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Design and Optimization of Microbolometer Multilayer Optical Cavity

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Microbolometers are the most widely used detectors in long-wave infrared uncooled thermal imagers. An optical cavity is required within a microbolometer structure to increase its optical absorption. In this work we present a detailed study on the design and optimization of a microbolometer optical cavity using Essential-Macleod package. In the simulations, the cavity is considered as thin film multi-layers that form cascaded Fabry-Perot optical cavities. In the design phase, the structures of layers are selected, which includes selection of materials and initial thickness. The absorbing layers are chosen to be made of vanadium-pentoxide (V_2O_5) and titanium (Ti). In the optimization phase, the designed layer thicknesses are varied to maximize optical absorption within the absorbing layers. The simulations show that Ti layer absorption dominates over the V_2O_5 layer. Also, the optimization proves that the thickness of cavity's air-gap is not equal simply to quarter-wavelength, because of the presence of a complex cascaded Fabry-Perot structure. The optimized air-gap thickness is found to be ≈ 3.5 μm at wavelength of 10.6 μm.

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1. Introduction

Microbolometers are the most widely used detectors in long-wave infrared (LWIR) uncooled thermal imagers. A microbolometer is a temperature dependent electrical resistor. The resistance of a bolometer will change when its temperature changes. Microbolometers are made out of metals, semiconductors and superconductors. A microbolometer is operated by passing a bias current through it and monitoring the voltage change (as a result of incident radiation) across its terminals [1]. The microbolometer design problem consists of several inter-related components: optical design, thermal design and mechanical components design. The overall design aims to optimize the material choice and the thicknesses of the thin films composing the microbolometer, while keeping in mind that the design should be possible to implement from a manufacturing perspective, preferably at the lowest possible cost. The optical/thermal/mechanical design of a microbolometer aims to optimize the absorption of the infrared radiation inside it, whilst keeping the thermal time constant and thermal insulation at an acceptable level for video frame rate imagery and high detectivity. The design, in the meantime, is considerate of achieving a mechanically robust structure.

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In this work we present a detailed study on the design and optimization of microbolometer optical cavity, aiming to optimize the infrared absorption in the microbolometer. The study was made using Essential-Macleod package [2]. This package is a comprehensive tool for designing and analyzing of optical thin-film multi-layers structures. It can be used to simulate reflection, transmission, and absorption in these structures as function of wavelengths. All the simulations here are carried out at the center wavelength of 10.6 μm within the LWIR spectral range from 8 to 12 μm. In the simulations, the cavity comprising absorbing layers and an air gap is considered as thin film multi-layers that are stacked together to form cascaded Fabry-Perot optical cavities, each with a different thickness and complex refractive index. The study is divided in two main phases: The design phase which focuses on the microbolometer's layers structure, and the optimization phase which focuses on maximizing device absorption.

2. Microbolometer multilayer design

In this phase, the structure of layers is selected, which includes selection of materials and initial thicknesses. The optical parameters of materials are obtained through ellipsometer measurements in the lab, and from the Macleod material library data. The optical parameters include the refractive index and extinction (absorption) coefficient as a function of wavelength. The infrared (IR) absorbing layers of the microbolometer are selected to be the vanadium-pentoxide (V_2O_5) and titanium (Ti).

The air-gap cavity of the microbolometer consists of a vacuum space between the IR absorbing (sensitive) layers and an IR reflective bottom mirror (metal) that is patterned on the device substrate, as shown in Fig. 1. This cavity plays a very important role in microbolometer operation, as it determines the absorption wavelength range and maximizes this absorption within the IR-sensitive layers. Therefore, an optical cavity can increase the microbolometer responsivity and detectivity [3, 4, 5]. The air-gap cavity enhances absorption inside different absorbing layers through multiple reflections; in addition it thermally isolates the absorbing layers because of the vacuum air-gap.

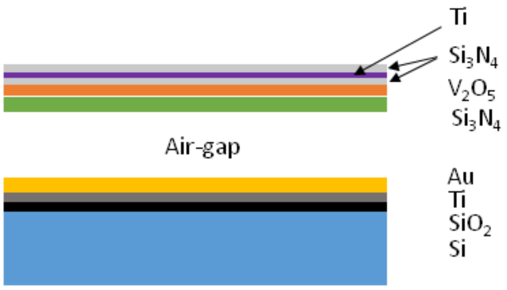

Fig. 1. The designed microbolometer layers structure.

