniaturization of Ni-HEBM.

To investigate the influence of Ni thickness dependency on the superconductivity, three types of samples were prepared and

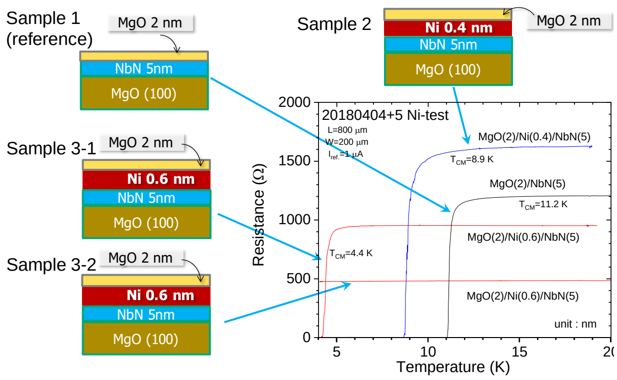
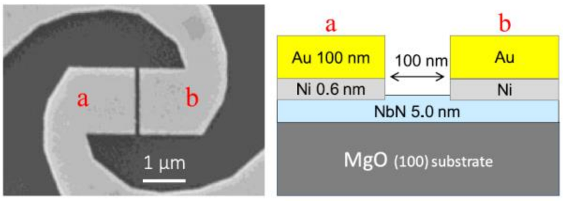


Fig. 1. Ni thickness dependency of NbN superconductivity in Ni/NbN bilayers. To investigate the influence of Ni thickness dependency on the superconductivity, three types of samples were prepared and tested.



(a) (b)

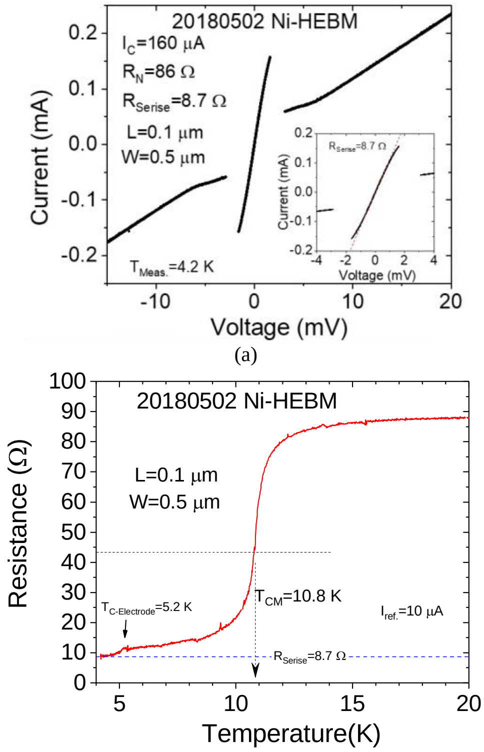
Fig. 2. A SEM image and a schematic of the cross section of the Ni-HEBM. The superconducting strip length and width were 0.1 and 0.5 µm, respectively. (a) A SEM image. (b) Cross section.

tested. Sample-1 had a bilayer of MgO (2 nm) and NbN (5 nm) which was fabricated as a reference of NbN superconductivity. Samples-2 and -3 are both three-layer films of MgO (2 nm)/Ni /NbN (5 nm), and only the Ni film thickness was changed. The Ni film thickness of the Sample 2 was 0.4 nm, and the Sample 3 was 0.6 nm. Here, the MgO layer which was deposited by an ion-beam sputtering was used as a passivation layer on the Ni or NbN surface [13], and all films were continuously deposited in high vacuum. Fig. 1 shows the schematics and the temperature dependences of resistance of each sample. Sample-1 exhibited a T_{CM} of 11.2 K. Here, T_{CM} is the temperature at which the resistance is halved. Sample-2 showed T_{CM} of 8.9 K, and it showed that 0.4 nm thick Ni thin film was insufficient. Sample-3 was fabricated two samples, and one showed that one was T_{CM} of 4.4 K and the other was no superconductivity. We think that 0.6 nm thick of Ni thin film is critical thickness to suppress the superconductivity of 5 nm thick NbN thin film. In actual device fabrication, it is considered that the superconductivity of the NbN thin film under the electrode is degraded because ion beam etching of the NbN surface of about 1 nm is performed before forming the Ni film. Therefore, we thought that 0.6 nm thick Ni thin film is enough, and this film thickness was adopted to fabricate Ni-HEBMs with the 0.1µm strip length.

B. Fabrication and evaluation of the Ni-HEBM with a strip length of 0.1 µm

HEBMs comprise a structure in which two metal electrodes are connected by an extremely thin superconducting strip. In general, to ensure a good electrical contact, the superconducting strip and both electrodes are usually connected via an overlapped region on the strip. In our proposal, a magnetic thin film is placed between the metal electrode and the superconducting strip in the overlapping region, and the superconductivity in that region is suppressed by the spin electron diffusion from the magnetic thin film. Thus, a HEBM structure with superconductivity only between the two metal electrodes can be realized stable. Details of the Ni-HEBM fabrication process have been published elsewhere [12].

