Broadening the IF band of a THz hot electron bolometer mixer by using a magnetic thin film

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Abstract— To expand the IF band and improve the sensitivity of a hot electron bolometer mixer (HEBM), we examined and proposed a new HEBM structure using a magnetic thin film. We found that it was possible to suppress the superconductivity of the 5-nm thick niobium nitride (NbN) thin film by the addition of a 1.8-nm thick nickel (Ni) thin film. It was also confirmed that the superconductivity disappeared in the Au (70 nm)/Ni (1.8 nm)/NbN (5 nm) tri-layer for forming the electrodes of the HEBM. By using the magnetic thin film for the electrodes, we suggested that the superconductivity of the HEBM strip would be affected and that hot spots near the electrodes would form. This approach is effective for shortening the hot electron drift length and will lead to the expansion of the IF bandwidth. We think that the new structure lowers the required LO power and improves the sensitivity by suppressing the proximity effect under the metal electrode. The HEBMs using a Ni thin film were fabricated and the IF bandwidth was evaluated at 1.9 THz. We confirmed that the IF bandwidth expands, and the evaluated bandwidths were in the range of 5.1–5.7 GHz at 4 K.

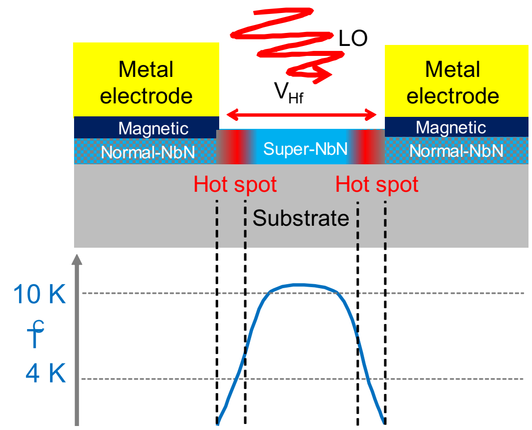

Fig. 1. Schematics of the structures of a new HEBM using a magnetic thin film.

I. Introduction

In the terahertz band, there are plenty of emission lines from atmospheric constituents, such as oxygen, atomic oxygen, water vapor, ozone, OH, and CO, which are applicable to observational studies of atmospheric dynamics and chemistry. For such applications, a heterodyne receiver with high frequency resolution is necessary. HEBMs are expected as extremely low noise mixer elements in applications above 1.5 THz. Several reports have already been made on the low noise operation of HEBMs with less than 10 times the quantum noise limit in the terahertz frequency range [1-3]. However, the IF bandwidth of a HEBM is not sufficient compared to a SIS mixer. Consequently, the usable IF band of receivers with HEBM still remain limited to typically 3-5 GHz [4,5]. It may not be sufficient for spectroscopic observations of a variety of atmospheric molecules or efficient wind measurement using several emission lines. Therefore, in recent years, several research efforts have focused on expanding the IF band.

To expand the IF band, efficient cooling of hot electrons is required. In general, there are two cooling mechanisms of HEBM, the heat dissipation process of excited electrons, and they are “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. However, many of the current HEBMs were designed on lattice cooling. Though they are good achievements, we think that there are still problems. One is reduction of the required LO power, and the other is that the operating temperature of low noise performance and wide IF band performance are different.

From this background, we have proposed and examined a new HEBM structure using a magnetic thin film. The schematics of the structure of the new HEBM using a magnetic thin film is shown in Figs. 1. The new structure aims to expand the IF band by positively utilizing diffusion cooling. In addition, we are aiming at lowering the required LO power and improving the sensitivity. HEBMs have a structure in which the two metal electrodes are connected by an extremely thin superconducting strip. In general, to ensure good electrical connection, 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 this overlapping region, and the superconductivity of the strip in this region is suppressed by spin electron diffusion from the magnetic thin film. Thus, an HEBM structure with superconductivity only between the two metal electrodes can be realized. Superconductivity of the strip near the electrodes is also

