Wideband THz HEB mixers using HPCVD MgB_2 thin films

E. Novoselov, N. Zhang and S. Cherednichenko
Chalmers University of Technology, Gothenburg 41296, Sweden

***Abstract*— We present results of experimental study of the gain bandwidth (GBW) of MgB_2 hot electron-bolometer (HEB) mixers at 0.1THz and 0.4THz. Antenna integrated 0.25-1.5um^2 area devices were made from thin MgB_2 films deposited with a custom made HPCVD system. Film as thin as 15-45nm had a T_c from 35K to 40K. The GBW was found to be independent on the bias conditions, the bath temperature, and the LO frequency. The maximum GBW of 6GHz was observed for 15nm thick HEBs. At an 0.7THz LO and a 23K bath temperature the receiver noise temperature of this mixer was 3000K (corrected for optical losses).**

I. Introduction

In order to perform astronomical observations in the terahertz (THz) range (0.1-10THz) cryogenic low noise heterodyne detectors are needed due to a low intensity of incoming THz waves and a high spectral resolution requirement (>10^6) for study of astronomical objects dynamics manifested in Doppler-shifted emission lines. Moreover, THz instruments have to demonstrate a broad instantaneous bandwidth to be able to cover fully these broadened lines. At frequencies >1THz superconducting hot-electron bolometers (HEB) are the only choice as a mixing element in high sensitivity heterodyne receivers. They have already been used in many receivers for astronomical observation programs, e.g. the Hershel Space Observatory [1], SOFIA [2], APEX [3], etc.

The gain bandwidth (GBW) of the current state-of-the-art NbN HEB mixers is <2GHz and the noise bandwidth is 4GHz, which is a significant limitation for many astronomical applications. Furthermore, a superconducting critical temperature (T_c) of thin NbN films of about 8-11K forces to use liquid helium (LHe) for device cooling, which reduces the operation time of spaceborne missions. MgB_2 HEB mixers have a potential to solve both of these problems. However, high quality thin MgB_2 films are required to achieve these goals.

II. HPCVD System

A custom made hybrid physical chemical vapour deposition (HPCVD) system was built at Chalmers University of Technology to explore limits for MgB_2 thin films. Detailes of the deposition process can be found in [4], [5]. During the HPCVD process Mg is supplied by evaporation of solid magnesium (Mg) pieces, whereas boron (B) is supplied by high temperature decomposition of diborane gas (B_2H_6). In our HPCVD system a single resistive heater is used both for substrate heating and Mg evaporation. Hydrogen (H_2) as a reduce gas (400sccm), and a 5% B_2H_6 mixture with H_2 (deposition gas, 2-10sccm) were supplied to the deposition chamber using a PC controlled gas panel consisting of pneumatic valves and mass-flow controllers (MFCs). A capacitance manometer and a throttle valve were connected to the pressure controller to set the desired process pressure of 20Torr.

MgB_2 thin films described in this paper were deposited on silicon carbide (SiC) substrates. Film thicknesses, measured

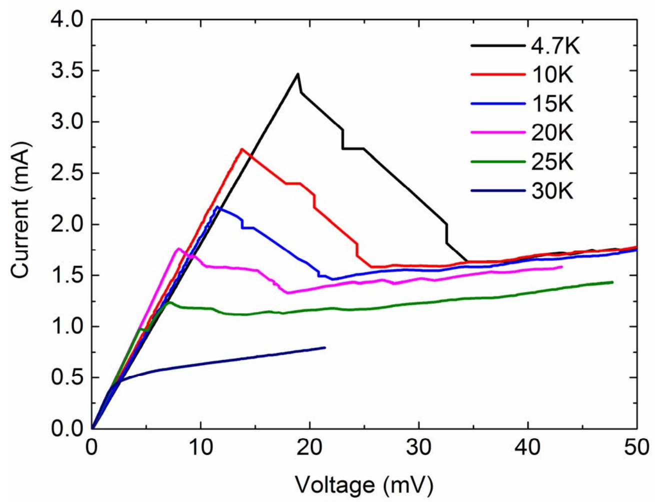

Fig. 1. I-V curve of HEB E6-7 measured in a dip-stick at various bath temperatures. At 4.7K, the critical current density is 2.3×10^7 A/cm^2.

with scanning probe microscope (SPM) on films etched with hydrochloric (HCl) acid, were from 15nm to 45nm depending on the deposition time and the B_2H_6 mixture gas flow. The T_c of deposited films was ranging from 35K (15nm) to 40K (45nm).

