Thermoelectric Single-photon Detector with High System Efficiency Based on Rare Earth Hexaborides

Astghik Kuzanyan, Lusine Mheryan, Vahan Nikoghosyan, Armen Kuzanyan

The Institute for Physical Research, 0204, Ashtarak, Armenia

System detection efficiency (SDE), the ratio of the number of detected photons to the total number of photons reaching the detector, is one of the key characteristics of single-photon detectors. High SDE is essential for use in quantum communications, computing, sensing, metrology, and other applications. Advances in single-photon detection in the mid-infrared range using superconducting nanowires, avalanche photodiodes, and photovoltaic detectors are presented in [1]. Superconducting nanowires have superior performance and provide SDE greater than 98% at 1550 nm [2]. Thermoelectric single-photon detectors have some advantages over superconducting ones and can compete with them if comparable characteristics are achieved [3].

We present the results of computer simulations of heat propagation in a multilayer thermoelectric sensor consisting of a molybdenum heat sink, a lanthanum-cerium hexaboride thermoelectric layer, and a tungsten absorber, all positioned sequentially on a sapphire substrate. Photon absorption in the 0.8–50 eV range was studied in a sensor with surface areas of 1 and 100 μm² at operating temperatures of 0.5, 1, and 1.5 K (for a 10-nm-thick $La_{0.99}Ce_{0.01}B_6$ thermoelectric layer), as well as at an operating temperature of 4.2 K (for a 5 and 10 nm thick CeB_6 thermoelectric layer). The thicknesses of the W absorber, Mo heat sink, and Al_2O_3 substrate were 40, 10, and 100 nm, respectively, in all simulations.

SDE is determined by three factors: the efficiency of optical coupling of the detected photon and the sensor (η_1), the efficiency of photon absorption (η_2), the efficiency of detection of the already absorbed photon (η_3) and is given by the equation $\eta = \eta_1 \times \eta_2 \times \eta_3$. For the sensor under consideration, the values of $\eta 1 \times \eta 2$ are determined by the reflection and transmission coefficients of tungsten [4], and for photons with energies of 0.8, 3.1, 22.5, 38, and 44.7 eV at an absorber thickness of 40 nm they will be 0.051, 0.199, 0.767, 0.948, and 0.971, respectively. The values of $\eta 3$ can be considered to be approximately equal to 1 if the signal-to-noise ratio (SNR) is greater than 1. To determine the SNR, computer simulations of heat propagation processes in a thermoelectric sensor were carried out based on the equation of heat transfer from a limited volume. It was shown that when detecting single photons with energies of 22.5, 38 and 44.7 eV at an operating temperature of 4.2 K, a SNR > 1 can be achieved. However, it is not possible to simultaneously achieve high efficiency of recording already absorbed photons and a high counting rate. At operating temperatures of 0.5 - 1.5 K, SNR values increase from 1.13 to 7050 with decreasing sensor surface area, decreasing operating temperature, and increasing photon energy. Thus, it can be concluded that SDE > 95% can be achieved by detecting EUV photons. At the same time, the count rate reaches values of 0.13 - 2.14 THz.

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