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Analysis of Tantalum Pentoxide Thin Films by Spectrophotometry for Defence-Grade Optical Components

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Abstract

This work presents a detailed spectrophotometric analysis of tantalum pentoxide (Ta_2O_5) thin films deposited for use in military optical components, with measurements conducted in the visible spectral range of 400–800 nm. The primary objective is to evaluate how the thickness of thin films and its surface and interface boundary roughness influence the optical response, particularly reflectance characteristics, which are critical for applications such as anti-reflective coatings, optical filters, and stealth-related technologies for military use.

KEY WORDS: *reflectance, thin films, tantalum pentoxide, spectrophotometry, defence optics, military technologies, surface roughness*

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1. Introduction

Modern military platforms increasingly depend on advanced optical systems whose performance is critically determined by the quality and reliability of thin-film coatings. These coatings are integral to electro-optical sensors, targeting systems, surveillance equipment, and avionics, where even minor deviations in optical properties can significantly impact operational effectiveness. Among high-index materials, tantalum pentoxide (Ta_2O_5) has emerged as a key constituent in defence-grade optical coatings due to its favourable refractive index, low absorption in the visible and near-infrared regions, and excellent environmental stability.

Thin films of tantalum pentoxide were prepared using controlled deposition techniques to ensure reproducibility and uniformity. Spectrophotometric measurements were performed to obtain reflectance spectra, which were subsequently analyzed using optical modeling methods. Special attention was given to deviations from idealized smooth-interface models, incorporating scattering and effective medium approximations to account for boundary roughness effects.

The results demonstrate that even nanometer variations in surface and interface roughness can lead to measurable changes in reflectance profiles. Increased roughness was found to induce diffuse scattering and reduce the effectiveness of interference-based reflectance minimization, thereby degrading optical performance. These findings are particularly relevant for defence applications, where precise control of optical signatures and maximization of signal fidelity are essential.

Furthermore, the study highlights the importance of optimizing deposition parameters and post-deposition treatments to minimize boundary imperfections. The correlation between roughness-induced optical losses and potential degradation in sensor accuracy or detectability is discussed, underscoring the strategic importance of material and process control in military optics manufacturing.

Tantalum pentoxide (Ta_2O_5) is widely utilized in the production of tantalum capacitors [1], which constitute essential components in modern military electronics. These capacitors are characterized by high reliability and stability under extreme environmental conditions, making them suitable for deployment in defence systems such as missile guidance units, radar installations, communication devices, satellites, aircraft, and naval electronics. Their high capacitance-to-volume ratio,

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combined with the ability to operate at elevated temperatures and high voltages, represents a critical advantage in applications where performance consistency and operational resilience are required.

In addition to its role in electronic components, Ta_2O_5 is employed as a high-temperature-resistant coating in demanding military environments. Its high melting point (approximately 3000 °C) and chemical inertness make it particularly suitable for protecting high-stress components, including jet engine turbines and missile system elements exposed to extreme thermal and mechanical loads. These properties contribute to enhanced durability and prolonged service life of critical defence hardware.

Tantalum pentoxide also plays a significant role in optical coatings for military-grade lenses, sensors, and advanced electro-optical systems [2–11]. Owing to its high refractive index and low optical absorption in the visible and near-infrared spectral regions, tantalum pentoxide is extensively used in multilayer thin-film stacks for interference-based devices. These include anti-reflective coatings for sensors [12–13], high-reflectivity mirrors, bandpass filters, and coatings designed for signature management in stealth technologies. In such applications, precise control of reflectance and transmittance is essential, as even minor deviations can affect detection, targeting accuracy, and overall system performance.

Beyond optical and electronic uses, tantalum and its compounds have been investigated for applications in protective systems. Although less common than traditional armour materials, tantalum's high density, mechanical strength, and corrosion resistance make it a candidate for specialized armour-piercing projectiles and reinforced armour systems. In oxide form, tantalum pentoxide can contribute to surface hardening and improved wear resistance. Furthermore, tantalum pentoxide coatings are considered for thermal protection systems in aerospace defence applications, where they can mitigate the effects of aerodynamic heating during high-speed flight or atmospheric re-entry.

The strategic importance of tantalum-based materials extends to emerging defence technologies, including advanced weapon systems and high-energy applications. Their robustness under extreme conditions has prompted continued research into their integration within next-generation platforms, such as directed-energy systems and advanced missile defence architectures.