III. HEB Fabrication and Characterization

Batches E2 and E3 were fabricated using e-beam lithography, whereas batch E6 was fabricated using photolithography. In all batches, HEBs were integrated with planar spiral antennas. More details on device design and fabrication can be found in [6], [7].

TABLE I
Fabricated Devices: Width (W), Length (L), Room Temperature Resistance (R300), T_c, Critical Current Density at 4.7K (J_C), Deposition Gas Flow and Deposition Time.

Device	W×L, um^2	R_{300}, Ω	T_c, K	J_c, A/cm^2	B_2H_6, sccm	t, sec
E2-2	1×1	40	39.4	6.5e7	10	120
E3-8	0.8×0.8	25	39	6.9e7	5	120
E3-2	0.5×0.5	25	39	6.7e7	5	120
E6-7	1×1.5	65	35	2.3e7	2	100
E6-4	1×1	45	35	1.6e7	2	100

First, for all fabricated devices DC tests were performed in a dip-stick placed in LHe. Selected devices were mounted in mixer blocks and placed inside a LHe cryostat for THz characterization. I-V curves for HEB E6-7 are presented in Fig. 1 as an example. Results of DC characterization, as well as film deposition parameters, are summarized in Table I.

Gain Bandwidth (GBW) measurements were performed at two LO frequencies of 0.1THz and 0.4THz, which are both below the superconducting gap frequency frequency. We observed that the GBW is independent on both the bias voltage and the bath temperature. Fig. 2 represents I-V curves measured

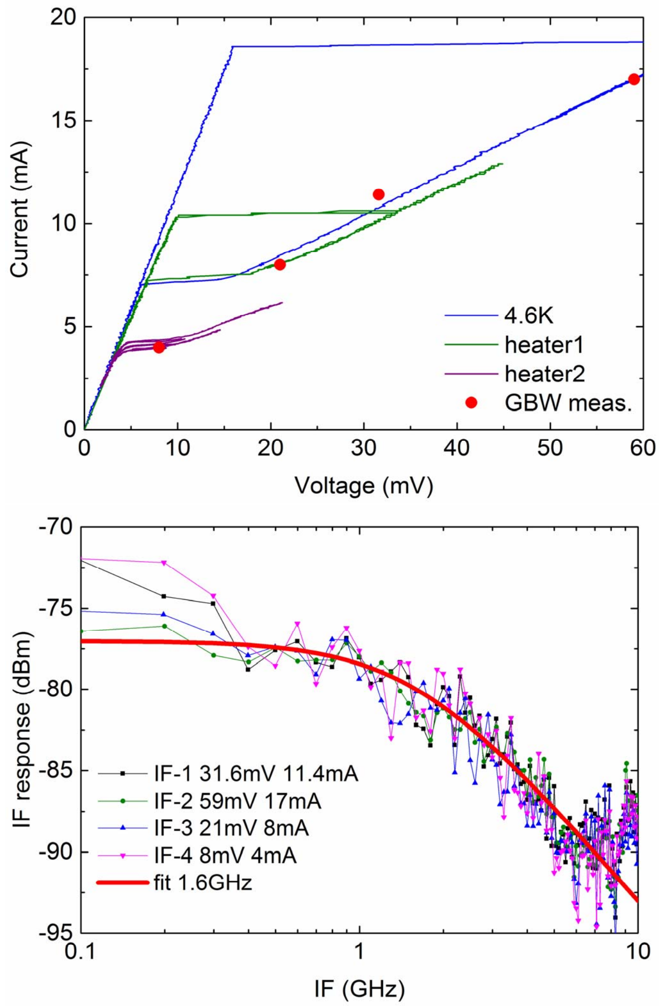

Fig. 2. (a) I-V curves measured in LHe cryostat measured at various bath temperatures and (b) IF response at 0.1THz at various bias points for HEB E2-2.