The initial simulations are performed to select a cavity mirror, by choosing an appropriate metal type and adjusting its thickness. The reflectance of mirror is calculated for different metal types: Gold (Au), silver (Ag), and aluminum (Al). The metal mirror was placed on silicon-dioxide (SiO_2) and a thin layer of Ti of 10 nm, was placed below the metal mirror to promote adhesion between the metal and the SiO_2. Titanium was chosen as an adhesion promoter between the metal mirror and SiO_2, because it is used as absorber in the top layer and thus the number of different metals used in the structure is reduced. This is convenient from the practical point of view. The SiO_2 thickness was selected to be 300 nm, which is commensurate with the typical thickness of a passivation layer placed on readout integrated circuits (ROIC). At the center wavelength of 10.6 μm, the reflectance of Ag is $\approx$ 99.13%, for Au it is $\approx$ 99.04%, and for Al it is $\approx$ 98.1%. Thus, it is obvious that the best reflectors are Ag and Au. The best metal thickness for all metal mirrors is found to be 50 nm, which is considered the minimum thickness above which the reflection reaches its maximum constant value. The mirror reflector in this work is selected to be Au because of its high reflectance in the LWIR range, beside its high resistance to oxidization.

The microbolometer absorption layers above the air-gap (Fig. 1) consist of silicon nitride (Si_3N_4), titanium (Ti), Si_3N_4, vanadium-pentoxide (V_2O_5), and then Si_3N_4. The Si_3N_4 layer above the V_2O_5 layer is used for electrical isolation between V_2O_5 and Ti layers, while the Si_3N_4 layer on top of Ti is used for passivation. The Si_3N_4 layer underneath the V_2O_5 is used to mechanically support the thin V_2O_5 layer. Table in Fig. 2 shows the optical refractive indices of each layer at 10.6 μm, together with the extinction coefficients and the initial selected values of each layer thickness. It is worth mentioning that the absorption layers together with the air-gap, and reflective mirror-metal act as a structure of cascaded Fabry-Perot (FP) optical cavities. Each FP has its own thickness and complex refractive index. These multi-layers are optimized in the next step to increase the device overall optical absorption.

Layer	Material	Refractive Index	Extinction Coefficient	Optical Thickness (FWOT)	Physical Thickness (nm)
Medium	Air	1.00000	0.00000		
1	PMMA(Elp)	1.28615	0.01217	0.00606675	50.00
2	Ti(1)	8.24000	19.34000	0.00621887	8.00
3	PMMA(Elp)	1.28615	0.01217	0.00606675	50.00
4	V2O5 ELP	1.63976	0.16412	0.02320415	150.00
5	Si3N4 (ir)	1.38990	1.34510	0.05244907	400.00
6	Air	1.00000	0.00000	0.24528302	2600.00
7	Au(1)	12.67000	71.40000	0.14343396	120.00
Substrate	Si	3.42140	0.00013		

Fig. 2. The optical parameters of microbolometer selected materials.

3. Optical multilayer-cavity optimization

In this phase, the designed layer thicknesses are varied simultaneously to maximize the optical power absorption within the designed absorbing layers, within the specified LWIR spectral range. The initial optimization simulations show that the Ti layer absorption dominates over other layers including the V_2O_5. Figure 3 shows the absorption-factor of Ti, V_2O_5, and Si_3N_4 versus wavelength. The absorption-factor is defined as the ratio of the absorbed power to the total incident radiation power. As shown, the Ti absorption at the wavelength of 10.6 μm is about three times more than that of Si_3N_4 and ten times more than that of V_2O_5. This is due to its much higher extinction coefficient, compared to the other layer materials, as already indicated in Fig 2.

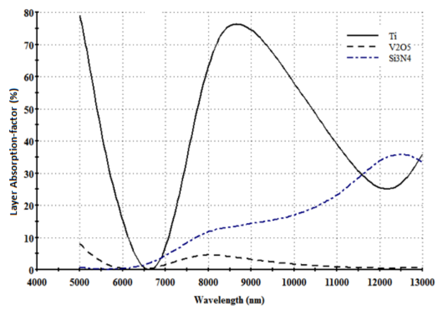

Fig. 3. The absorption-factor of each absorbing layer versus wavelength.