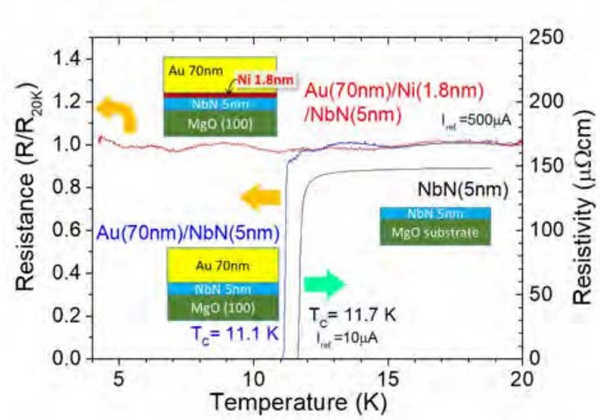

Fig. 2. Suppression of the NbN superconductivity under the HEBM metal electrode by insertion of a Ni thin film.

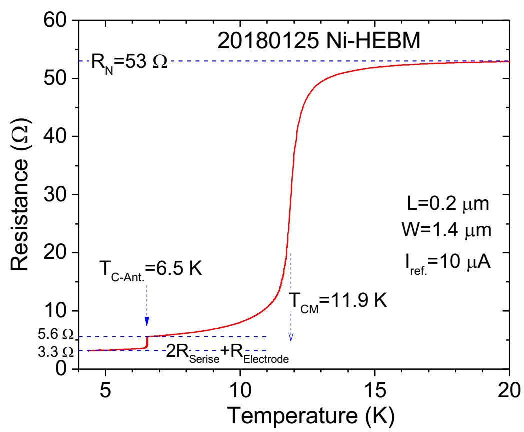

Fig. 3. The resistance–temperature characteristics of a typical Ni-HEBM. The inset shows characteristics near zero voltage.

suppressed by the magnetic thin film. Under LO irradiation, we think that the regions near the electrodes lose the superconductivity first and two hot spots are formed near the electrodes. As a result, the drift length of the hot electrons is shortened and the diffusion efficiency of the hot electrons to the electrodes is improved. Therefore, it is expected that the IF band will be expanded.

We also expect to reduce the required LO power and improve the HEBM sensitivity. In the conventional HEBM structure, the superconductivity under the electrode is remained. During operation of the HEBM, a hot spot is formed at the center between the electrodes with poor cooling efficiency, but it is considered that the superconductivity under both electrodes is maintained by the shielding effect of the metal electrodes against the LO. Therefore, the proximity effect due to the superconducting region under the electrodes is supposed to suppress hot spot formation. Thus, we believe that sensitivity reduction and the required LO power increases, i.e., limiting the superconducting region to only between the electrodes by the addition of a magnetic thin film makes it possible to further minimize the length of the superconducting strip and to realize the widening of the IF band and the reduction of the required LO power. In this paper, Ni thin films were used as the magnetic thin film; therefore, we denote the new HEBM structure as Ni-HEBM.

II. Fabrication of Ni-HEBM

A. Suppression of NbN superconductivity by Ni film

The Ni and Au thin films were deposited by using thermal evaporation methods. The deposition rates of Ni and Au were ~1.8 and ~36 nm/min, respectively, at room temperature. A 5-nm thick NbN thin film was used as the superconducting thin film. The NbN film was deposited by reactive sputtering at room temperature and epitaxially grown by using a magnesium oxide (MgO) single crystal substrate. Details of the NbN film deposition have been published elsewhere [6].