To realize the full potential of Ta_2O_5 in optical applications, it is necessary to understand and control the properties of thin films at the micro and nanoscale. Various deposition techniques, including electron beam evaporation [14], magnetron sputtering [15], chemical vapor deposition [16], and pulsed laser deposition, have been employed to fabricate Ta_2O_5 thin films. The resulting optical and structural properties—such as refractive index, extinction coefficient, density, and surface morphology are strongly influenced by deposition conditions, including substrate temperature, oxygen partial pressure, and deposition rate.

In particular, the quality of film interfaces and surface roughness plays a decisive role in determining optical performance. Deviations from ideal smooth interfaces can introduce scattering losses, modify interference conditions in multilayer coatings, and ultimately degrade reflectance and transmittance characteristics. For defence-grade optical components, where stringent performance requirements are imposed, understanding these effects is essential.

Therefore, this work focuses on the spectrophotometric characterization of tantalum pentoxide thin films in the visible spectral range (400–800 nm), with emphasis on quantifying the influence of boundary roughness on reflectance behavior. By correlating experimental measurements with optical modeling, the study aims to provide insights relevant to the optimization of high-performance coatings for military optical systems.

2. Preliminaries

In this study, the spectral dependences of the coherent reflectance of a single tantalum pentoxide (Ta_2O_5) thin film deposited on a silicon substrate are investigated within the visible spectral range. The analysis is focused on the influence of boundary roughness on the optical response of the system, which is of particular importance for high-precision optical coatings used in defence applications.

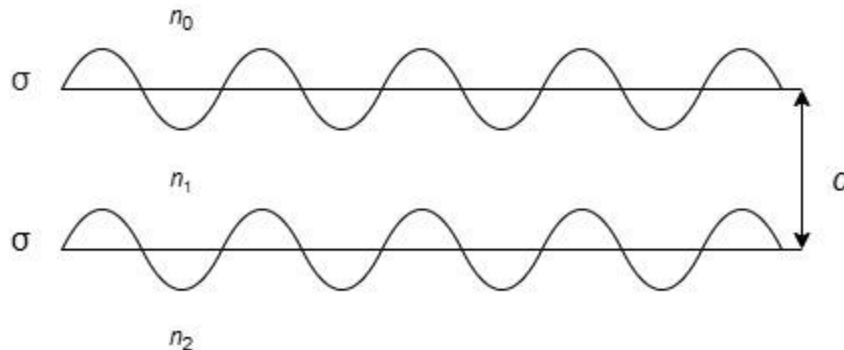

Fig. 1. Single thin film on substrate with identically randomly rough boundaries.

A schematic representation of the considered structure is shown in Fig. 1, where a single thin film with identically randomly rough upper and lower boundaries is deposited on a substrate. The parameter σ denotes the root-mean-square (rms) value of the heights of the surface irregularities characterizing the boundary roughness. It is assumed that both interfaces the

ambient/film interface and the film/substrate interface exhibit identical statistical properties; therefore, the rms roughness values are equal for both boundaries. The refractive index of the ambient medium is denoted as n_0 (for air, $n_0 = 1$), n_1 represents the refractive index of the Ta_2O_5 thin film, and n_2 is the refractive index of the silicon substrate. The mean physical thickness of the thin film is denoted by d.

The spectral dependence of the reflectance is derived under the assumption of normal incidence of light, using the scalar theory of diffraction. This theoretical framework enables the incorporation of both interference effects and scattering losses induced by boundary roughness. The model accounts for variations in film thickness, dispersion of optical constants, and statistical properties of the surface morphology [17–20].

For the theoretical treatment, the following assumptions defining the physical model of the Ta_2O_5 thin film are adopted (cf. [21–26]): both boundaries are locally smooth, meaning that their curvature radii are large compared to the wavelength of incident light; shadowing effects and multiple reflections among surface irregularities are neglected; the roughness of the boundaries is described by a stationary, isotropic, Gaussian stochastic process [27-28] with zero mean value; and the mean boundary planes are parallel. Furthermore, the rms roughness σ is assumed to be significantly smaller than the wavelength λ of the incident radiation, ensuring the validity of the perturbation approach. The lateral dimensions of the illuminated part of samples are much larger than λ, which justifies the use of far-field approximations. From an optical standpoint, both the Ta_2O_5 thin film and the silicon substrate are considered homogeneous and isotropic media.

