Josephson vs HEB Mixing in Superconducting MgB_2 THz Heterodyne Detectors

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Abstract— **Heterodyne detection in the far infrared is important to isolate key elements involved in the early formations of stars. Typically Nb superconductor-insulator-superconductor (SIS) tunnel junctions are utilized up to about 1 THz. Above this frequency the workload falls on hot electron bolometers made with NbN thin films. In this work, we have fabricated superconducting microbridges using MgB_2 ultra-thin films. The films were fabricated using the hybrid physical chemical vapour deposition which is capable of producing films less than 10 nm thick, which still exhibit critical temperature above 30 K. These microbridges exhibit the Josephson Effect when the film thickness is less than 15 nm, probably due to grain boundary effects. This phenomenon can be used as a mixer with properties similar to an SIS mixer. There are some major benefits of a Josephson detector made in this fashion including the high critical temperature allowing for increased operating temperature, the low capacitance allowing for easier tuning of the antenna-coupled circuit, and higher frequency operation from the larger superconducting gap in MgB_2. Additionally, the same microbridges can be used as hot electron bolometers at higher frequencies, still allowing for higher temperature operation and an intermediate frequency bandwidth three times larger than NbN technology. Here we present the initial results for a microbridge which exhibits the Josephson effect at 600 GHz and one that does not, verifying the good properties of these microbridges as both a Josephson detector, as well as a hot electron bolometer.**

I. INTRODUCTION

Identification of the CII, HD, and OI lines at 1.9, 2.7, and 4.7 THz, respectively, plays a key role in establishing our knowledge of early star formation[1]. The Herschel HIFI instrument utilized NbN hot electron bolometers (HEBs) to observe the galactic center up to 1.9 THz[2]. Since multiplexing of such devices is not yet possible, observation times for this frequency were extremely long. This is exacerbated by the narrow intermediate frequency (IF) bandwidth of NbN HEBs around 2-3 GHz, making multiple scans of the same location necessary to ensure a complete set of data. The liquid helium required for cooling such devices limited the lifetime of the mission, and therefore observation time was an extremely limited resource. Additionally, demand for IF bandwidth only becomes greater as the trend to higher frequencies continues due to Doppler broadening of these lines, especially as quantum cascade lasers (QCLs) become more widely used as local oscillator sources, which have much less tunability than the solid state sources used on HIFI.

Magnesium diboride (MgB_2) is a simple metallic superconductor discovered in 2001 to have a transition temperature, T_c, around 40 K[3]. Early on, there were some attempts to realize detectors made with MgB_2 [4,5] but the lack of high quality thin films has made no real impact on the detector community with the exception of some moderate progress on MgB_2 HEBs[5], which have nearly identical properties to NbN devices. Recently, however, the hybrid physical-chemical vapor deposition (HPCVD) method which yields thin films with better-than-bulk properties [6], has created reason to revisit this material for detector applications. Using the HPCVD process to grow films, we have developed HEBs with critical temperature above 30 K which are at least 3 times faster than NbN devices, corresponding to a tripling of the IF bandwidth. The advantage in speed of these devices can be attributed to the strong electron-phonon interaction corresponding to the high critical temperature, leading to a small electron-phonon time constant, $\tau_{e\text{-}ph}$, and the large sound velocity in MgB_2 (~ 3-times of that in NbN). The high acoustic transparency across the interface between the film and the substrate (typically SiC) also accelerates the electron energy relaxation. Until recently, there was difficulty in obtaining devices which compete with NbN HEBs in terms of mixer noise temperature, with our most recent results achieving just under 4000 K (DSB)[7]. It was noted that the main difficulty came in creating good contact between the MgB_2 bridge and the antenna due to the unavoidable native oxide of MgB_2. In order to overcome this problem, we simply used a thicker MgB_2 layer for the antenna, where the loss should be even less than in a normal metal for frequencies below the gap frequency, f_Δ[8]. In this work, we present the results obtained utilizing the MgB_2 antenna. One side effect that came about with this process was the existence of Shapiro steps in our devices, indicating that the Josephson effect is at least partly responsible for transport across the bridge. As a result, we present our device as it operates in two different frequency regimes. First, when the detecting/LO frequencies are below f_Δ of MgB_2 where the Josephson effect dominates. At this point, we call it a Josephson detector in hopes to differentiate the mechanism at higher frequencies, above f_Δ

