Thermoelectric single-photon detector

A A Kuzanyan, V A Petrosyan, A S Kuzanyan
Institute for Physical Research, National Academy of Sciences, Ashtarak 0203, Armenia
E-mail: kusanian@yahoo.com

Abstract. The ability to detect a single photon is the ultimate level of sensitivity in the measurement of optical radiation. Sensors capable of detecting single photons and determining their energy have many scientific and technological applications. Kondo-enhanced Seebeck effect cryogenic detectors are based on thermoelectric heat-to-voltage conversion and voltage readout. We evaluate the prospects of CeB₆ and (La,Ce)B₆ hexaboride crystals for their application as a sensitive element in this type of detectors. We conclude that such detectors can register a single UV photon, have a fast count rate (up to 45 MHz) and a high spectral resolution of 0.1 eV. We calculate the electric potential generated along the thermoelectric sensor upon registering a UV single photon.

1. Introduction
In recent years the progress in telecommunications and information systems is frequently connected with the advent of quantum cryptography and information processing by quantum systems (quantum computers). In this context the interest towards single-photon detectors of optical radiation, allowing to register single quanta of light with high efficiency, has grown significantly. The employment of single-photon detectors can also favour the creation of a new generation of laser tomographs and lidars, X-ray analysers and defectoscopes. Without single-photon detectors it is hard to imagine the progress in such areas of science, as cosmic astronomy and particle physics.

Detectors based on photomultiplier tubes (PMT) and avalanche photodiodes (SPAD) are capable of operating in a single-photon regime. But, unfortunately, they do not possess wide spectral sensitivity, high energy resolution and count rate. At this point of time the superconducting single-photon detectors (SSPD) are considered the most promising among single-photon detectors [1–4]. They have exceptional technical characteristics but they too have deficiencies, such as the need of a rigid temperature regime and the complexity of construction. The low-temperature thermoelectric single-photon detectors can serve as an alternative to SSPDs. Detectors based on CeB₆ and (La,Ce)B₆ crystals can detect a single UV photon, have very fast count rate (up to 1.8 GHz in case of thin-film geometry) and a spectral resolution of 0.1 eV. These detectors do not require strict temperature conditions and are simpler in construction [5–7]. The comparison of features of currently available single-photon detectors and the thermoelectric detectors with a thin-film sensor is presented in [7]. In this work we will focus in more detail on the possibility of creating a thermoelectric detector with a monocrystalline sensor and will discuss its characteristics.
2. The crystalline thermoelectric single-photon sensor

2.1. The structure of the crystalline thermoelectric single-photon sensor
In principle the sensitive element of the thermoelectric detector on the basis of single crystals can be composed of only two elements (Figure 1): a thermoelectric monocrystal and an absorber, as well as two contacts through which one can register the voltage generated upon absorbing a photon.

![Figure 1. The schematic of a thermoelectric single-photon detector based on single crystals.](image)

The method of preparing the monocrystalline sensitive element is protected by an Armenian patent [8] in which one of the two possible constructions of the monocrystalline sensor is described and a method of its fabrication is proposed.

2.2. The spectral resolution
The most important characteristics of a detector are the photon count rate and the spectral resolution. The physical processes occurring in a pixel of a thermoelectric detector after a single photon is absorbed are described in detail in [6]. The full-width at half-maximum expression of spectral resolution of a monocrystalline thermoelectric sensor based on the observable response to monoenergetic photons is:

\[
\Delta E_{\text{FWHM}} = 2.35 \left[ 2k_B T^2 C_{\text{abs}} \left( 1 + (ZT)^{-1} \right) \right]^{1/2},
\]

