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Modeling of Planck-high frequency instrument bolometers using non-linear effects in the thermometers

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Abstract

The Planck satellite, which is planned to be launched in 2007, is dedicated to surveying the Cosmic Microwave Background (CMB) to a high precision. Aboard this mission, the High-Frequency Instrument (HFI) will use 52 NTD Ge spiderweb bolometers made by Caltech-JPL and cooled to 100 mK by a dilution cooler. In this paper, we present a model of these detectors that includes non-linear effects seen in NTD Ge thermometers: electron–phonon decoupling and electrical field effect. We show that this model leads to consider only electrical field effect. Furthermore, the optical characterization of the HFI bolometers clearly shows a non-ideal behavior that is explained by non-linear effects in the thermometer. We finally show that these effects have to be taken into account for optimized CMB observations and to fully understand the physics of semi-conducting bolometers.

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Keywords: Spider web bolometer; Planck HFI; Electrical field effect; Electron–phonon decoupling effect

1. Introduction

The ESA satellite Planck is dedicated to surveying the far infrared sky and especially the Cosmic Microwave Background (CMB) anisotropies [1]. To achieve this goal, the High-Frequency Instrument (HFI) will use 52 NTD Ge bolometers cooled to 100 mK and covering the frequency range 100–857 GHz.

NTD Ge thermometers have been modeled and tested in order to control temperature fluctuations at a level of $10\,\mathrm{nK\,Hz^{-0.5}}$ [2]. This work clearly shows that both electrical field and electron–phonon decoupling effects have to be taken into account for reproducing the behavior of these devices at 100 mK. In this paper, we present an extension of this work to Planck-HFI Ge spider web bolometers made by JPL.

2. The model

2.1. Thermometer model

The electrical field effect can be expressed as follows, in the limit of small and uniform electrical field $E = V/L << mk_B T_e/(eL_h)$ [3]:

$$R(V, T_e) = R_0 \exp\left(\frac{T_0}{T_e}\right)^m \exp\left(-\frac{eVL_h}{k_B T_e L}\right)$$

where R_0, T_0 and $m = 0.5$ are very low bias power parameters, T_e is the electronic temperature, e is the electron charge, L_h is a characteristic length for the hopping process, L is the inter-electrodes length and k_B is the Boltzmann constant. The characteristic hopping length is expected to vary as $L_h(T_e) = L_{h0} \times T_e^{-m}$ where $L_{h0} = L_h(T_e = 1\,\mathrm{K})$ [3].

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Table 1
Parameters deduced from the fit on V–I curves of s16-217 bolometer

Case	Loading	T range (mK)	R_0 (Ω)	T_0 (K)	L_{h0} (nm)	G_{e-ph} (W/K^6/cm^3)	G_{s0} (pW/K)	β	P_r (pW)	χ^2/DOF
1	Blanked	90–200	**156.1**	**15.28**	0	∞	**42.98**	**1.12**	**0**	2800/671
2	Blanked	90–200	**145.6**	**15.51**	**15.6**	**6457**	**44.75**	**1.09**	0	641/671
3	300 K	90–200	145.6	15.51	**15.7**	∞	**45.23**	**1.09**	**1.78**	324/670
4	300 K	90–200	145.6	15.51	**15.1**	**84**	**45.24**	**1.09**	**1.78**	324/670
5	77 K	90–160	145.6	15.51	**18.2**	∞	**46.25**	**1.06**	**0.56**	588/520
6	77 K	90–160	145.6	15.51	**17.4**	**114**	**46.21**	**1.06**	**0.56**	587/520

Bold parameters were determined from the fits.

The electron–phonon decoupling effect can be modeled by the following expression [4]:

$$P = G_{e-ph}\mathrm{Vol}(T_e^n - T_{ph}^n)$$

where $P = VI$ is the bias power, G_{e-ph} is the coupling factor, Vol is the device volume and n is a constant found experimentally close to 6 for NTD Ge [4].

At any bias current I, the bias voltage across the sample must satisfy $V = R(V, T_e) \times I$ which can be solved numerically. A thermometer is characterized by its set of parameters {R_0, T_0, m, L_{h0}, L, G_{e-ph}, n, Vol}. This model was implemented and validated on NTD Ge and on NbSi thin film thermometers [5]. It allowed us to evaluate the non-linearity parameters (G_{e-ph} and L_{h0}) of Haller–Beeman Associates (H–B) NTD Ge materials and to optimize sensitivities of Planck-HFI thermometers [5].