Under these conditions, the coherent reflectance R_0 of an ideal (i.e., optically smooth) single thin film on a substrate for normal incidence can be expressed as [21]:

$$R_0 = \left|\frac{r_1 + r_2\,exp(-i\Delta)}{1 + r_1 r_2\,exp(-i\Delta)}\right|^2, \tag{1}$$

where the Fresnel reflection coefficients at the ambient/film and film/substrate interfaces are given by

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1}, r_2 = \frac{n_1 - n_2}{n_1 + n_2}$$

and the phase thickness Δ is defined as

$$\Delta = \frac{4\pi n_1 d}{\lambda}.$$

To account for the presence of boundary roughness, the coherent reflectance is modified by an attenuation factor that describes the loss of coherence due to scattering. The resulting expression for the coherent reflectance of a randomly rough tantalum pentoxide thin film on a silicon substrate can be written as [21,26]:

$$R = R_0\ \exp\left(-\frac{16\pi^2 n_0^2 \sigma^2}{\lambda^2}\right)\ , \tag{2}$$

where λ is the wavelength of the incident light, σ is the rms roughness of the boundaries, and R_o is the reflectance of the corresponding smooth system. This exponential factor indicates that increasing roughness or decreasing wavelength leads to a stronger reduction of coherent reflectance due to enhanced scattering effects.

The wavelength dependence of the refractive index of the Ta_2O_5 thin film is described using the Cauchy dispersion relation [29], which is appropriate for dielectric materials in the transparent spectral region:

$$n_1 = A + B/\lambda^2\,. \tag{3}$$

where A and B are material-specific coefficients determined experimentally. This relation allows accurate modeling of dispersion within the investigated spectral range and is essential for precise fitting of spectrophotometric data.

The presented theoretical framework forms the basis for evaluating the influence of boundary roughness on the optical performance of Ta_2O_5 thin films. By combining spectrophotometric measurements with this model, it is possible to extract key parameters such as film thickness, refractive index dispersion, and roughness characteristics, which are critical for optimizing optical coatings intended for demanding military applications.

3. Experiment, analysis and discussion

The spectral dependences of reflectance of Ta_2O_5 thin films were measured using the Lambda 1050+ spectrophotometer (see Fig. 2).

The PerkinElmer Lambda 1050+ UV/Vis/NIR two-channel spectrophotometer is a high-end research-grade spectrophotometer designed for precise optical characterization across a very wide spectral range (UV, visible, and near-infrared). Its advantages mainly relate to performance, flexibility, and advanced materials analysis. This spectrophotometer is designed for very low stray light and high absorbance measurements (important e.g. for optical filters, laser materials). We measured the spectral dependences of the relative reflectance of two samples of tantalum pentoxide for various thicknesses in visible region. The relative reflectance means the ratio of reflectance of sample of tantalum pentoxide thin film on silicon substrate with respect to reflectance of the back of the sample (smooth silicon substrate).

Fig. 2. Spectrophotometer PerkinElmer Lambda 1050+.

Two thin films samples of Ta_2O_5 were deposited on float-zone c-Si wafers using e-beam evaporation of polycrystalline Ta_2O_5 assisted by an advanced plasma source (APS). The substrates were kept at relatively low temperature of 120 °C during the deposition. The starting pressure was 8×10^{-6} mbar, while deposition pressure was 3×10^{-4} mbar with oxygen flow rate of 20 sccm. The thicknesses of the individual thin films were monitored using a quartz crystal monitoring system (QCM). The deposition rate of thin films was 0.3 nm/s (see e.g. [18]).

Now, we will focus on the evaluation of experimental data. The spectral dependences of relative reflectance were evaluated by its own software based on a nonlinear method of least squares. We obtained information about thickness of tantalum pentoxide thin film d, the rms value of the heights of the irregularities of the boundary roughness σ and optical constants of this thin film, i.e. parameters A and B in eq. 2 that represent spectral dependences of refractive index of thin film. The spectral dependences of the refractive index of silicon substrate are taken from [30].

In Fig. 3 and Fig. 4 we see a very good agreement between the experimental data and the theoretical calculated curve for the spectral dependence of relative reflectance for Samples 1 and 2. Within the nonlinear least squares method we determined the following parameters of samples (see Table 1).