(1)

where \(C_{\text{abs}}\) is the absorber heat capacity (an element in the construction of the detector which absorbs the photon), \(ZT\) is the thermoelectric figure of merit \((ZT = TS/\sigma k)\), \(S\) is the Seebeck coefficient, \(\sigma\) and \(k\) are, respectively, the electrical and thermal conductivity, \(T\) is the absolute temperature. For a 1 µm³ tungsten absorber at 9 K the \(C_{\text{abs}}\) is equal to \(\sim 10^{-15} J/K\). If we take into account the \(ZT_{\text{max}} \sim 1.19\) (for CeB₆ crystals [7]), we can find at 9 K the spectral resolution to be \(\sim 12.7\) eV. This means that a thermoelectric detector built on CeB₆ crystals may be able to distinguish UV range photons (which have an energy of 3–124 eV) of not very low energy, as well as X-ray photons. That, in turn, means that the detector will be able to detect a single X-ray photon and can be used in cosmic X-ray astronomy, in X-ray microanalysis, etc.

In case of \((\text{La}_{0.99}\text{Ce}_{0.01})\text{B}_6\) we can choose \(C_{\text{abs}} \sim 10^{-17} J/K\) (at 0.5 K temperature and 0.25 µm³ volume) and, taking into account that the \(ZT\) for this hexaboride is 0.1, we can find the value of energy resolution to be \(\sim 0.1\) eV [6]. The single-photon detector built on \((\text{La,Ce})\text{B}_6\) will be capable of registering even low-energy single UV photons.

2.3. The count rate
The second important characteristic of the detector is its photon count rate. Before proceeding to the calculation of this parameter, we need to clarify the characteristics of the absorber, namely the absorber material and its geometric dimensions which are required for a reliable absorption of a photon of certain energy. In many detectors heavy metals are used as an absorber. We opted for the tungsten; now let us see what absorber thicknesses are required.
The absorption of incident radiation is determined by the Beer–Lambert law:

\[ I = I_0 e^{-\mu l}, \]  

(2)

often written as \[ I = I_0 e^{-\left(\frac{\mu}{\rho}\right)\rho l}, \] where \( \mu \) is the linear attenuation coefficient (it depends on photon energy), \( \rho \) is the absorber density (for tungsten \( \rho = 9.3 \, \text{g} \cdot \text{cm}^{-3} \)), \( l \) is the absorption depth.

Figure 2 demonstrates the probability of reaching a certain depth in tungsten for photons of 100 eV and 1 keV energy. The graph shows that the maximum depth the photons with energies of 1 keV can reach is about 1.5 \( \mu \)m, whereas photons with an energy of 100 eV cannot overcome the 0.5 \( \mu \)m thickness.

The count rate of the thermoelectric single-photon detector with a crystalline sensor is determined by the speed of heat outflow from absorber to crystal. This time is determined by the following expression [6]:

\[ \tau_{\text{heat flow}} = C_\text{abs} / G = C_\text{abs} l / k A, \]  

(3)

where \( C_\text{abs} \) is the absorber heat capacity, \( G \) is the heat conductance of the crystalline sensor, \( l \) is its length, \( k \) is its thermal conductivity and \( A \) is its cross-sectional area. So, the count rate is strongly dependent upon the detector’s geometry. If we choose the crystal size as 0.3 mm \( \times \) 1 mm \( \times \) 1 mm and the absorber size as 1 \( \mu \)m \( \times \) 1 mm \( \times \) 1 mm, then taking into account that at 9 K \( C_\text{abs} = 10^{-8} \, \text{J/K} \) and \( k = 10 \, \text{mW/cm K} \) [9], we obtain for the heat flow time \( \tau_{\text{heat flow}} = 300 \, \text{ns} \), which corresponds to a count rate of about 3 MHz.

Obviously, by adjusting the geometric dimensions of the crystal and the absorber one can achieve higher count rates. With today’s capabilities of crystal processing one can have crystals sized only few tens of microns. In Table 1 we demonstrate the count rates corresponding to different absorber–sensor geometries. It is notable, that with 20 \( \mu \)m \( \times \) 20 \( \mu \)m \( \times \) 20 \( \mu \)m sized crystals a count rate of 45 MHz is achievable.
Table 1. The count rate of the thermoelectric detector with different geometries