2.2. Bolometer thermal model

For consistency inside the HFI collaboration, we use the same notation as Sudiwala et al. [6]. We assume that the thermal conductivity of the thermal link follows a power law: $k(T) = k_0 \times (T/T_{ref})^\beta$, which leads to the following expression of the power through the link:

$$P_{link} = \frac{G_{s0}}{(\beta+1)T_{ref}^{\beta}}(T_b^{\beta+1} - T_0^{\beta+1})$$

where T_0 and T_b are the bath and the bolometer temperatures, respectively, G_{s0} is the static thermal conductance at $T_0 = T_{ref}$ and β is a constant. Given a bias current I, the temperature of the bolometer can be obtained by solving numerically $R(V, T_b)I^2 + P_r = P_{link}$, where P_r is the incident radiative power. At each iteration of the solver, the resistance of the thermometer has to be computed through the thermometer model. We can characterize a bolometer with the set of parameters {R_0, T_0, m, L_{h0}, L, G_{e-ph}, n, Vol, G_{s0}, β, T_0, Pr} (T_{ref} is assumed to be 100 mK).

3. Fitting parameters on real data

To estimate the values of parameters, we used V–I data of different Planck bolometers at different temperatures. These data has been acquired either at Cardiff University or at JPL, with and without incident optical power. We present as an example the case of the s16-217 GHz bolometer. Other equivalent studies have been done on some of Planck bolometers and lead to similar results. We have assumed a global 0.4% accuracy on the measured voltage, which includes uncertainties in the bias current and temperature fluctuations. This accuracy is consistent with the measurement setup.

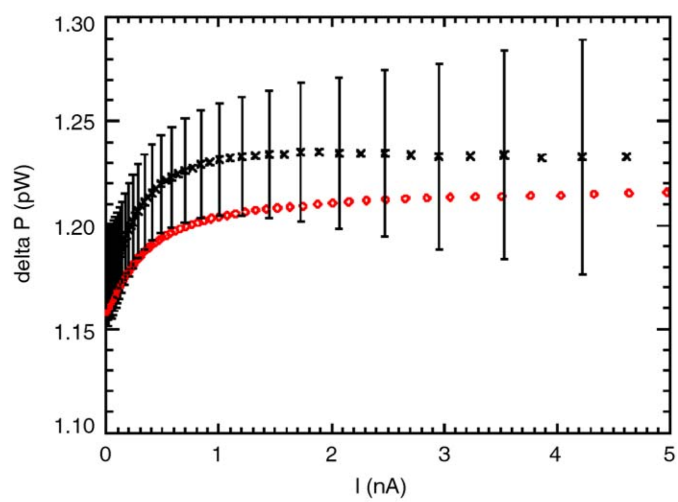

Fig. 1. Crosses (×): Experimental differences in the electrical powers of 300 and 77 K loaded V–I curves at 110 mK, as a function of bias current of 300 K loaded data. The error bars include uncertainties in the voltage (0.4%) and in the absolute temperature value (0.2%). The diamonds (◇) represent the values obtained with the bolometer model of case 2.

Table 1 gives the results of the fit on the parameters with χ^2 values. Case 1 corresponds to the classical bolometer model fit on blanked data. It does not reproduce accurately enough the data at low temperatures, typically below about 130 mK, where non-linear effects are more important. The case 2 includes non-linear effects in the response of the thermometer and gives better χ^2. The results from cases 1 and 2 on the low bias power and heat leak parameters are close but significantly different due to non-linear effects. The L_{h0} parameter is consistent with the literature. However, the G_{e-ph} tends to have much higher values than reported elsewhere [5]. This suggests that no electron–phonon decoupling effect is seen in the data. This result, still under discussions, could be explained by the fact that one electrode is electrically connected to the gold layer on the spider web, allowing for a better thermal contact between electrons and phonons.

For optically loaded data (cases 3–6), we keep R_0 and T_0 at their previously determined values. However, the estimation of non-linear parameters is more difficult due to the higher working temperature of the bolometer. The deduced L_{h0} and the heat leak parameters are consistent when compared to each other. The best fits (cases 4 and 6) give values of G_{e-ph} lower than the blanked off ones. Considering no electron–phonon decoupling (cases 3 and 5) leads to χ^2 values not significantly higher meaning that this effect is not relevant due to the higher temperatures.

For a perfect bolometer, the difference in optically absorbed power between 300 and 77 K loaded data is the difference in electrical power for points with the same resistance. Therefore, a constant absorbed power for different resistance values (or bias current for one of the *V–I* curves) is expected. However, Fig. 1 shows that a decrease in the deduced absorbed power is seen below about 1 nA, which could be mainly explained by introducing the electrical field effect in the thermometer.

4. Conclusions

Fitting *V–I* curves of some Planck-HFI bolometers shows that electron–phonon decoupling effect is much smaller than electrical field effect. This study has to be generalized to the whole set of Planck bolometers, since their design is the same.

References

[1] J.M. Lamarre, et al., LTD9, AIP Conf. Proc. Ser. 605 (2002) 571.
[2] M. Piat, et al., LTD9, AIP Conf. Proc. Ser. 605 (2002) 79.
[3] T.W. Kenny, et al., Phys. Rev. B 39 (1987) 8476.
[4] N. Wang, et al., Phys. Rev. B 41 (6) (1990) 3761.
[5] M. Piat, et al., JLTP 125 (5/6) (2001).
[6] R. Sudiwala, et al., LTD8, Nucl. Instr. and Meth. A 444 (2000) 413.