MgB_2 HEB Mixers at Operation Temperatures above Liquid Helium Temperature

Evgenii Novoselov*, Naichuan Zhang, and Sergey Cherednichenko
Chalmers University of Technology, Gothenburg, 41296, Sweden
*Contact: evgenii@chalmers.se, phone +46-31-772 1849

Abstract—**In this paper we discuss results of MgB_2 thin films deposition for the hot-electron bolometer (HEB) application. For this purpose a custom made hybrid physical-chemical vapour deposition (HPCVD) system was built. For films thicknesses *d* in the 15-45nm range the critical temperatures were from 34K to 40K. For bridges as narrow as 500nm the critical current density was $>10^7 A/cm^2$ indicating a high film quality. The intermediate frequency (IF) gain bandwidth (GBW) was measured at 0.4THz at various temperatures and bias points. The GBW follows the 1/*d* trend and is at least 6GHz for the 15nm thick sample.**

I. Introduction

Superconducting hot-electron bolometer (HEB) mixers are widely used in heterodyne instruments for sub-mm wave astronomy observations at frequencies of 1.3-4.7THz [1]–[3]. Applicability of currently used NbN HEB mixers are limited to an intermediate frequency (IF) bandwidth of 3-4 GHz. However, for some astronomical observations a larger bandwidth is preferred [4]. For example, with a larger IF bandwidth several spectral lines can be detected during the same scan.

It has been suggested that magnesium diboride (MgB_2) HEB mixers can provide an IF bandwidth up to 10 GHz [5], [6] due to a good film-substrate phonon matching and short electron-phonon interaction time. The demonstrated sensitivity at 4K was comparable to NbN HEB mixers [7], [8]. Moreover, due to a higher T_c (up to 40K in bulk) MgB_2 HEB mixers can be utilized at operation temperatures higher than NbN devices, e.g. >20K. Fabrication of MgB_2 HEB mixers with a T_c above 30K will allow for the use of compact cryocoolers instead of liquid helium (LHe) for the device cooling, which will lead to the increase of spaceborne mission lifetimes.

Superconductivity of MgB_2 was reported in 2001 [9] and immediately triggered a great interest to MgB_2 film deposition. Several methods for thin film growth have been reported: e.g. co-evaporation [10], molecular beam epitaxy (MBE) [11], and hybrid physical-chemical vapour deposition (HPCVD) [12]. HPCVD has been demonstrated as a very effective MgB_2 thin films fabrication method with excellent crystallinity and superconducting properties. HPCVD-made MgB_2 films were also demonstrated to be a promising material for HEB mixer fabrication [13], [14].

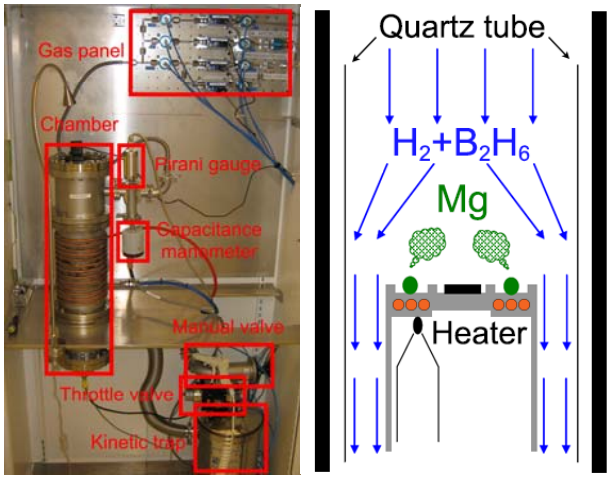

Fig. 1 (a) Chalmers in house built custom MgB_2 HPCVD system and (b) schematic of its deposition chamber.

II. Chalmers HPCVD System

A custom made HPCVD system was built at Chalmers University of Technology to have an in-house source of MgB_2 thin films. The main idea behind HPCVD is that Mg is supplied from evaporation of solid magnesium (Mg) pieces, whereas boron (B) is supplied by high temperature decomposition of diborane gas (B_2H_6). For the deposition process details one can refer to [15], [16]. Our system is shown in Fig. 1a. Both hydrogen (H_2) as a reduce gas, the B_2H_6 mixture with H_2 (deposition gas), and nitrogen (N_2) (purging) are supplied to the deposition chamber using a PC controlled gas panel consisting of pneumatic valves and mass-flow controllers (MFCs). A pirani gauge is mounted on the deposition chamber to monitor the base pressure. A capacitance manometer and a throttle valve are connected to the pressure controller to set the desired process pressure. A kinetic trap follows the deposition chamber in order to protect the throttle valve and the pump from the residuals of deposited material carried by the gas flow. After the throttle valve a manual vacuum valve is installed to be able to keep deposition chamber under vacuum during the idle time. The vacuum pump and the scrubber (used for B_2H_6 disposal) are placed outside the main cabinet at the utility room.

