Four-layer Thermoelectric Single-photon Detector Sensor

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We present the results of computer simulation of heat propagation processes in a four-layer thermoelectric single-photon detector sensor after absorption of photons with energies of 0.8, 1.65 and 3.1 eV. The sensor had the following design: a square surface with an area of 100, 4 and 1 μm^2, consisting of an antireflective layer (SiO_2), an absorber (W), a thermoelectric layer ($La_{0.99}Ce_{0.01}B_6$), a heat sink (Mo), and a dielectric substrate (Al_2O_3), arranged sequentially on top of each other. The thickness of the antireflective layer was determined based on the minimum reflectivity condition: $d_1 = \lambda/(4\times n)$, where λ is the photon wavelength and n is the refractive index of SiO_2. For the selected photon energies, the thickness d1 will be equal to 268, 129, and 68 nm. The following thicknesses of the remaining layers were considered: absorber - 20, 30 and 40 nm, thermoelectric layer - 10 and 5 nm, heat sink - 10 nm and substrate - 100 nm. Another variable was the operating temperature of the sensor, which took values of 0.5, 1.0 and 1.5 K.

Computer simulation of heat propagation processes in the sensor after thermalization of a single photon at the center of the absorber surface was performed using the finite difference method to solve the heat transfer equation from a confined volume. This methodology, as well as the equations for calculating the equivalent noise power, noise power, signal power, and signal-to-noise ratio, are described in [1].

The heat propagation characteristics associated with the addition of a SiO_2 layer to the sensor design were investigated. The key heat propagation patterns were determined, and the time dependences of temperature in various surface areas of all layers, the average surface temperature of the layers, and the average temperature gradient at the boundaries of the thermoelectric layer, which determines the signal generated at the sensor, were studied. The equivalent noise power of the sensor with various geometries was calculated, and the signal voltage, signal power, noise power, and signal-to-noise ratio were determined. For the absorption of photons with energies of 3.1 and 1.65 eV, the obtained signal-to-noise ratio were greater than unity. Therefore, the proposed sensor can effectively detect an already absorbed photon. This is a positive result. For photons with energies of 0.8 eV, the signal-to-noise ratio are less than unity, precluding their detection. Therefore, the proposed four-layer thermoelectric detector sensor design is not optimal for the near-infrared range. Other materials could be considered for the top two layers, or a three-layer design with an absorber that provides high efficiency for both absorption and optical communication. It is also necessary for the absorber to be made of a conducting or superconducting material, since the absorber is also one of the contacts for recording the voltage arising at the boundaries of the thermoelectric layer.

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References

[1] A. A. Kuzanyan, V. R. Nikoghosyan, A. S. Kuzanyan, IEEE Sens. J. 25, 34558 (2025).