Study of mid infrared hot electron bolometer mixers

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Abstract— To design antennas for mid-infrared (MIR) hot electron bolometers (HEBs), the surface impedance of Au thin films at cryogenic temperatures was evaluated using Fourier transform infrared spectroscopy (FTIR) with a sample cooling system. For the evaluation, resonator arrays that were constructed by gold (Au) thin film strips were fabricated and the corrected surface reactance was estimated. MIR HEBs with a twin-slot antenna for operation at 61 THz were designed and fabricated using the corrected surface impedance. For evaluating the mixer properties of the MIR HEBs, measurement setup without beam splitter was constructed. In this setup, IF output power characteristics of the MIR HEB mixer was observed. But the obvious difference of the IF output power between 1000 K and 30 K thermal loads have not been confirmed.

INTRODUCTION

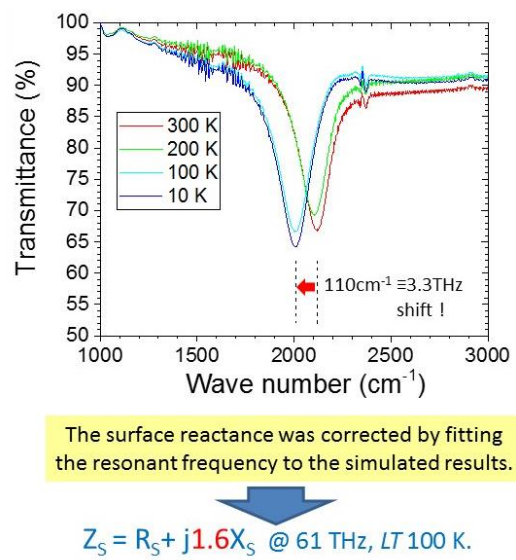
Electromagnetic waves generally exhibit both particle and wave properties. Many conventional mid-infrared (MIR) detectors are designed with structures and mechanisms based on the particle nature of light. One of the reasons for this design choice is that photons possess high energy with short wavelengths. However, such detectors usually suffer from a tradeoff between sensitivity and response speed because sensitivity depends on the detection area, and the electrostatic capacitance of a detector tends to increase with increasing area. Therefore, there were several reports of IR detection utilizing the wave nature of light [1], [2]. We also propose the use of nano-antennas to improve the response performance of infrared detectors [3]-[6].

Significant research and development in superconducting hot-electron bolometer (HEB) mixer has led to the emergence of low noise electromagnetic wave receivers in the terahertz frequency range [7]-[9], and we also contributed to this research and development effort [10]. Such mixer typically consists of a planar antenna for efficiently capturing electromagnetic waves in the air, combined with a small detector made of a niobium nitride(NbN) thin film strip located at the feeding point of the antenna. The upper limit of the operating frequency of HEB is considered to be determined by the physical structure of the device. We therefore recognized the potential for achieving greater response speed and efficiency in infrared photo-detectors, by separating the mechanisms for receiving and detecting light as the optical antenna and micro detector, and optimizing their functions.

In this paper, we report on the evaluation of the surface impedance of gold (Au) thin films under cryogenic conditions. Using the corrected surface impedance, we designed and fabricated MIR HEBs. The fabricated MIR HEB was evaluated at 61.3 THz.

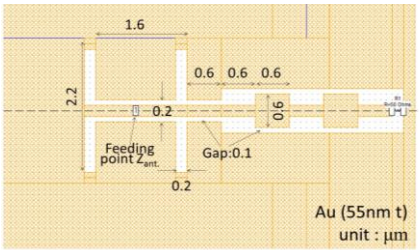
DESIGN AND FABRICATION OF MIR HEBS.

