High and Mid Temperature Superconducting Sensors for far IR/Sub-mm applications in space.

Brook lakew[*], J. C. Brasunas
NASA- Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

In this review paper an overview of the potential applications of high Tc (~90 K) superconductors (HTS) and mid-Tc (~ 39 K) superconductors (MTS) thin films in far IR/Sub-mm thermal detectors is presented. HTSs (YBCO, GdBCO etc.) were discovered in the late 80s while superconductivity in MgB_2, an MTS, was discovered in 2001. The sharp transition in transport properties of HTS has allowed the fabrication of composite infrared thermal detectors (bolometers) with better figures of merit than thermopile detectors - thermopiles are currently on board the CIRS instrument on the Cassini mission to Saturn.
The potential for developing even more sensitive sensors for IR/Sub-mm applications using MgB_2 thin films is assessed. Current MgB_2 thin film deposition techniques and film quality are reviewed.

INTRODUCTION

YBCO and GdBCO
HTS materials were discovered almost 15 years ago. Two of the most known among them are $Y_1B_2Cu_3O_{7-x}$ (YBCO) and $Gd_1B_2Cu_3O_{7-x}$ (GdBCO). The potential uses of these materials especially HTSs have been enumerated in many papers. Just to list a few applications: SQUID readouts, far IR bolometers, lossless power transmission cables, energy storage devices, filters for the mobile phone communications etc. The early euphoria has subsided and the mechanism by which these materials superconduct is yet to be explained. However the interest in HTS superconductors has remained constant in the planetary exploration arena.
Bolometers using HTS materials can be particularly suited for far IR instruments on planetary missions. These missions typically take many years (7 years for the Cassini mission to Saturn)[1] and have stringent mass and power budgets limitation thus making it impossible to carry heavy cryogens or use high power cryocoolers.

MgB_2
Since early 2001, yet another material, MgB2 has been found to be superconducting. MgB_2 is simpler than HTSs and superconducts[2] at 39 K. It is a simple binary intermetallic compound and a common reagent in the chemical reactions in which compounds exchange partners[3]. MgB_2's lower Tc in conjunction with the strong cryocoolers development effort at NASA[4] could yield more sensitive bolometers for application in planetary and Earth sciences.

1. **Bolometers:**

Bolometers are composite IR detectors consisting of a substrate that has a thermistor on one side, a radiation absorber on the other and coupled to a heat sink via a thermal conductance G. The temperature coefficient of resistance **ß** of the thermistor = $1/R(dR/dT)$. And if the total heat capacity of the bolometer is C, the thermal time constant $\tau = C/G$.

---

[*] *Contact information for B. Lakew- Email: brook.lakew-1@nasa.gov*

Responsivity, NEP and specific detectivity D*:
When the HTS thin film is current biased, the voltage across it is
V = IR and if the effect of thermal feedback neglected then the responsivity is commonly expressed as:

$$S = V\beta /G (1 + i2\pi f \tau)$$

where f is the chopping frequency of the incoming radiation

The sensitivity of the bolometer is usually expressed as the noise equivalent power (NEP). It is defined as the input signal power such that the signal-to–noise ratio at the output is 1 (in a 1 Hz bandwidth). It is usually obtained by summing the squares of statistically independent contributions to the noise. The Noise Equivalent Power (NEP)[2] is the sum of the squares of statistically independent contributions. Thus:

$$\text{NEP} = \left(\frac{4k_B{}^5 T^5{}_B A\Omega}{c^2 h^3} \int_0^{x_c} \frac{t^4 e^t dt}{(e^t - 1)^2} + 4k_B T_c{}^2 G + \frac{4k_B T_c R}{|S|^2} + \frac{AV}{f|S|^2} + \frac{4k_B T_N R}{|S|^2} \right)^{1/2} \quad (1)$$

Of particular interest are the two dominant terms of equation 1: the second term (phonon noise) and third term (Johnson noise in the HTS)[5].

The specific detectivity D* is a normalized figure of merit that is widely used. For a detector of area A it is expressed as:

$$D* = \frac{\sqrt{Area}}{NEP} \quad (cm.Hz^{1/2}.W^{-1})$$

The lower the NEP the higher the D*.

2. YBC0 and GdBCO based TES bolometers

In HTS bolometers the thermistor is a superconducting thin film operated near the mid-point of its transition. The substrate is typically either Al_2O_3, YSZ, MgO or $SrTiO_3$. The thermistor is an HTS thin film: YBCuO, GdBCuO etc. (typically 1000 to 1500 Å thick). It is either current or voltage biased.
A selection of the most sensitive ones is put in table 1.

Authors	Sensing element	Substrate	Time constant (ms)	NEP (W/Hz$^{1/2}$)	D* (cmHz$^{1/2}$W^{-1})	IR Source
Kakehi et al	25µm^2	Thick MgO	NG	2.1×10^{-14}	2.5×10^{11}	0.830 µm laser
Lakew et al	GdBCO1x 1 mm^2	Al_2O_3 (7 µm) + absorber	100	8×10^{-12}	2×10^{10} at 3.8 Hz*	Black Body
Li H et al	GdBCO 0.7 mm^2	YSZ (50 µm)	1-5	3.8×10^{-12}	1.7×10^{10}	Black Body
de Nivelle et al	GdBCO 0.9 mm^2	SiN 0.62 µm +buffer	115	5.5×10^{-12}	1.8×10^{10}	Black Body

Table 1. *A selection of the most sensitive HTS bolometers on thick, thin and ultrathin substrates. Kreisler and Gaugue have compiled an excellent list of 34 HTS bolometers[6].*

3. HTS bolometers and other thermal detectors:

The NASA/Goddard HTS bolometer is compared to other uncooled or moderately cooled thermal detectors in Table 2.