Table 1.
Comparison of the evaluated parameters for Samples 1 and 2

parameters of thin film	**Sample 1**	**Sample 2**
thin film thickness d (nm)	131 ± 1	396 ± 1
roughness σ (nm)	5 ± 1	4 ± 1
A	2.03 ± 0.01	2.02 ± 0.01
B (nm^2)	26000 ± 2000	28000 ± 1000

Table 1 shows similar results for parameters A and B describing the spectral dependence of the refractive index of tantalum pentoxide for both samples. The roughness values σ of the two samples are expected to be very similar.

If we had independent information on the course of the thin film refractive index, using a nonlinear method of least squares, we could fix the parameters A and B, and the remaining measured parameters could be determined with less uncertainty. In general, a combination of more independent methods of determining parameters appears to be more reliable (e.g. [31-35]).

It should also be recalled that we assume that both boundaries of thin films are identical [21]. If there was reason to assume that this was not the case, it would be necessary to include this in the evaluation.

The ability to precisely determine the parameters of thin films is very important in terms of the development of new army technologies. Our work shows that spectrophotometry method and our data evaluation, allows us to analyse thin films of tantalum pentoxide and detect potential defects and imperfections resulting from manufacturing.

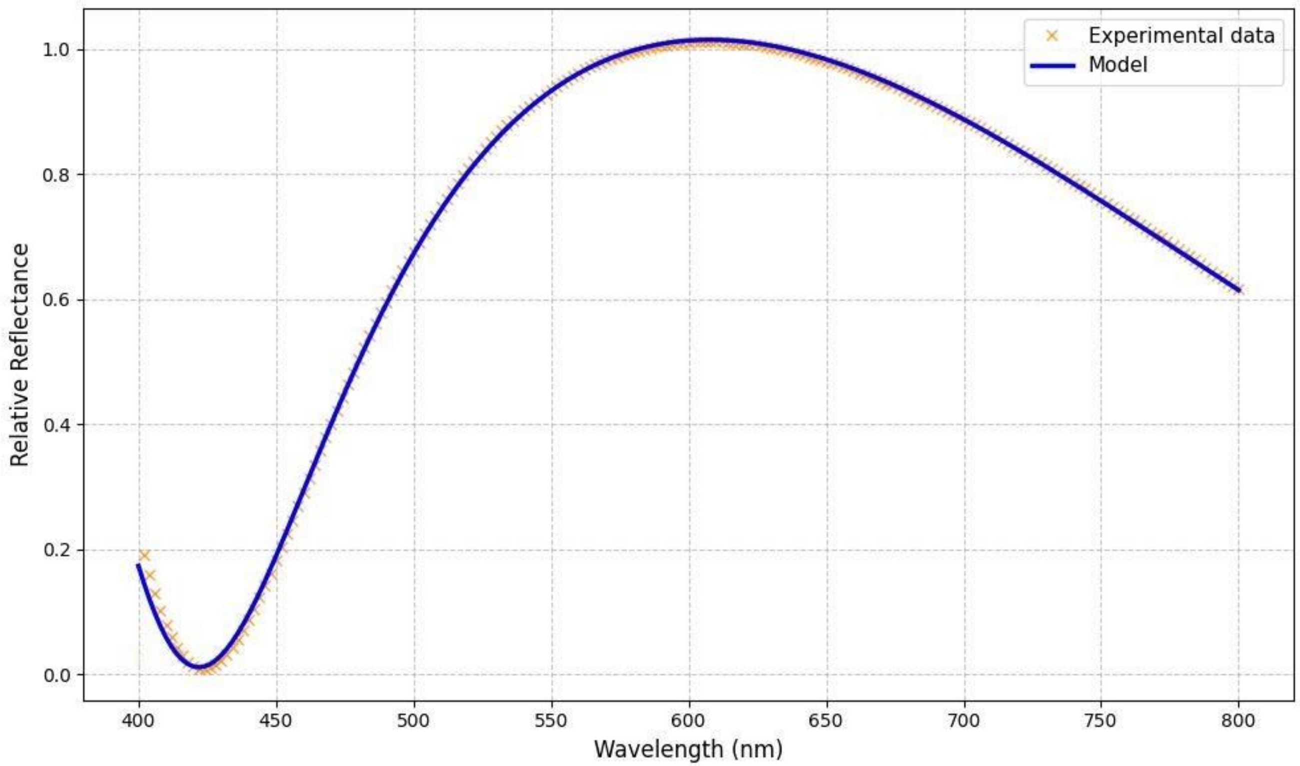

Fig. 3. Spectral dependences of relative reflectance of single tantalum pentoxide thin film - Sample 1

