INTRODUCTION

The most effective mechanism for the absorption of IR radiation is provided by high porosity surfaces.\(^1\) New surface modification techniques have emerged in the fabrication of black metals (platinum, tungsten, titanium and gold), that exhibit extremely low reflectance and correspondingly high absorptance across the IR spectra.\(^2\) More recently, black gold and black silicon (BSi) have been reported to be used as IR absorber materials. Black gold, obtained by thermal evaporation methods, exhibits absorptance close to unity, but the fragile structure of this material and the degradation of absorption properties, when it is exposed to temperatures higher than 300 °C, do not make it feasible for mass production.\(^3\)

BSi, a surface modification of crystalline silicon (c-Si),\(^4-8\) exhibits absorptance close to unity in the wavelength range of 0.8-25 μm; but, the thin film fabrication process technology that is required for the deposition and patterning of this material may not be fully compatible with all semiconductor processes and it does not allow the mass production of low cost infrared detectors.

Therefore, there is a need for low cost standard semiconductor materials with high emissivity in the IR spectrum. These materials also need to be compatible with the actual manufacturing process and should enable easy integration of components, circuits and systems. In this study, the radiative properties of common dielectric materials such as Al\(_2\)O\(_3\), SiO\(_2\), AlN and Si\(_3\)N\(_4\) are simulated in the infrared spectral range of 1.5-14.2 μm. These dielectric materials are routinely used as electrical insulators and anti-reflection coatings, as well as passivation layers in a variety of applications including displays, light emitting diodes, microbolometers, sensors, solar cells and other photonic devices. In particular, the design of coatings (highly reflective and antireflective) requires accurate knowledge of the radiative properties of the dielectric materials considered.
INFRARED ATMOSPHERIC TRANSMISSION WINDOWS

The infrared radiation in the atmosphere is restricted to certain spectral windows, due to the existence of transmission bands as the result of atmospheric gas molecules (CO₂, H₂O, O₃ and O₂), that absorb and scatter the IR radiation. The atmospheric transmission bands are limited to 0.8-2.5 μm (near-IR wavelength), 3-5 μm (medium-IR wavelength) and 8-14 μm (long-IR wavelength). Each component of the IR spectrum provides different information and targets different applications. In this study, the infrared spectral range of 1.5-14.2 μm (near to long IR wavelength) is considered. The specific applications include imaging, high temperature detection such as fire-fighting, non-contact temperature measurements, aircraft detection, and heat seeking missiles. Fig. S1 shows the IR transmission in the earth’s atmosphere. The IR band, 8-14 μm (long-IR), is the infrared spectral region of choice by infrared imaging detection systems due to the existence of an atmospheric window and at 300K, this band registers the maximum infrared radiation emissivity of materials.

Fig. S1. IR transmission in the Earth’s atmosphere [Redrawn based on Figure 1 in reference (9)].

Multi-Rad

Multi-Rad is an optical modeling software developed by Massachusetts Institute of Technology (MIT). Multi-Rad facilitates the calculation of the optical properties of thin films using the matrix method of multilayers. This method predicts the emissivity (ε), reflectance (R) and transmittance (T) of a multilayer stack with the assumption that the layers are parallel and optically isotropic. The radiative properties can be calculated for different angles of incidence (0-90°) and in the spectral range of 0.4-20 μm. For a multilayer stack with specific values of index of refraction (n) and extinction coefficient (k) for each layer, at specific temperature, the radiative properties such as absorptance, reflectance and transmittance are determined.

For normal incidence, the coherent optical reflectance and transmittance of a multilayer structure are readily represented as a product of matrices. A multilayer structure composed of optically isotropic and homogeneous layers, with plane and parallel faces, is assumed for this
matrix method. The elements of the system, transfer matrix, can be written in terms of the complex-amplitude reflection and transmission coefficients $R$ and $T$ of the multilayer structure.\(^9\)

Fig. S2 shows a generic layer structure. There are $N$ layer interfaces (circled) and $N+1$ "layers (squared)", including the unbounded transparent media on each side of the actual stack. $A_i$ and $B_i$ are the amplitudes of the forward and backward propagating electric field vectors on the left side of interface $i$. The prime notation on $A'_{N+1}$ and $B'_{N+1}$ indicates that these are the amplitudes on the right side of interface $N$. Light is incident on interface 1, with an angle of incidence $\theta_1$.\(^9\)

![Fig. S2. Notation of matrix method of multilayers [Redrawn based on Figure 3 in reference (9)].\(^9\)](#)

The multilayer theory relates the amplitudes on the left side of interface 1 with those on the right side of interface $N$ and is expressed in this equation:

$$
\begin{pmatrix}
A_1 \\
B_1
\end{pmatrix} = 
\begin{bmatrix}
P_1 & D_1^{-1} & D_1 \end{bmatrix}
\begin{bmatrix}
A'_{N+1} \\
B'_{N+1}
\end{bmatrix} = 
\begin{bmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{bmatrix}
\begin{bmatrix}
A_{N+1} \\
B_{N+1}
\end{bmatrix}
$$

(1)

where $P_i$ is the propagation matrix, $D_i$ is the dynamic matrix, and $m_{ij}$ is an element of the transfer function matrix. The propagation matrix accounts for the effects of absorption and interference within a layer $i$ bounded by two interfaces.\(^9\)