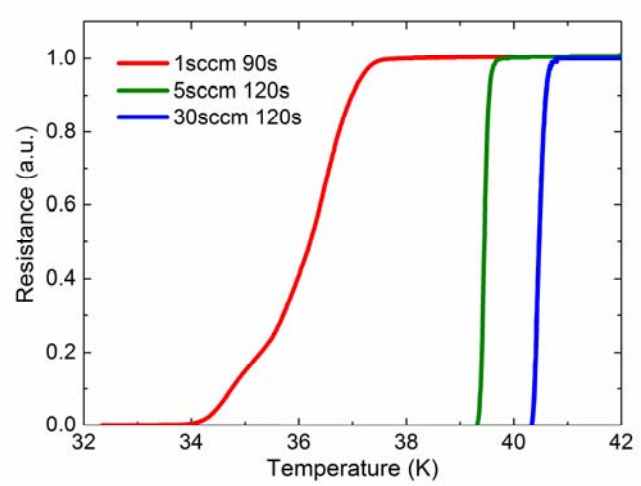

Fig. 2 Normalized R-T curves for MgB_2 films deposited at various B2H6 gas flows with different deposition times. Deposition pressure is 20mTorr (red and green curves) or 40mTorr (blue curve).

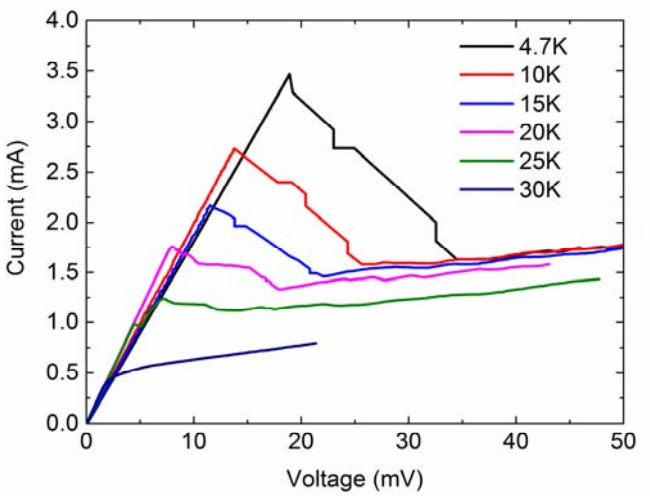

Fig. 3 I-V curves for HEB E6-4 recorded in a dip-stick.

A schematics of the MgB_2 HPCVD system chamber is presented in Fig. 1b. The quartz tube prevents material deposition on water cooled metal walls of the chamber. Both the substrate and the solid Mg are placed on a heated holder. A coaxial heater wire is clamped between the upper and the bottom parts of the holder and mounted just under the area where Mg is placed. Due to a temperature gradient the temperature of the central part (where the substrate is placed) is lower. A thermocouple is mounted on the bottom part of the holder to monitor the temperature.

Thin film depositions were performed at either 20mTorr or 40mTorr pressures, in a temperature range of 750-800°C at various B_2H_6 gas flows. In this work we use 6H-SiC substrates. R-T curves for films deposited under various conditions are shown in Fig. 2. As one can see, for thinner film (90 s deposition time and 1sscm gas flow) a double superconducting transition is observed. For thickest films, the measured T_c is higher than for bulk, with a sharp transition.

III. MgB_2 HEB Fabrication and Characterisation

Several batches of HEBs (all integrated with planar spiral antennas) were fabricated using either photolithography (batch E6) [6] or e-beam lithography (batches E2, E3) process [7]. Since Chalmers HPCVD system does not provide possibility for *in situ* Au passivation, MgB_2 films were covered *ex situ* with 2nm Ti and 20nm gold by magnetron sputter shortly after the MgB_2 deposition. Each batch contained either 10 (photo-) or 8 (e-beam) chips. The yield was high and all HEBs survived both dicing and testing. Several devices from the fabricated batches were selected for the GBW measurements. Data for the tested devices are summarized in Table I.