in LHe cryostat and IF response curves at 0.1THz for GBW measurements of HEB E2-2. The IF response curves taken at different bias points and bath temperatures well coincide. A higher output power of the 0.1THz LO allowed for GBW measurements of the thickest device at a wider range of bath temperatures.

Fig. 3 presents the IF response of HEBs E3-8, E3-2 and E6-7 at 0.4THz. Similar to HEB E2-2, these devices demonstrated GBWs which were almost independent on the bath temperature and the bias condition. Moreover, some devices were tested at both LO frequencies and the same GBWs were achieved. The largest GBW of 6GHz was observed for HEB E6-7 made from the thinnest MgB_2 film. This is about 2-3 times larger than for typical phonon-cooled NbN HEB mixers made of 3-5nm thick NbN films. However, the MgB_2 film thickness is 15nm and there is a room for further improvement.

Preliminary, the mixer noise temperature measurements were performed for device E6-4 using the Y-factor method. The mixer block with the device was followed by a bias-T and a cryogenic 0.1-5GHz LNA placed on the cryostat's cold plate. At 0.7THz LO (far-infrared gas laser) the maximum Y-factor was about 0.15dB at a mixer temperature of 23K. That corresponds to a receiver noise temperature of 6000K (not

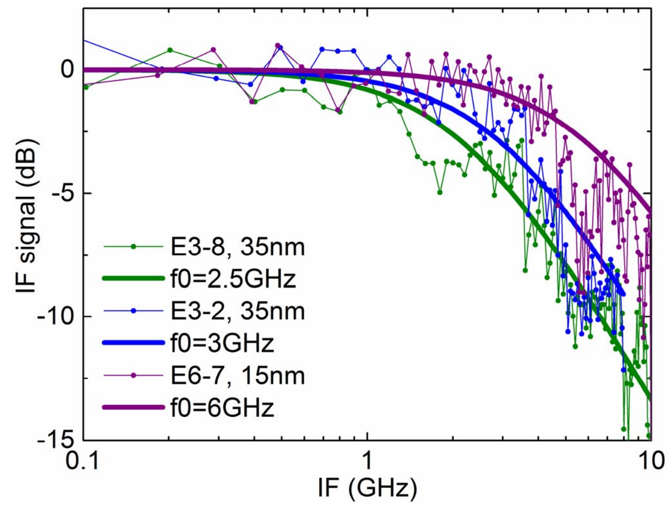

Fig. 3. The GBW of fabricated MgB_2 HEB mixers measured by mixing of radiation from BWO and multiplier source at 0.4THz.

corrected for optical losses) or about 3000K if the contribution from the known optical losses are removed (mostly, from the thick beam splitter). Testing mixers at lower temperatures was not possible at this moment due to the lack of the LO power.

IV. SUMMARY

A possibility of broadband and sensitive HEB mixers fabrication was demonstrated using Chalmers custom made HPCVD deposition system. The full development process from material growth till device THz characterization can be performed at a single place. This gives more opportunities in HEB optimization and improvement.

For our devices, a GBW of 6GHz (2-3 times the one for NbN HEB mixers) was achieved with a $1\times1.5um^2$ MgB_2 device made by photolithography from a 15nm thick HPCVD MgB_2 film with a T_c of about 35K. This result approximately coincides with a GBW of 8GHz reported in [8]. In order to fulfill requirements for astronomical observations, the noise temperature has to be reduced from the current 3000K to about 1000K. The most evident direction for reducing the mixer noise temperature is reduction of the MgB_2/Au interface contact resistance (between the HEB and the Au antenna).

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