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Effect of ionizing radiation on noise in MgB_2 thin film – a candidate material for detector development for post-Cassini planetary missions

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Abstract

A thin film of MgB_2, grown on a SiN–Si substrate, with a superconducting transition temperature, T_c, near 39 K has been irradiated with γ-rays from a ^{60}Co source. The total dose was 100 Krads (Si). Its pre- and post-irradiation noise has been measured and noise spectral density plots made. No change in dR/dT, pre- and post-irradiation was measured. At the mid-point of the transition, $T = 38.24$ K, a noise spectral density $S_V = 0.34$ nV $Hz^{-1/2}$ was measured at 10 Hz. The temperature noise, K_n, of the MgB_2 film at different frequencies is compared to that of high temperature superconducting (HTS) thin films (YBaCuO and GdBaCuO with $T_c \sim 90$ K) used currently in HTS transition-edge bolometers. Even with the observed post-irradiation small increase in noise, its lower T_c and K_n values predict that high performance far IR bolometers can be developed using MgB_2 as a thermistor.

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Keywords: Magnesium diboride; MgB_2; Bolometer; Noise spectral density; Ionizing radiation; Superconductor

1. Introduction

Mid and far infrared wavelengths data from the outer planets is still critical to the study of the formation of the solar system. The CIRS instrument on the Cassini spacecraft carries mid and far IR detectors. The future exploration missions to Uranus and Neptune will require even more sensitive detectors in the mid and far IR.

One important consideration when selecting which detector to baseline for a space borne instrument is its robustness to ionizing radiation. Jupiter and Saturn have harsh radiation environments to which is added the radiation from the spacecraft's own radioisotope thermal generator systems. The Cassini spacecraft will have been exposed to about 100 Krads of ionizing radiation over its lifetime. Infrared detectors in the CIRS instrument were required to survive exposure to a total radiation dose of 100 Krads before being selected to fly.

We have enumerated the various sources of primary radiation that impact the spacecraft in a previous paper [1]. A portion of the primary radiation is converted into secondary radiation by the spacecraft's structure and the other shielding material. All sources generate both ionization damage and displacement damage in the material under study. The energy in the ionization damage is however significantly higher than in the displacement damage. γ-rays are found both in the primary radiation and in the secondaries. In this paper we report on the effect of γ-rays on noise in an MgB_2 thin film.

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2. MgB_2 thin film based infrared bolometers

2.1. A simpler compound

The sharp transition in transport properties of high temperature superconducting (HTS) thin films (e.g., YBCO) has allowed the fabrication of transition-edge superconducting (TES) infrared detectors [2–4]. These detectors show better figures of merit than far IR thermopile detectors, which are currently on board the CIRS instrument on the Cassini spacecraft.

MgB_2 is a simple binary intermetallic compound that has a hexagonal $A1B_2$-type structure and was found to be superconducting in early 2001 by Nagamatsu et al. [5] with a superconducting transition at 39 K. Compared to the cuprate HTSs, the lower T_c and very sharp transition of MgB polycrystalline thin films, $\Delta T_c \approx 0.2$–0.3 K, offers the possibility of even more sensitive bolometers for future applications in planetary exploration. For the foreseeable future only moderately cooled focal planes (30–90 K) are feasible on such missions because of stringent mass and power budgets. The lower operating temperatures are achievable using advanced cryocooling technology being developed both at NASA and elsewhere.

Brinkman et al. [6] have reported on superconducting thin films of MgB_2 grown on silicon using pulsed laser deposition. They noted a very broad transition with an onset transition temperature of 27 K and zero resistance between 11 K and 15.5 K for various films. High quality MgB_2 thin films have recently been grown by reactive evaporation on Si–SiN substrates exhibiting sharp transitions with T_c near 39 K [7]. These films show a *c*-axis alignment even on amorphous substrates [8] and an in-plane random texture [9]. One distinct advantage of growing high quality MgB_2 thin films on silicon substrates is the potential for fabricating single and 2D bolometer arrays using standard micro-electro-mechanical systems (MEMS) micromachining processes.

2.2. Better signal-to-noise (S/N) ratio expected

In an ideal bolometer device the three uncorrelated main contributors to the noise are Johnson noise, phonon noise and $1/f$ noise, which add in quadrature [10] (for this work the film is in a cryostat with blanked off windows, thus photon noise is not considered). The noise spectral density can thus be expressed as:

$$S_v = \left(4k_B TR + 4k_B T^2 G|S|^2 + A\frac{I^2R^2}{f}\right)^{1/2} \quad (1)$$

and the noise equivalent power (NEP) is defined as:

$$\mathrm{NEP} = \sqrt{\frac{S_v^2}{|S|^2}} \quad (2)$$

Here k_B is the Boltzman constant, S is the responsivity of the device in V/W, T is the operating temperature in Kelvin, R is the resistance of the thermistor in Ω, G is the effective thermal conductance between the absorber and the heat sink in W/K, A is a measured quantity that depends on the thin film and scales inversely with the film's volume and I is the bias current and f is the frequency in Hz. The lower the NEP (in $\mathrm{W}/\sqrt{\mathrm{Hz}}$), the better the S/N and the higher the detectivity, $D^* \propto \mathrm{NEP}^{-1}(\mathrm{cm}\sqrt{\mathrm{Hz}}/\mathrm{W})$ of a bolometer. Lower T clearly reduces the overall NEP. Since MgB_2 has a lower T_c compared to the cuprate HTSs, one can expect a lower NEP and thus a higher detectivity $D*$ with MgB_2 based TES bolometers.

3. Experimental

3.1. Si–SiN substrate

The substrate used for growth of MgB_2 thin film was a 4 in. diameter, 380 μm thick ⟨1 0 0⟩ Si wafer with a 500 nm thick low pressure chemical vapor deposition (LPCVD) silicon nitride coating (Virginia Semiconductor Inc., USA). The LPCVD technique involves a reaction between ammonia (NH_3) and dichlorosilane ($SiCl_2H_2$) at 800 °C. The temperature of the reactor and the concentration of the gases determine the electrical and mechanical properties of the silicon nitride film including its residual stress. This technique gives a low silicon nitride tensile stress between 100 MPa and 140 MPa.

3.2. MgB_2 film growth

The MgB_2 film was deposited onto the SiN–Si wafer by a reactive evaporation growth technique that is described in detail elsewhere. In brief, the substrate rotates on a platter into and out of a quasi-blackbody heater that is maintained at a temperature of 400–600 °C inside a vacuum deposition chamber. As the substrate passes through the heater it is exposed to a pocket of Mg vapor that is sealed from the rest of the vacuum chamber by a small gap. When the substrate passes out of the interior of the heater it is exposed via an open window to the vacuum chamber, thereby allowing deposition of B, which is evaporated from an electron beam source. This technique enables the growth of very high-quality MgB_2 films. The films are epitaxial, free from oxygen contamination, are quite stable, have high T_c values, low resistivity values and low surface resistance [11]. Other groups have used different methods to deposit MgB_2 on SiN [12].

For the work presented here the MgB_2 thin film was grown at 550 °C at a rate of about 0.1 nm/s to a thickness of about 500 nm. No visible evidence of any chemical reaction between the MgB_2 and Si through the SiN layer was observed.

3.3. Sample preparation

It is known that the superconducting properties of MgB_2 deteriorate under long term (97 h) humidity exposure [13],