The thickness of deposited films was measured using a contact profilometer on accompanying 5×5 mm^2 wafers placed next to the main wafer during each deposition. Measured thicknesses were 45nm, 35nm and 15nm for batches E2, E3 and E6, respectively.

DC characteristics of the discussed HEBs were tested in a dip-stick placed in a LHe dewar. I-V curves (Fig. 3) were recorded at different bath temperatures and were similar for the most of devices.

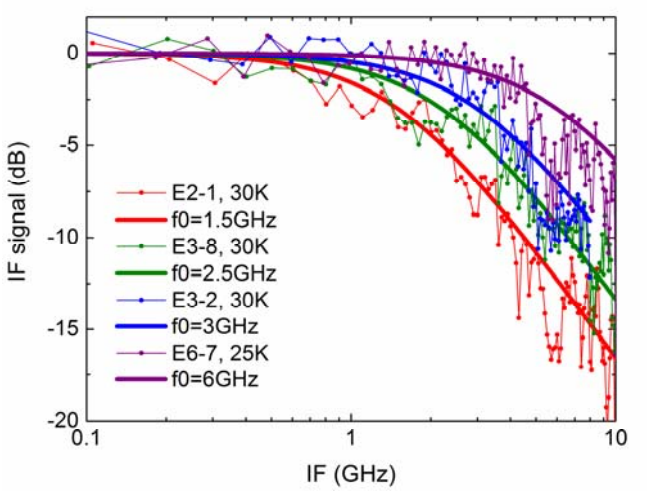

Fig. 4 Corrected IF response for HEB GBW measurements at 0.4THz.

TABLE I
Fabricated Devices

Device	W×L, um^2	R_{300}, Ω	T_c, K	J_c, A/cm^2	B_2H_6, sccm	t, sec
E2-1	1×1	40	39.5	6.6e7	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

For GBW measurements, HEBs were mounted in mixer blocks with silicon (Si) lenses for radiation coupling into devices. The tests were done in LHe optical cryostats. Resistive heaters were attached to the mixer blocks to vary the mixer temperature during experiments. A bias-T and a set of 0.1-20GHz LNAs were placed outside the cryostat at room temperature. The GBW was measured by mixing two 0.4THz sources. The radiation from a Local Oscillator (LO) (a backward wave oscillator (BWO)) and from a signal source (a multiplier based source) were combined with a thin Mylar beam splitter. Results, presented in Fig. 4, were corrected for the IF

chain gain (the cryostat coax line, the bias-T, the room temperature coax, and the LNAs) and normalized to the same level at low IFs. The effect of the mixer blocks was not included into the calibration, but it is not believed to be significant though. The IF response was measured at many bias points (variation of both the LO power and the bias voltage). The measured GBW was the same at all bias points for a given sample. Measured data were fitted with the single pole Lorentzian function to estimate the 3dB roll-off frequency (which defined the mixer gain bandwidth). The largest GBW of 6GHz was measured for the 15nm thick device. MgB_2 films thinner than that could also be made by further reduction of the gas flow and the deposition time. Alternatively, films could be thinned down by ion-beam milling after the deposition [17].

Preliminary noise temperature measurements were performed for device E6-4 using the Y-factor method at both 0.7THz and 1.6THz LO (a far-infrared gas laser). A mixer block with the device was followed by a bias-T and a cryogenic 0.1-5GHz LNA, all placed on the same cold plate of the LHe cryostat. However, the limited available output power at 1.6THz did not allow for proper device pumping with a thin beam splitter. At 0.7THz the maximum Y-factor was about 0.15dB at a bath temperature of 23K. That corresponds to a receiver noise temperature of 6000K (not corrected for optical losses). Further study of device sensitivity and calibration of IF chain are required.

IV. Conclusion

The custom made HPCVD system for ultrathin MgB_2 superconducting films was constructed and successfully launched at Chalmers University of Technology. The in-house source of MgB_2 thin films allows for performing full HEB mixer development at one place from film deposition till device characterisation. It gives more flexibility in HEB optimization and improvement.

A gain bandwidth up to 6GHz was already achieved with quite thick films (~15nm). However, device sensitivity is still under the question.

The future plans include investigation of noise measurement setup problems; thinning down of MgB_2 films; reducing the contact resistance by *in situ* pre-cleaning before Au deposition. We will also continue with mixing and noise measurements at higher frequencies (>1THz).

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