For the simulation of MIR circuits, the dielectric constant of the magnesium oxide (MgO) substrate [11] and the complex surface impedances of the Au films were needed. The impedances could be derived using the measured complex refractive indices, however, these derivations were insufficient for designing superconducting MIR devices operating at cryogenic temperature. Therefore, we corrected the surface impedance at cryogenic temperatures by using a FTIR with sample cooling system. For the evaluation, resonator arrays constructed of thin film strips of Au were fabricated. Their length and width were set at 1.3 µm and 0.2 µm, respectively. The Au thickness was 55 nm. In the transmittance spectrum, the resonant frequency was observed as absorption properties at around 61 THz. When the temperature changed from 300 K to 10 K, it was found that the resonant frequency shifted to the low

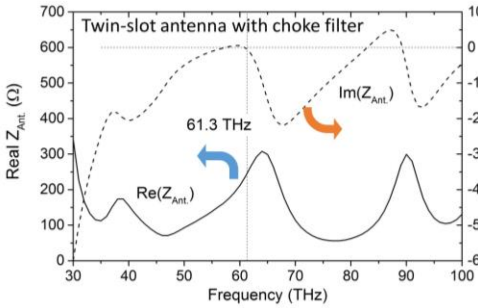


(b) The transmittance spectrums at various temperatures.

Fig. 1. Transmittance spectrums of the resonator array at various temperatures.



(a) Design of the twin-slot nano-antenna



(b) Simulated impedance of the twin-slot nano-antenna at feeding point

Fig. 2. Design and impedance of the twin-slot nano-antenna.

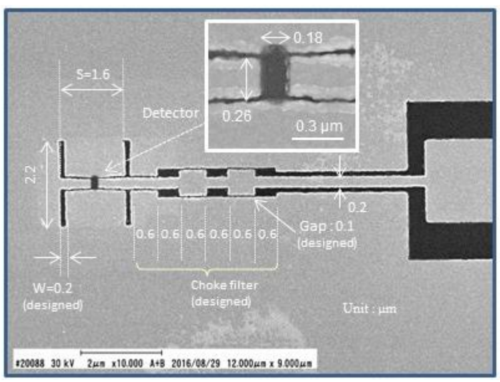


Fig. 3. SEM image of the MIR HEB,

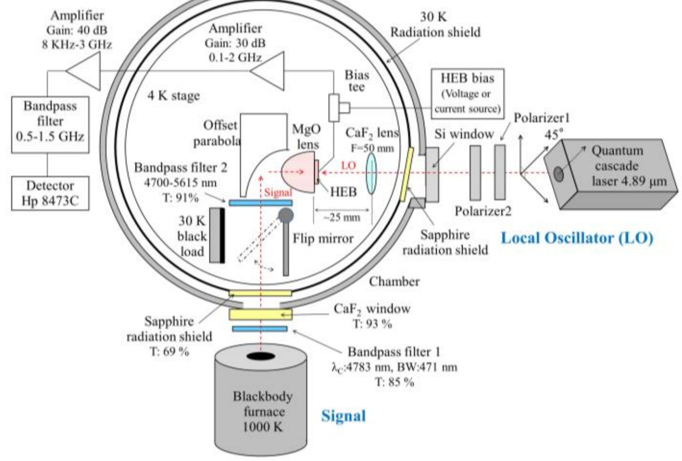
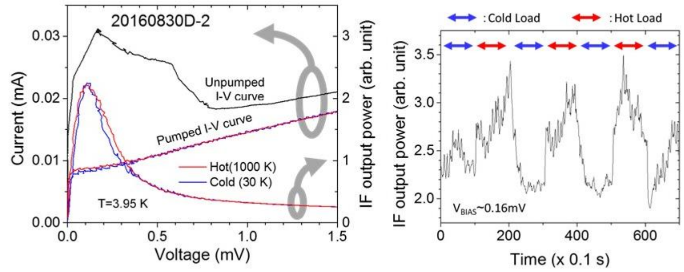


Fig. 4. Measurement setup for evaluating the MIR HEBs.



