Design and fabrication of mid-infrared superconducting hot-electron bolometers

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Abstract
To design antennas for mid-infrared superconducting hot-electron bolometer (HEB), the surface reactance of Au thin film at cryogenic temperatures was evaluated using Fourier transform infrared spectroscopy with a sample cooling system. We fabricated mid-infrared resonator arrays that were constructed by gold thin film strips, and found that the resonant frequency was lowered by the low frequency side as the temperature was lowered. By fitting the resonant frequency to simulated results, the corrected surface reactance was established. Prototypes of a mid-infrared HEB formed by a twin-slot antenna with a niobium nitride strip were fabricated. When the HEB was biased close to the critical current under mid-infrared pulsed light (λ=4.89 μm) irradiation, the detector output synchronized with the trigger signal was observed. The output waveforms comprised voltage pulse trains, and the full width at half maximum of the pulse was evaluated to be approximately 0.25 ns.

I. Surface impedance correction of gold under cryogenic

Because of the mid infrared light range is at the region of occurrence of anomalous skin effect, the complex surface impedances of the Au films were needed for the simulation of MIR circuits. The impedances were derived using the measured refractive indices. However, these derivations were insufficient for designing superconducting MIR devices. Therefore, we corrected the surface impedance of cryogenic temperatures by using a FTR with sample cooling system.

II. Design of mid-infrared twin-slot antenna with Xc correction

By using the corrected surface impedances, the antenna size was designed using the Sonnet EM simulator for operation at approximately 60 THz. The designed frequency -0.17 THz [0.848ppm].

The antenna was twin-slot antenna and the slot length and width were set at 2200 and 200 nm, respectively. The passive circuits were also designed by the simulator. At designed frequency of 61.3 THz, the antenna impedance was expected to be Z = 250 - j0.6 Ohm.

III. Fabrication of MIR HEBs with a twin-slot nano-antenna

1. Study of MIR-HEB structure using NbN

It is expected that Cooper pairs are injected into the hot spot region close to the superconducting region due to the proximity effect, which is undesirable as a reduction in response to the incident radiation. Since it is difficult to construct a superconducting slot only at the feeding point (see fig. (a)), we attempted suppression of superconductivity under the electrodes by using a magnetic thin film under the metal electrode (see fig. (b)).

We found that superconductivity of Nb (2.5 - 5 nm) / Mo (5 nm) just below electrodes can be eliminated by adding an Ni thin film with a film thickness of 1.8 nm. In this case, the same electrode structure is adopted for MIR-HEB fabrication.

2. Fabrication of MIR HEBs

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 of our lithography processes. To realize this process, two types of inorganic resists of NbN and MgO were used.

IV. Evaluation of MIR HEB detectors

1. Measurement setup for MIR HEB Mixen

A mid-infrared quantum cascade laser (QCL) was used as the local oscillator. Here, the wavelength was 4.8 μm. The polarization of the LO was dictated by “Polarizer”. C. The antenna gain directivity is strong substrate side, but it remains also on the vacuum side. In MIR region, the dielectric constant of MgO was reduced to be about 2.66. Radiation power ratio of substrate P_s and the vacuum direction P_v of the slot antenna formed on a thick dielectric substrate can be expressed as follow(1):

P_s = 2π/3 P_v

Here, using ε = 2.66, the ratio of P_s/P_v = 0.23. This is same or bigger than the reflection of the ordinary beam splitter. Therefore, we thought that, it is possible to use the vacuum side gain to avoid the beam splitter loss. (2) [Infrared and Millimeter Waves, Vol. 15, Part 1, p58]

A black body furnace set at 1000 K was used as a reference signal. 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 Solttoby diode detector.

2. The I-V characteristics of the MIR HEB

was suppressed to almost zero by LO irradiation, and it was found that sufficient power can be given to HEB even with LO irradiation from the space side.

3. IF output power characteristics

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.

V. Output waveform of the HEB under pulsed MIR-light irradiation

1. Operation of the superconducting mid-infrared detector

First, the HEB is biased close to Ic. By the irradiation of mid-infrared light, the electron temperature will be increased and Ic will be reduced. When the Ic is reduced less than the bias current, the output voltage will be observed.

2. Output waveform of the HEB under pulsed MIR-light irradiation.

Under the condition that the incident light was sufficiently attenuated so that the HEB element is not saturated, the detector output was observed to be synchronized with the trigger signal when the HEB was biased close to Ic. The detector showed an output voltage synchronized with the irradiation pulse light. In addition, the individual output voltage waveform was a voltage pulse train having a half width of approximately 0.25 ns.

3. Output waveform under CW-MIR-light irradiation

Due to fluctuation of the transverse wave (CW) of MIR light, the pulse output which was averaged by 4096 pulses was also observed under constant bias. The obtained the full width at half maximum of the pulse was about 0.21 ns.