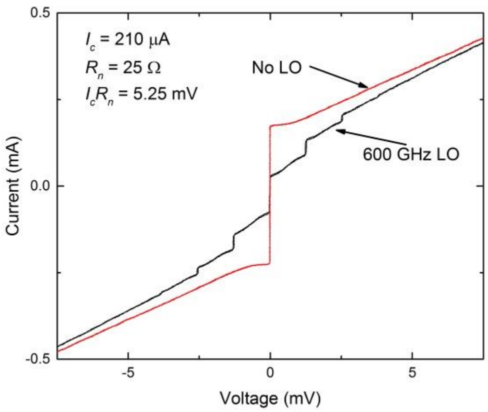

Fig. 1. IV curve with, and without pumping by a 600 GHz local oscillator source at 11 K bath tempearture. The steps are at voltages corresponding to the AC Josephson Effect.

where the mixing is purely a bolometric effect where we characterize the detector as an HEB.

II. JOSEPHSON DETECTOR

The idea of a Josephson detector has been realized before (see, e.g., [9]), though never accepted over an SIS mixer, which achieved lower noise temperature initially, and therefore gained more popularity leading to additional research and a more mature technology. Both mixers proved to have a very large IF bandwidth, low LO power requirements with relatively large margins, and lower noise temperature than HEBs. While SIS mixers were found to have a lower noise temperature, there is a benefit of Josephson detectors in that the complicated tuning circuit necessary to couple SIS mixers to an antenna may be somewhat less complex with a much lower capacitance in Josephson Junctions. Of course with MgB_2 Josephson detectors, there is also the major benefit of operation above 20 K where cryocoolers are a much more practical option than at 4 K, requiring two orders of magnitude less power consumption[10].

Figure 1 shows the IV curve of an MgB_2 mixer with enhanced Josephson behavior both with and without incident radiation at 600 GHz. The first, second, and third steps correspond to a voltage of 1.247 mV/step which accurately describes the LO frequency as 603 GHz. A figure of merit of any type of Josephson junction is the characteristic voltage, V_c, given by the product of the critical current, I_c, and the normal resistance of the junction, $R_{n.}$ Typically, it is recognized that V_c is directly related to the superconducting gap parameter of the material. In this case, V_c is around 5.25 mV indicating that the larger σ-gap of MgB_2 plays a role in the Josephson effect of these junctions. This is further verified by the n = 2,3 steps also seen, indicating harmonics of the initial 600 GHz radiation. It is usually assumed that harmonics can be seen up to the gap frequency, related to the gap value again by the AC Josephson effect. For this device, a third harmonic implies a gap frequency of at least 1.8 THz while the characteristic voltage may imply a gap frequency as high as 2.5 THz. Further work can still be done to try to increase this value to ensure that these detectors could be useful to observe the desirable 1.9 THz line, currently only possible with HEB devices, which exhibit somewhat higher noise temperature. It should be pointed out that this work was done around 11 K, and so if operated at a lower temperature, f_Δ could prove to be somewhat higher.

In the case that it is indeed possible to utilize these detectors at 1.9 THz, another major benefit of these detectors is that they are much faster than HEBs which are standard detectors for this frequency. The noise bandwidth for this device was measured and found to be only limited by the cryogenic low noise amplifier (LNA) which has a bandwidth from 1-12 GHz. Further results on the noise bandwidth as well as the gain bandwidth will be presented elsewhere.

