All electron bolometer for radiation detection

S. Marnieros¹, L. Dumoulin², A. Benoit¹, L. Berge¹, P. Camus², S. Collin¹, A. Juillard¹ and C.A. Marrache-Kikuchi³

1 CSNSM, CNRS-IN2P3, Paris 11 University, Orsay, France
2 CRTBT, CNRS, Grenoble, France
E-mail: Stefanos.Marnieros@csnsm.in2p3.fr

Abstract. In order to measure the Cosmological Microwave Background (CMB), high performance "bolometric cameras" similar to CCDs are currently developed. They are made out of thousands of pixels, each of which is a bolometer on its own. In order to meet the requirements for future CMB experiments - notably the measurement of the CMB B-mode polarization - the sensitivity of each pixel should be improved by one or two orders of magnitude compared to what now exists. Taking advantage of the solid-state properties of amorphous NbₓSi₁₋ₓ thin films, we here present a proposal for a new bolometer structure that would increase the pixels’ sensitivity, its response time and allow a simplification of the fabrication process. In this resistive detector (that can be either high impedance or TES) the three functions of a classical bolometer (wave absorption, temperature measurement and thermal decoupling) are achieved in a single NbₓSi₁₋ₓ film. The frequency properties of this material allow the merger of the two first functions. The natural thermal decoupling between electrons and phonons at low temperature then makes it possible to use this single object as bolometer. This new type of detector solely uses the electronic properties of the NbₓSi₁₋ₓ thin films and is free of any phononic mediation of the energy.

1. Scientific context
The measurement of the Cosmological Microwave Background (CMB) is now reaching the sensitivity limit of single bolometer-type detectors. Numerous observations related to the millimetric domain are limited by the photon noise and further improvement of the detectors imply optimizing the focal plane filling factor by the use of large bolometric matrices. Among all CMB measurements that the scientific community has not yet been able to perform, the CMB B-mode polarization is probably the most constraining from the instrumental point of view. The signature of primordial gravitational waves which give a B-type polarization, is one of the utmost goals in today’s cosmology and amongst the first objectives in the field.

The current European Spatial Agency Planck satellite program, which will perform measurements of the CMB temperature with a resolution down to 5 arc minutes, already has 52 detectors in the telescope’s focal plane. However, for future programs which will focus on the detection of the CMB B-mode polarization, the sensitivity of the angular power spectrum measurement will have to be improved by at least two orders of magnitude. The noise equivalent power sensitivity (NEP) will have to be kept down to about 10⁻¹⁸ W/√Hz, and the number of detectors in the telescope’s focal plane will have to be drastically increased up to many thousands. A number of solutions are currently being developed by the different collaborations to achieve fabrication of high performance "bolometric cameras" similar to CCDs. This implies
fabricating matrixes with thousands of pixels, each pixel having performances at the level of the experimental photon noise. The structure of a single pixel must therefore be compatible with a highly-reliable collective fabrication and multiplexed readout electronics.

2. Principle of operation of an all electron bolometer
The base structure of a single pixel for submillimetric measurements is composed of three important elements: a radiation absorber, a thermometer and a thermally isolated holder enabling a very weak coupling of the former two with respect to the cold bath. The different existing detectors differ in the nature of the absorber (horns, absorbing films, antennas), the nature of the thermometer (high impedance-type, or superconducting Transition Edge Sensors) and in the answer given to the thermal decoupling problem (diversely manufactured membranes, micromesh membranes). The latter is an extremely critical point: the sensitivity of a bolometer to an incident power $P$ is limited by its Noise Equivalent Power: $\text{NEP}^2 = 4k_BT^2G$ and therefore directly depends on the thermal decoupling $G$ between the absorber and the thermometer on the one hand and the cold bath on the other. Moreover, in order to experimentally realize this thermal decoupling, very delicate clean room processes is required. In the Planck experiment, for example, the bolometer is placed at the center of a spider web-shaped membrane which decouples the bolometer from the cold bath. Its extremely weak thermal coupling of $10^{-11}$ W.K$^{-1}$ is perfectly matched to the value of the Planck CMB background power of the order of pW but the fabrication of such structures is difficult and many groups worldwide are currently making huge efforts to obtain high performance membranes for bolometer matrixes. All currently investigated devices have in common to use phonons as vectors for energy transport between the different parts.

We here present a proposal for an innovative device which replaces these delicate membrane-based structures and eliminates the mediation of phonons: the incoming energy will be directly captured and measured in the electron bath of an appropriate sensor and the thermal decoupling will be achieved via the natural decoupling that exists between electrons and phonons of the sensor at very low temperature. This has been studied in detail for amorphous Nb$_x$Si$_{1-x}$ thin films [1] [2] giving: $G_{eph} = \partial P/\partial T = KT^4$ and $K = 500$ W.K$^{-4}$.cm$^{-3}$ (figure 1.a.). It follows that $G_{eph} = 5.10^{-11}$ W.K$^{-1}$ at 100 mK for a 100 nm thick 100 $\mu$m x 100 $\mu$m thermometer. Because $G_{eph}$ varies proportionally to $T^4$, the performances of such a detector are directly linked to the possibility of working at very low temperature, a constraint which is anyhow unavoidable in order to improve the performances of existing detectors. The use of temperatures below 100 mK (Planck’s nominal temperature) will be necessary in order to maintain the sensor’s thermodynamical noise - called ”phonon noise” - below the ”photon noise” due to the measured light sources when the latter becomes very weak. The limitation in the operation temperature is then set by the desired response time: the intrinsic relaxation time of NbSi thin films is of the order of 10 ms at 30 mK and varies proportionally to $T^{-4}$ (figure 1.b.).