To confirm the superconductivity under the metal electrode of Ni-HEBM, a Au (70 nm)/Ni (1.8 nm)/NbN (5 nm) tri-layer was continuously deposited onto the MgO substrate under high vacuum. Fig. 2 shows the temperature dependence of the resistance of the tri-layer. For comparison, the Au (70 nm)/NbN (5 nm) bilayer, which is used for electrodes in a conventional HEBM, was also fabricated and measured. The Au/Ni/NbN tri-layer film did not show superconductivity until 4.2 K. However, the Au/NbN bilayer film showed a decrease in T_C of ~0.6 K, which is considered to be due to electron diffusion from the metal electrode, but it transited to the superconducting state at 11.1 K. From these results, a Au (100 nm)/Ni (1.8 nm) bilayer was used for the Ni-HEBM metal electrode.

B. Fabrication of Ni-HEBM

A 5-nm thick NbN thin film was used as the superconducting strip. To secure a high T_C, a single crystal MgO (100) substrate was used. NbN thin films were deposited by using DC reactive sputtering, and they showed a T_C of ~12 K. The electrode interval to determine the strip length was set at 0.2 µm and the strip width was set to 0.8–1.4 µm. As a plane antenna, a log spiral antenna was adopted. For both electrodes connected to the superconducting strip, a Au (100 nm)/Ni (1.8 nm) bilayer film was used. The electrode pattern at ~7 µm from the center was drawn by an electron beam lithography system. In this region, the NbN thin film constituting the superconducting strip exists under the Au / Ni bilayer, but the superconductivity was suppressed by the Ni film. On one hand, the antenna pattern of the outer region was formed using a photolithographic process. The antenna was patterned using an Au (150 nm)/Nb (5 nm)/NbN (5 nm) tri-layer by the lift-off method. The tri-layer in this region shows superconductivity. Fig. 3 shows the resistance–temperature characteristics of a typical Ni-HEBM. It was measured by the four-terminal method. The NbN strip length and width are 0.2 and 1.4 µm, respectively. In Fig. 3, the normal resistance (R_N) at 20 K is ~53 Ω and the transition temperature at which the resistance reached half of R_N (T_{CM}) was 11.9 K. The antenna pattern made of the Au/Nb/NbN tri-layer film showed superconductivity at 6.5 K. The residual resistance of 3.3Ω less than 6.5 K is considered as the sum of the NbN strip resistance of the regions near the electrodes which lost superconductivity due to the influence of Ni and the electrode resistances at ~7 µm from the center.

III. Evaluation of the IF bandwidth of Ni-HEBM

The evaluation setup for the IF gain bandwidth is shown in Fig. 4. Here, the IF gain bandwidth of the HEBMs were evaluated at 1.9 THz which is above the NbN gap frequency. As a signal, a stable source, which was generated using a uni-

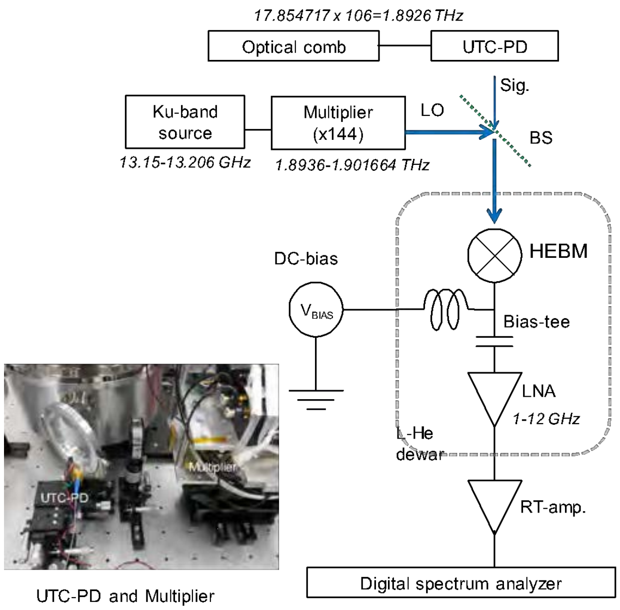

Fig. 4. The IF gain bandwidth evaluation setup of HEBM at 1.9 THz.