(a) I-V and IF output power characteristics (b) IF output power – Hot/Cold Loads

Fig. 5. I-V and IF output power characteristics of the MIR HEB as a function of bias voltage.

frequency side (See Fig. 1). By using resonant frequency under cryogenic, we corrected the surface reactance by fitting the resonant frequency to the simulated results. The correction value was found to be 1.6 times the surface reactance at room temperature.

MIR nano-antennas were designed for operation at 61.3 THz. Fig. 2. shows the design and the calculated impedance of the antenna. The antenna was a twin-slot antenna, and the slot length and width were decided by the simulated results and set at 2200 and 200 nm, respectively. The size of the choke filter was also decided. At the designed frequency, the antenna impedance was expected to be $Z_{Ant.} = 250 - j6\ \Omega$.

For impedance matching between the superconducting strip and the antenna, we used an Nb(2.5-δ nm)/NbN(5 nm) bilayer as the superconducting strip. Here, for electric contact, the surface of the bilayer was etched by Ar ion beam and the etched depth δ was estimated at less than 1 nm. Fabricating the MIR HEBs with an antenna structure requires the building of fine structures on nano scales. We developed a new fabrication process using electron beam lithography for all our lithography processes. The details of the fabrication process have already been described elsewhere [3], [4]. Fig. 3 shows a SEM image of the fabricated MIR HEB, the inset is a magnified view of the detector. The detector width and length were approximately 0.18 and 0.26 μm, respectively. The critical current and the normal resistance of the HEB were approximately 32 μA and 200 Ω, respectively.

EVALUATION OF MIR HEBS.

Fig. 4 shows the measurement setup for evaluating the mixer properties of the MIR HEBs. The HEB was cooled by a GM refrigerator. A mid-infrared quantum cascade laser (QCL) with a wavelength of 4.89 μm was used as the local oscillator (LO). In this case, the LO power was irradiated from the surface of the HEB. In order to concentrate the LO power, a CaF_2 lens was used. However, we had to slightly defocus the lens to reduce the influence of the vibration of the GM refrigerator. The signal from the thermal load was irradiated from the back of the HEB through an offset parabolic mirror and an anti-reflection coated MgO hyper-hemisphere. A black body furnace set at 1000 K was used as a reference signal. A carbon-nano-tube coated copper block was also used as a 30 K thermal load at which temperature was monitored. Band-pass filters and sapphire windows were used to exclude thermal radiation, except for the signal around LO-wavelength from the furnace. The total transmittance of the two band-pass filters and two windows in the signal input optical path was estimated to be about 50%. The IF signal was amplified by a 0.1–2 GHz cooled low-noise amplifier and an 8 kHz to 3 GHz room temperature amplifier. The signal was then filtered by a bandpass filter centered at 1

GHz with bandwidth of 1 GHz and the IF power was monitored using a Schottky diode detector.

Fig. 5 shows the pumped and unpumped I-V characteristics and IF output power characteristics of the MIR HEB mixer. The IF output showed a maximum at around 0.15 mV. However, the periodic noise caused by the vibration of the GM refrigerator was observed in the IF output characteristics, and the obvious difference of the IF output power between 1000 K and 30 K thermal loads have not been confirmed.

Conclusion

To design superconducting MIR devices, the surface reactance of Au thin films at cryogenic temperatures was evaluated using FTIR with a sample cooling system. Resonator arrays constructed with Au thin film strips were fabricated. The resonant frequency was set at about 61 THz. When the temperature was changed from 300 K to 10 K, it was found that the resonant frequency shifted to the low frequency side. By fitting the resonant frequency to the simulated results, the surface reactance at 10 K was corrected. MIR HEBs with a twin-slot antenna were designed and fabricated using the corrected surface impedance. For evaluating the mixer properties of the MIR HEBs, measurement setup without beam splitter was constructed. IF output power characteristics of the MIR HEB mixer was observed but the obvious difference of the IF output power between 1000 K and 30 K thermal loads have not been confirmed.

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