| Absorber size (length × width × height) | Sensor crystal size (length × width × height) | Absorber heat capacity | Count rate with a CeB$_6$ sensor at 9 K |
|----------------------------------------|----------------------------------------------|------------------------|----------------------------------------|
| 1 μm × 1 mm × 1 mm                     | 0.3 mm × 1 mm × 1 mm                         | 10$^{-9}$ J/K          | 3 MHz                                  |
| 1 μm × 0.5 mm × 0.5 mm                 | 0.3 mm × 0.5 mm × 0.5 mm                     | 0.25 · 10$^{-9}$ J/K   | 3 MHz                                  |
| 1 μm × 1 mm × 1 mm                     | 1 mm × 1 mm × 1 mm                           | 10$^{-9}$ J/K          | 1 MHz                                  |
| 1 μm × 50 μm × 50 μm                   | 50 μm × 50 μm × 50 μm                        | 0.25 · 10$^{-11}$ J/K  | 18 MHz                                 |
| 1 μm × 20 μm × 20 μm                   | 20 μm × 20 μm × 20 μm                        | 4 · 10$^{-13}$ J/K     | 45 MHz                                 |

2.4. Generated thermopower

In this section we consider the order of magnitude of the thermopower generated along the detector’s sensor upon absorbing a single photon. To be more precise, we estimate the generated maximum thermopower which will occur under the most favorable conditions, namely the value of the thermoelectric figure of merit is maximal, the photon is absorbed near the absorber–thermoelectric sensor border, the thermopower is recorded at the initial time, when it is maximal.

Thus, in accordance with the definition of the Seebeck coefficient, the voltage generated along a thermoelectric material is proportional to the temperature gradient and is defined by the equation:

\[ U = S \Delta T. \]  \hfill (4)

Figure 3 shows the temperature dependence of the Seebeck coefficient of the CeB$_6$ crystal, according to which \( S = 265 \) μV/K at 9 K \([10]\). This is the maximum value of the Seebeck coefficient of the CeB$_6$ crystal we were able to find in the literature.

Figure 3. The S(T) dependence of a good CeB$_6$ crystal from Naushad Ali and S. B. Woods, Transport properties of Kondo lattice CeB$_6$, J. Appl. Phys. 57, 3182 (1985).
In its turn, the temperature gradient occurring along the thermoelectric detector’s sensor upon absorbing a photon with an energy of $E_{ph}$ is

$$\Delta T = \frac{E_{ph}}{C_{abs}}.$$  \hspace{1cm} (5)

For tungsten between 5–15 K we have $C(J/\text{mole} \cdot \text{K}) = 1.11 \times 10^{-3}T + 1943(T/378)^3$ [11]. It is not difficult to calculate what temperature gradient occurs along the sensor upon absorbing photons with a certain energy. The values of the temperature gradient occurring along the thermoelectric sensor at 5–15 K temperature upon absorbing a 100 eV photon are shown in Figure 4 (absorber size is 1 $\mu$m$^3$).

![Figure 4. The values of the temperature gradient generated along the thermoelectric sensor at 5–15 K upon absorbing a 100 eV photon.](image)

Assuming the best values of $S$, the thermopower generated upon absorbing a 100 eV ultraviolet photon should be $\sim 1.80 \mu\text{V}$ at 5 K and $\sim 1.07 \mu\text{V}$ at 9 K.

3. Conclusion

In this paper we have tried to show both the possibility of creating an actual design of a thermoelectric detector sensor using actual materials and the possibility of registering a UV range single photon absorption. The calculated values of energy resolution and count rate make us hopeful that the thermoelectric detector can be used for solving a number of specific scientific and technical problems. Optimistic calculations show that the voltage arising on the sensor of the thermoelectric detector can reach microvolts. Such voltages are measured with great accuracy by the most common voltmeters. If we assume that the real signal is several orders of magnitude weaker, in that case too its measurement will not be very difficult. The same can be claimed if we consider the time of the photon absorption process. Exact calculations of thermal processes occurring in the sensor of a thermoelectric detector upon the absorption of a single photon will be conducted and published in the near future.

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