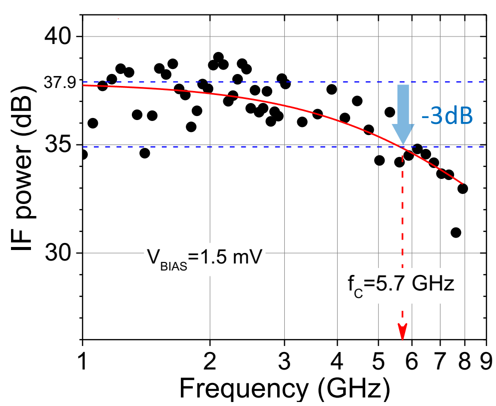

Fig. 5. IF gain bandwidth of the Ni-HEBM. The LO frequency, the measurement temperature, and the bias voltage were 1.9 THz, 4 K, and 1.5 mV, respectively

traveling carrier photodiode (UTC-PD) using the difference frequency component of two optical comb signals, at an appropriate frequency interval of 106 was used. As LO, the output of a multiplier manufactured by VDI was used. A DC bias voltage (V_{BAIS}) was applied through the bias tee to the Ni-HEBM, and the IF output was amplified using a cooled LNA that has a bandwidth of 1–12 GHz. Here, in the IF band measurement, the signal frequency was fixed and the LO frequency was changed. However, the output power changes with respect to the set oscillation frequency. Therefore, by controlling the LO output power with a LO-attenuator so that the bias current flowing in the HEBM becomes constant, the LO power incident on the HEBM was kept constant. The IF output power was measured using a digital spectrum analyzer and the difference between the IF output and the ground level near the IF signal was taken as the IF output value. All of the IF gain bandwidths were evaluated at ~4 K.

For comparison, the IF gain band evaluation of the conventional HEBM was performed. The NbN strip thickness, length, and width were 3.0 nm, 0.4 μm, and 3.2 μm, respectively. Details on the conventional HEBMs have been published elsewhere [7,8]. The IF roll-off frequency was decided by fitting to the equation of the low-pass filter model. As a result, the IF gain bandwidth of the conventional HEBM was ~4.1 GHz when the V_{BIAS} was 1.5 mV. The IF gain bandwidths of HEBM at a V_{BIAS} of 1.0 and 2.0 mV were also measured and they were 3.3 and 4.4 GHz, respectively. We also reported the IF noise bandwidth of the conventional HEBM. The NbN strip thickness, length, and width of the HEBM were 3.0 nm, 0.2 μm, and 2.0 μm, and the IF noise bandwidth was ~3 GHz [8]

Next, the IF gain bandwidths of the Ni-HEBM were evaluated and are shown in Fig. 5. The NbN strip thickness, length, and width of the conventional HEBM were 5.0 nm, 0.2 μm, and 0.8 μm, respectively. The IF bandwidths of the Ni-HEBM were evaluated at a V_{BIAS} of 1.0, 1.5 and 2.0 mV, and they were found to be 5.1, 5.7, and 5.7 GHz, respectively, which were wider than the bandwidth of the conventional HEBM. From these results, it is concluded that the IF bandwidth of the Ni-HEBM was expanded compared to the conventional HEBM.

Conclusions

To increase the IF bandwidth and improve the sensitivity, we proposed a new HEBM structure, Ni-HEBM, which used a magnetic Ni thin film. It was found that it is possible to suppress the superconductivity of the 5-nm thick NbN thin film by using a 1.8-nm thick Ni thin film. It was also confirmed that the superconductivity disappeared in the Au(100 nm)/Ni(1.8 nm)/NbN(5 nm) tri-layer forming the electrodes of the Ni-HEBM. By using these electrodes, hot spots are formed near the electrodes, which are effective for shortening the relaxation time of the hot electrons. The HEBMs using a Ni thin film were fabricated and the IF bandwidth was evaluated at 1.9 THz. We confirmed that the IF bandwidth expands, and the evaluated bandwidths were in the range of 5.1–5.7 GHz at 4 K.

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