Figure 2 shows the IF output power as a function of the voltage bias of the device. The red curve is when the LO is mixed with a 300 K blackbody through a Mylar beam splitter while the blue curve is for a 77 K blackbody (dipped in liquid nitrogen). The noise temperature is calculated using the standard Y-factor technique. This curve indicates clearly where the steps are located in the sharp anti-peaks. On either side of the step, as the transition to the resistive state occurs a local maxima is seen in the rf output power. In between these local maxima is where the minimum noise temperature is seen. As expected, the noise temperature of these Josephson detectors was found to be quite low. Even without any optimization of the optics, the lowest noise temperature of this device was around 1100 K at 13 K. NbN detectors typically work up to about 0.8*T*c, and so we expect similar performance out of the MgB_2 counterparts. Optimistically, for a device with T_c of 34 K, we could expect the noise temperature to double at ~ 27 K, so operation at this temperature would in fact be practical. Our aim is to operate around 20 K which leaves some room for unexpected difficulties.

A further reduction in noise temperature can be expected if the device impedance is better matched to the antenna and if an antireflective coating is used on the Si lens in the quasi-

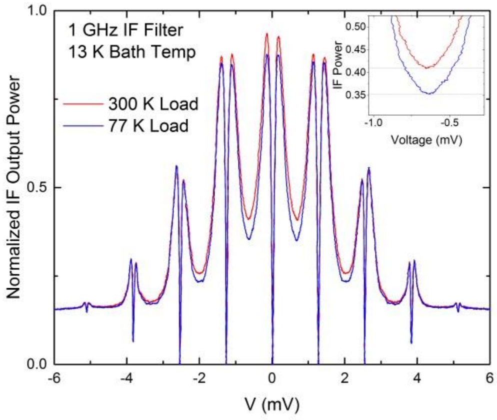

Fig. 2 IF output power as a function of bias voltage for the Josephson Detector. The inset shows a reduced scale at the point where the minimum noise temperature is found to be 1100 K.

optical scheme. More than 50 % improvement can be expected just by increasing the device resistance from 25 Ω to 75 Ω and optimizing the optics. Additional improvements may be seen if the thickness of the superconducting antenna is increased as the current thickness is only about double the reported value of the penetration depth of the HPCVD films[11]. This implies that the optimized noise temperature of this type of detector may be similar to the state of the art SIS mixers, just 2-3 times higher than the quantum limit.

III. HOT ELECTRON BOLOMETER

When the film thickness is around 15 nm or more, grain boundary junctions are less common and do not dominate transport through the bridge. In this case, the device is characterized as a hot electron bolometer. In general, the Josephson effect is minimized as the film gets thicker, probably due to the fact that film growth can be thought of like piling pancakes on top of one another, so additional layers add a third dimension for current to travel which may be less resistive than if the current travelled directly across a grain boundary. This is also the case when the detection frequency is much larger than f_Δ and the pumping mechanism is purely bolometric. These devices have been previously characterized and found to be much faster than NbN devices. Figure 3 shows the gain bandwidth of an HEB made with 15 nm film at different bias points from [12]. The dashed line shows the best fit where f_c indicates the cut-off frequency. Here an optimally biased device around 3 mV is found to have a bandwidth of about 7 GHz, which is about double the bandwidth of a NbN HEB with film thickness around 5 nm. The difference in film thickness is important to note as MgB_2 film deposition has made some recent progress, where it is capable to produce devices with film as thin as 6 nm. More results will be presented on film growth advancement elsewhere.

Figure 4 from [7] is a similar measurement of the same device as in Fig. 3, except that the different curves describe the gain bandwidth at different temperatures. Although there is some discrepancy about the bias point for different temperatures, since the IV curve will have a different shape and there is a bias dependence in the gain bandwidth, but we avoided this issue by biasing optimally at low temperature and attempting to maintain a similar bias point, decreasing from 3 mV at 9 K to about 2 mV at 25 K. This corresponds to a point just past the transition peak seen in the IF power as a function of bias voltage. The general idea is to present the fact that the gain bandwidth increases as a function of temperature. The result is that we see a bandwidth of 8.6 GHz at 25 K. We expect that a device made with 10 nm film can reach 10 GHz of bandwidth. Going much thinner than this will yield even large bandwidth, and has the additional benefit of minimizing LO power requirements, however bandwidth much larger than 10 GHz seems like it would already require new technologies on the back end of a receiver. While the data in Fig. 4 do not give an accurate representation of the quantitative dependence of bandwidth as a function of temperature, the device did not exhibit such a large bandwidth at 9 K for any bias point, and so there is definitive verification that the bandwidth has some, yet unknown, dependence on temperature.