The spectral directional absorptance is calculated by assuming Kirchhoff's law on a spectral basis:
\[
\alpha_{\lambda, \theta} = \varepsilon_{\lambda, \theta} = 1 - R_{\lambda, \theta} - T_{\lambda, \theta}
\]  

(2)

where, absorptance \( \alpha \) and emittance \( \varepsilon \) are function of wavelength \( \lambda \) and incident angle of the incoming radiation \( \theta \). Kirchhoff’s law, on a spectral basis, is valid if the emitting object is in local thermodynamic equilibrium and it can be characterized by a single temperature. The emission and absorption coefficients depend on the nature of the surface (roughness) and wavelength. Kirchhoff’s law is valid if there is no significant temperature gradient or if the phonons and electrons are in thermal equilibrium.\(^{12}\)

Multi-Rad predicts the radiative properties and the total values of the radiative properties as a function of the wavelength range. In order to calculate the total radiative properties, the amount of the IR radiation absorbed, reflected and transmitted in a certain spectral range are integrated with respect to wavelength for a certain blackbody distribution of energy. The total absorptance in a wavelength band \( i \) is,

\[
\alpha_i = \frac{1}{\sigma T_b^4 \phi_{Ts}^k} \int_{\lambda_1}^{\lambda_2} e_b(\lambda, T_b) \alpha_{\lambda}(\lambda) d\lambda
\]

(3)

where, \( \phi_{Ts}^k \) is the fraction of the blackbody energy in the spectral range evaluated, \( e_b \) is the Planck function evaluated at the blackbody source temperature \( T_b \) in the spectral range \( \lambda_1 - \lambda_2 \) and \( \alpha_{\lambda} \) is the spectral absorptance. The emittance, transmittance and reflectance are calculated similarly. Multi-Rad has been discussed in our previous works. For completeness, it is presented in the above section.

**DIELECTRIC MATERIALS AS IR FILTERS**

With the rapid growth of application of materials in the infrared range of wavelengths and advancements in the related technology, manufacturers have begun to utilize IR materials in the design and manufacture of micro-optics components such as band-pass filters, beam splitters, lenses, mirrors, and polarizers in the IR. These IR materials vary in their optical, mechanical, thermal and electrical properties, and these properties determine their applications in the IR.

IR radiation is comprised of wavelengths that are longer than visible radiation; the two regions behave differently when propagating through the same optical medium. IR materials are often limited to a small band within the IR spectrum, especially when anti-reflection coatings are applied.
IR optical filters are used in many systems for military and commercial applications. These IR filters are essential components in the development of optical sensing systems that can be optimized by using materials better suited to the task. Materials such as calcium fluoride, germanium, optical glass N-BK7 and potassium bromide are the standard IR filter materials used by the IR industry, but at the microfabrication level, there is a need to replace them with new materials that are more compatible with the actual microfabrication process.

CASE STUDY: HONEYWELL MICROBOLOMETER

The necessity for low weight and low cost IR imaging arrays has positioned uncooled thermal infrared detectors as the device of choice to develop the new generation of cost-effective IR imaging systems. An uncooled infrared microbolometer is a thermal detector that is used in the infrared spectral range. A microbolometer is a device that absorbs the incident IR electromagnetic radiation and converts it to heat, which causes changes in some physical properties (resistance) of an active element.\(^{13,14}\)

The performance of a microbolometer is determined by the electrical and optical properties of the associated materials and structural design parameters. In order to obtain a high performance microbolometer, efficient absorption of radiation is required, as well as a high thermal coefficient of temperature resistance of the microbolometer active element, and a high thermal isolation. The optimum thermal isolation of the microbolometer structure can be obtained in devices with the microbolometer multilayer structure suspended over a cavity.\(^{15}\)

The uncooled microbolometer structure, considered in this study, was originally developed by Honeywell, Inc. and licensed to several companies for the development and manufacture of focal plane arrays of uncooled microbolometers.\(^{16}\) In the “monolithic” Honeywell microbolometer structure, the multilayer microbolometer consists of two level structures with a cavity separating them as shown in Fig. S3, with a reflective layer deposited on top of the lower level of the structure.\(^{9}\) This multilayer layer structure is designed to work in the infrared wavelength range of 8-14 µm.
The microbolometer thermosensing element has been chosen to be Vanadium oxide (VO$_x$). VO$_x$ is a non-crystalline material that is widely used as a IR thermosensing material, with high temperature coefficient of resistance (TCR) that can reach up to 4 %/K. In order to achieve a high sensitivity detector response, high values of the electrical resistivity of the thermosensing element are needed to increase the TCR.

The upper level of the microbolometer is comprised of a thermally isolated structure suspended over a silicon layer read-out circuit on a silicon substrate (wafer), as is shown in Fig. S4. The microbolometer consists of a 0.5 µm thick suspended bridge (square shape 50x50 µm) of Si$_3$N$_4$ with VO$_x$ (0.05 µm thick) encapsulated in the center. The bridge is suspended 2 µm above the silicon substrate and is supported by thin legs of Si$_3$N$_4$ that secure the required thermal isolation between the suspended structure and the substrate (heat sink). The combination of the resonant cavity (2 µm) and an aluminum reflectance layer on the lower level of the structure, enhances the emissivity of the multilayer at a wavelength near 10 µm. At room temperature, an object reaches its highest emissivity around 9.66 µm.
REFERENCES

7. S. R. Marthi and N. M. Ravindra, Proc. of MS&T 2016 (Salt Lake City).