A SEM image (a) and a schematic of its cross section (b) of the Ni-HEBM are shown in Fig. 2. The electrode interval was set at 0.1 µm and the strip width was set to 0.4 – 0.7 µm. A log spiral antenna was adopted as a plane antenna. For both electrodes connected to the superconducting strip, an Au (100 nm)/Ni (0.6 nm) bilayer film was used. The electrode pattern at about 7 µm from the center was drawn by an electron beam lithography system, and the pattern for a lift-off process was formed.



(a)

(b)

Fig. 3. I–V and Resistance–temperature characteristics of a Ni-HEBM with a strip length of 0.1 µm. (a) I–V characteristics of a typical Ni-HEBM at 4.2 K. (b) A typical resistance–temperature characteristics.

Fig. 3 shows the *I–V* characteristics (a) and resistance–temperature characteristics (b) of the typical Ni-HEBM measured by the four-terminal method. The NbN strip length and width were 0.1 and 0.5 µm, respectively. In Fig. 3(b), the transition temperature T_{CM} was about 10.8 K. The antenna pattern made of the Au(150nm) /Nb(5nm)/NbN(5nm) trilayer film showed superconductivity at about 5.2 K. However, the metal electrodes in the central region of about 7 µm did not show superconductivity due to the presence of Ni. The resistance of the metal electrodes ($R_{Electrode}$) was evaluated to be about 0.8 Ω [12]. Meanwhile, the Ni-HEBM showed a series resistances (R_{Series}) of 8.7 Ω at 4.2 K. It is considered that the superconductivity of the NbN strip near both electrodes was also suppressed by the effect of the Ni. As a result, both regions of NbN strip near both electrodes are considered to be series resistances ($2R_{Strip}$) and $2R_{Strip}$ was estimated to be about 7.9 Ω. We think that the optimization of Ni influence was insufficient and it is necessary to reduce R_{Strip}.

III. Evaluation of the Ni-HEBM

The IF bandwidth of the fabricated Ni-HEBMs was evaluated at 1.9 THz. As a signal, a stable source that was generated by a unitraveling carrier photodiode using the difference frequency component of two optical comb signals with an appropriate frequency interval of 106 was used. As a local oscillator, 144 times VDI multiplier was used. The HEBM

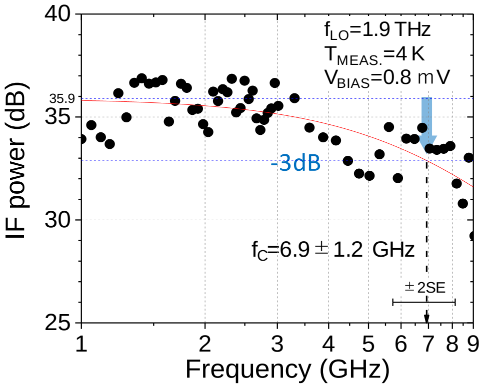


Fig. 4. The IF gain bandwidth of the Ni-HEBM. The superconducting strip length and width were 0.1 μm and 0.5 μm, respectively. The LO frequency and the measurement temperature were 1.9 THz and 4 K, respectively.

was biased with a voltage source, and the irradiation power of LO was controlled to keep a constant current value with the attenuator. Details of the evaluation setup for the IF gain bandwidth have been published elsewhere [12].

Fig.4 shows the evaluation of the IF gain bandwidth of the Ni-HEBM with strip length of 0.1 μm. Here, ±2 times the standard error (SE) is written as f_C error bars in the figure. The IF bandwidth was evaluated about 6.9 GHz at 4 K. The uncorrected receiver noise temperature of same Ni-HEBM was also evaluated at 4 K, and it was about 1220 K(DSB) at 2 THz.

IV. Conclusion

To expand the IF band of a HEBM, we have proposed and examined a new structure of Ni-HEBM. To realize the miniaturization of Ni-HEBM, the thickness dependency of Ni to NbN superconductivity was evaluated and we found that 0.6 nm thick of Ni thin film was critical thickness to suppress the superconductivity of 5 nm thick NbN thin film. By using the Au (100 nm) / Ni (0.6 nm) bilayer for the electrodes, Ni-HEBMs with a NbN strip of 0.1 μm-length were fabricated. However, the Ni-HEBM fabricated showed the series resistance of 7.9 Ω which was caused by Ni influence and further optimization is needed. The IF bandwidth of the fabricated Ni-HEBMs was evaluated at 1.9 THz and it was about 6.9 GHz at 4 K.

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