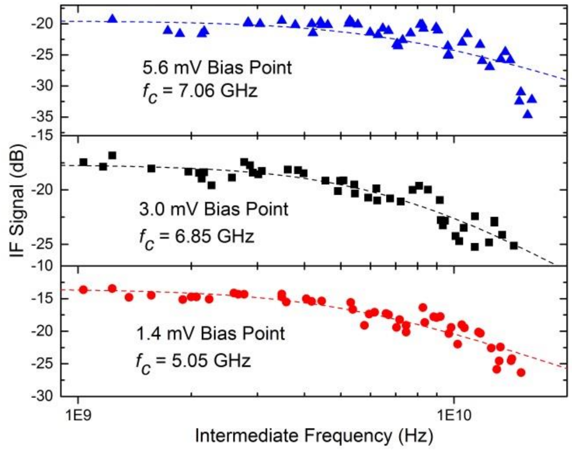

Fig. 3. Gain bandwidth of a MgB_2 HEB for different bias points from ref. 12.

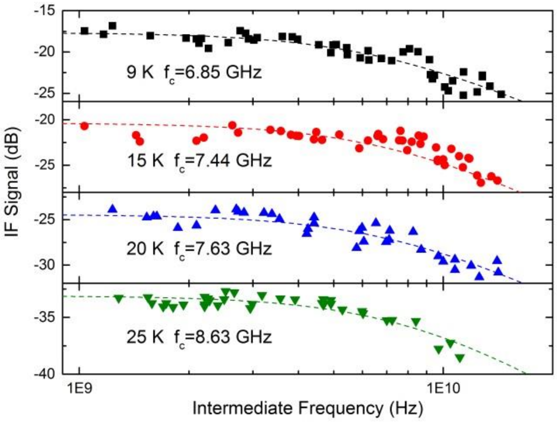

Fig. 4. Gain bandwidth of a MgB_2 HEB for different bath temperatures from [7].

Although no data are currently available for higher frequency measurements of these devices, the device presented from Figs. 3 and 4 do not exhibit any Josephson effect at 600 GHz, probably because the thickness is greater than some percolation limit of the film. The noise temperature of this device was around 4000 K, but investigations presented in [7] showed that there was a large contribution to the RF loss due to a fabrication issue in the antenna. Upon adding the thick superconducting antenna, we see about an order of magnitude better coupling of the radiation to the device, and so we would expect a similar device to have about 25% of the noise temperature, or around 1000 K. Measurements using a FIR gas laser are expected to be completed soon with monochromatic lines up at 1.0, 1.6, 2.5, and 4.3 THz. If the relatively low noise temperature remains at these frequencies, MgB_2 will prove to outperform NbN devices in bandwidth, operating at 20 K, without any significant loss in sensitivity. At this point we hope to begin development of an MgB_2-based receiver with a QCL LO and mixer both mounted in the same cryocooler for operation around 20 K.

IV. CONCLUSIONS

To summarize, we have presented a mixer made with MgB_2 ultra-thin films developed using the HPCVD growth process. The results presented here, and in recent publications include a low noise Josephson detector potentially working to frequencies up to 2 THz, and a large bandwidth HEB for operation at 20 K. We hope to fully conceptualize the advantages of MgB_2 mixers for heterodyne detection of FIR frequencies at an operating temperature of 20 K by verifying a noise temperature similar to that obtained using NbN HEBs at 4.2 K. In the future we plan begin work on receiver utilizing these mixers.

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