Figure 4 shows the 2D-contour plots of total device absorption as a function of wavelength and layers thickness. These figures are utilized to select the optimum thickness of each layer in order to maximize the total absorption-factor of the microbolometer device. In Fig. 4a, it is found that the optimum thickness of Ti-layer, around wavelength of 10 μm, is about 5 nm, for which the total absorption reaches a maximum value of approximately 90%. In Fig. 4b, it is found that the optimum thickness of V_2O_5-layer is almost 150 nm, around the wavelength of 10 μm, where absorption reaches a maximum of approximately 88%. In Fig. 4c, the optimum thickness of Si_3N_4 is found to be almost 300 nm, for which the absorption reaches approximately 89%. In Fig. 4d, the optimum thickness of air-gap is almost 3500 nm, for which the total absorption reaches approximately 80%.

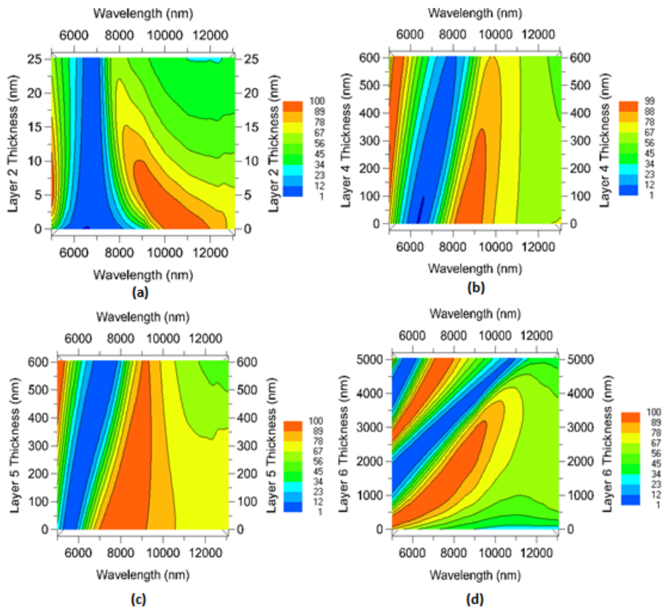

Fig. 4. The total absorption-factor of microbolometer device, versus wavelength and the thickness of the different layers: (a) Ti, (b) V_2O_5, (c) Si_3N_4, (d) Air-gap cavity.

Figure 5 shows the total device absorption versus air-gap thickness at the center wavelength of 10.6 μm. It is clear that the optimum thickness for maximum absorption is 3500 nm, for which the absorption is $\approx$ 76%. Thus, the optimized air-gap cavity thickness is not simply equal to $\lambda/4$ (i.e. 2.65 μm at center wavelength of $\lambda = 10.6$ μm), because of the complex configuration of microbolometer multilayer structure, that acts as several cascaded Fabry-Perot cavities. Therefore, the complex interplay between optical phase-shifts of multi-layer cascaded FP can be accurately calculated through numerical simulations in order to determine the optimum air-gap cavity thickness.

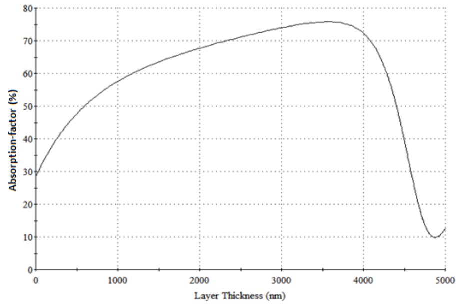

Fig. 5. The total absorption-factor versus air-gap layer thickness at wavelength of 10.6 μm.

4. Conclusions

A detailed study of the design and optimization of microbolometer optical cavity using Essential-Macleod package is presented. The microbolometer layers are considered as thin-film stacked multi-layers that form complex structure of cascaded Fabry-Perot optical cavities. The structure of layers is selected during the design phase, including the selection of materials and initial thicknesses. The simulations show that the absorption of Ti layer dominates over that of V_2O_5 layer. The optimization phase proves that the optimal thickness of air-gap cavity is not simply equal to quarter-wavelength, and has a value of ≈ 3.5 μm at the centre wavelength of 10.6 μm.

Acknowledgments

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