Detector	Sensing element	Operating temp (K)	Time constant (ms)	D* (cmHz$^{1/2}$W^{-1})
Thermopile	BiTe	140 – 300	25	3.9 x 10^9
Pyroelectrics	LiTaO3	>240	0.3	2 to 3 x10^8
NASA/Goddard HTS	GdBCO	90	100	2 x 10^{10}
Optimal HTS bolometer	YBCO	90	56	~7 x 10^{10}*

Table 2. *Performance of NASA/GSfC's HTS bolometers vs other thermal detectors. Note: *Calculated using G ~ 1 µW/K and C ~ 0. 1 µJ/K for current biased bolometer[5]. For higher G values the time constant of the ideal bolometer can be made smaller but with a smaller D* as a consequence.*

4. MTS bolometers- the case of MgB$_2$

MgB$_2$'s crystal structure consists of hexagonal honeycombed planes of boron atoms separated by planes of magnesium atoms, with the magnesium atoms along the *c* axis in the hexagonal lattice[2].

It is believed that MgB$_2$ forms by diffusion of Mg into Boron grains[7]. Unlike HTS, MgB2 grain bounderies are not weak and can carry large currents[8]. Experiments by Bud'ko *et al* have shown that lower mass isotopes of B increase T_c indicating that phonons play an important role in the superconducting interaction[9].

Advantage of MgB$_2$ thin films as thermistors:
Assuming that thermal noise and Johnson noise dominate in Equation 1 then NEP ~ $(4k_BT^2_cG + 4k_BT_cR/S^2)^{1/2}$. Everything else being equal, including thin film quality, the noise will be smaller when T_c is smaller. Thus the promise of more sensitive bolometers with MgB$_2$ thin films as thermistors.

MgB$_2$ thin films growing methods:
- Hybrid Physical-Chemical Vapor Deposition (HPCVD): a combination of Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD)– at ~750 ^{o}C, film grows epitaxially on (0001) sapphire and (0001) 4H-SiC substrates[10].

- Molecular beam epitaxy (MBE) – Pure metal sources are evaporated via electron beam evaporators in vacuum chamber (1x10^{-9} Torr)[11].

- Sintering (the Ames Method) – A stoichiometric mixture of Mg and B are sealed[7] in Ta tube and heated to 950 ^{o} C.

- Pulsed Laser Deposition (PLD): *ex situ* or *in situ* :
  Ex situ : (PLD and Ames method): Boron deposited via PLD on SITiO$_3$ (100) and (111) at 800 ^{o}C, then reacted with Boron in a sealed Ta tube.
  In situ : (1) PLD from sintered MgB$_2$ target; (2) PLD of multilayers of MgB$_2$ and Mg followed by *in situ* anneal at high temperature, (3) PLD of multilayers of B and Mg followed by *in situ* anneal at high temperature. Better Tc obtained with *ex situ* anneal[12].

Summary

Method	Growth temp (^{o} C)	Transition Temp (K)	Substrate	Application
HPCVD	650	40	SiC/ sapphire (0001)	IR Sensors
MBE	150-350	36	$SrTiO_3$ (001), Sapphire R & C, Si (001)	Junctions& multilayers
Sintering (Ames method)	950	39.2* 40.2**	Mostly wires and pellets	Transport properties/ Research
Pulsed Laser Deposition	900	22 *(in situ anneal)* 40 *–(ex situ anneal)*	R plane sapphire	Single& multilayers

Table 3. *Summary of current MgB₂ thin films growing methods. * Isotope Mg^{11} ; **Mg^{10}*

Film Quality:
The main obstacle to obtaining good quality films is the high volatility of Magnesium[11,13] . Degradation of MgB_2 due to exposure to water on film quality has also been noticed[14].

5. Conclusion

For space borne IR instruments that have moderately cooled focal planes, HTS and MTS bolometers remain, to date, the sensors with the highest signal to noise (S/N). MgB_2 with a T_c at 39 K promises even better S/N. Improvements in the fabrication methods will hopefully improve the quality and stability of MgB_2 thin films.

REFERENCES

1. V. Kunde et al., Vol. 2803, SPIE, Vol. 2803, Denver, CO, 1996.
2. J. Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani, and J. Akimitsu*, Nature 410, p. 63, 2001.*
3. R.J. Cava*, Nature 410*, p. 23, 2001.
4. R.G. Ross, Jr., R.F Boyle, P.Kittel, *NASA's space cooler program – A 2003 overview*, TDW03 Workshop on Thermal Detectors in press, 2003.
5. P. L. Richards et al, Appl. Phys Lett., 54, p 283, 1989.
6. A. Kreisler, A. Gaugue, Supercond. Sci. Technol.,13, , 1235-1245, 2000*.*
7. P.C. Canfield, et al., Phys. Rev. Lett., 86(11):2423-6, 2001.
8. D.K. Finnmore, J.E. Ostenson, S.L. Bud'Ko, G. Lapertot and P.C. Canfield , Phys rev Letters, 86, p 2420, 2001.
9. S.L. Bud'ko, G. Lapertot, C. Petrovic, C. Cunningham, N. Anderson and P.C. Canfield, Phys. Rev Lett., 86, 1877, 2001.
10. X. Zeng et al, Nat. Mater., 1, 35-38, 2002.
11. Ueda et al, Appl. Phys. Letters, vol 79, 2001.
12. S.R. Shinde, S.B. Ogale, R.L, Greene, T. Venkatesan, P.C, Canfield, S.L. Bud'ko, G. Lapertot and C. Petrovic, Appl Phys. Letters, vol 79, No 2, p 227, 2001.
13. Zhai et al, Supercond. Sci. Technol., 14, 425-428, 2001.