In order to use the natural electron-phonon decoupling as the bolometric thermal decoupling, it is crucial to absorb the wave directly into the electron bath of the thermometric material used. Recent studies [3] on a-Nb$_x$Si$_{1-x}$ thin films, known to undergo a superconductor-metal-insulator transition when the niobium concentration or the thickness is varied, allow us to propose different answers to this question. We consider detectors where the absorption is achieved by the thermometer alone or by the thermometer electrically coupled to antennas. For either case, our proposal can adapt to high-impedance (R>100 k\$\Omega\$) or SQUID-based readouts (R<1 $\Omega$).

3. A single superconducting thin film for the absorber and the thermometer
A first possible device consists in a single superconducting thin film which both absorbs the wave and measures the temperature. In order to be suitable for matrix fabrication, the absorber
Electron-phonon thermal coupling constant $G_{eph}$ for a 100 nm thick, 100 µm x 100 µm NbSi thermometer ($G_{eph}$ is proportional to the film volume). In our case the time constant is independent of the size of the film.

Square resistance versus temperature of a 25 nm Nb$_{15}$Si$_{85}$ thin film.

must have a size of the order of the wavelength ($\simeq 1$ mm) and meet the vacuum impedance (377 Ω per square) so that the wave absorption is optimum. In the case of a superconducting absorber, the detected incoming photons will see the normal resistance since they have energies larger than the superconducting gap: $h\nu \gg k_B T_c$. We have previously shown [2] [3] that a-Nb$_x$Si$_{1-x}$ is a compound where the superconducting temperature $T_c$ and the normal resistance can be separately tuned through the composition of the alloy $x$ and the film thickness $d$. Figure 2 shows the superconducting transition of a a-Nb$_{15}$Si$_{85}$ 25nm thin film which normal resistance is optimum for the absorption and could be used as a TES at the temperature of $^3$He (300 mK). However, the composition and thickness of the alloy could also be adapted in order to fabricate a TES working around 50 mK, which is the optimum temperature for a performant thermal decoupling and a not-too-long response time.

This device could, in principle, be combined to an optimal readout system. Keeping a constant normal impedance with respect to the incoming electromagnetic wave, the TES transition resistance could both be adapted to a SQUID-based readout - via interdigitated electrodes - or to classic transistor readout - via a meander shape of the film.
4. Antennas and TES
A second possible device consists of an antenna coupled to a superconducting film. Antennas are made out of superconducting films having a specially designed geometry in order to absorb the incident radiation with high selectivity with respect to the energy spectrum and polarization. In standard existing devices, the absorbed power is routed via superconducting strips towards a resistive load where dissipation occurs. The thermometer and the resistive load are designed to be very close although they stay (in principle) electrically decoupled. Thus, the energy transfer is phonon-mediated. Some attempts have already been made [4] to transfer the absorbed energy from antennas directly to the electrons in a TES. However high-frequency impedance matching of antennas to conventional TES is difficult because of their low normal state impedance. The properties of a-Nb$_x$Si$_{1-x}$ thin films enable such a fine tuning since its normal impedance is rather high (a 100 nm thick TES film has a normal square resistance of typically 150 $\Omega$ per square). In addition to the intrinsic advantages of using antennas - high selectivity, good filling coefficient - they would in our case enable to reduce the size of the thermometric thin film and thus decrease the value of the equivalent thermal leak $G_{\text{eph}}$ which is proportional to the volume of the film.

5. Absorbers and thermometers are Anderson insulators
Last, the absorber and the thermometer could be made out of an Anderson insulator. Indeed, low temperature fundamental studies on Anderson insulators and most particularly on a-Nb$_x$Si$_{1-x}$ [5] at concentrations where it is insulating ($x<9\%$) show that the real part of the impedance at a high frequency $h\nu$ is essentially the same as the low frequency impedance at a temperature $T$ given by $k_B T = h\nu$. This means that at 150 GHz, the value of the film resistivity is equal to the one measured with DC bias at a temperature of 10 K. This is independent of the DC film resistance at the working temperature which can be of a few M$\Omega$ at 50 mK and hence perfectly suitable for a JFET type electronic readout.

6. Conclusion
Many groups throughout the world (including the French DCMB collaboration) work on the realization of matrixes under the very classical scheme of absorber-thermometer-decoupling device. The present project which proposes to gather all three functions in one material presents a original way to improve and simplify the detectors so that, in particular, to meet the challenge of the B-mode CMB polarisation measurement.

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