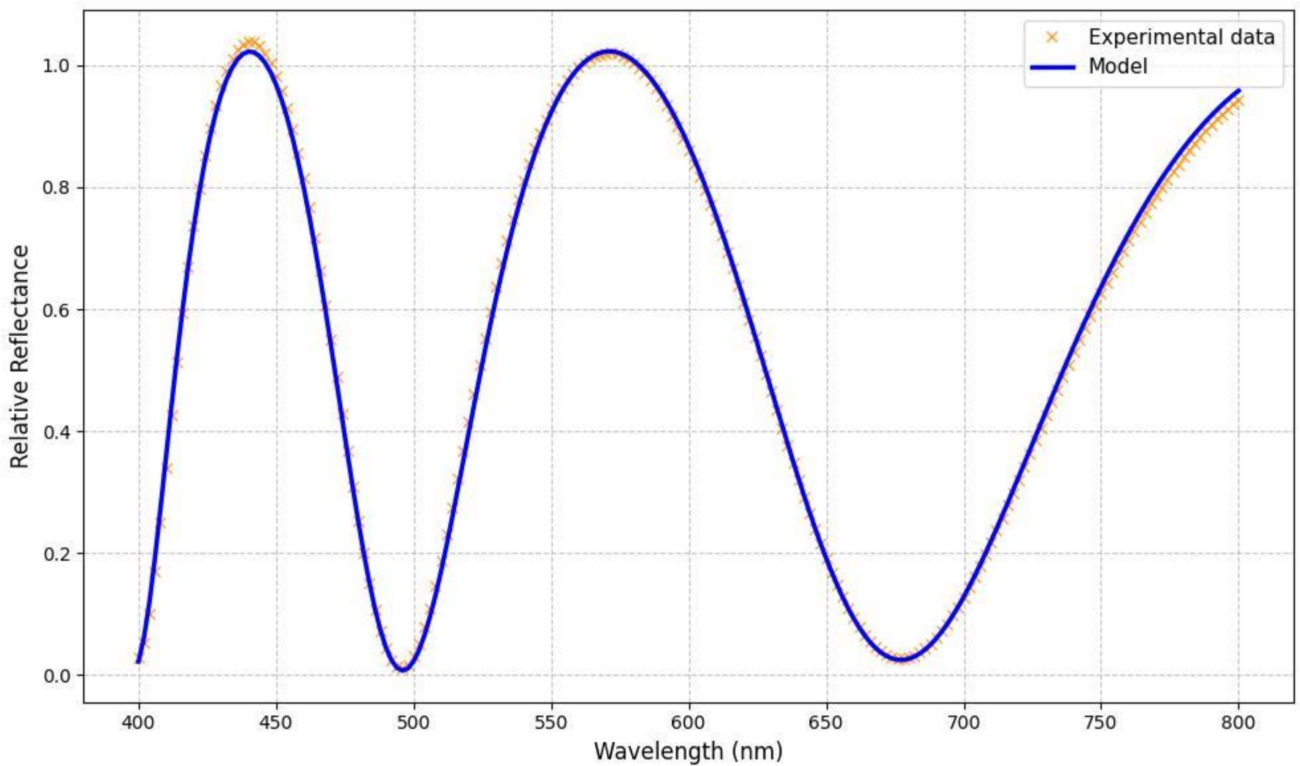

Fig. 4. Spectral dependences of relative reflectance of single tantalum pentoxide thin film - Sample 2

4. Conclusions

This work presents successful optical characterization of Ta_2O_5 thin films in visible region using spectrophotometry for two samples within the scalar theory of diffraction. By comparing parameters evaluated by nonlinear least squares method for both samples we can confirm good agreement for roughness and spectral dependence of refractive index of tantalum pentoxide thin film. The limitation of our analysis is the assumption of identically rough boundaries between air and tantalum pentoxide and between tantalum pentoxide and silicon substrate. The second limitation is to search for multiple parameters simultaneously. A combination of more independent methods and the ability to detect some parameters in a different way, looking for a smaller number of unknown parameters, appear to be better. This would also positively affect the size of the uncertainty of the individual parameters.

In conclusion, this work provides a comprehensive assessment of the relationship between boundary roughness and optical performance in Ta_2O_5 thin films. The insights gained contribute to the development of more reliable and high-performance optical coatings tailored for demanding defence applications, where both durability and precision are paramount.

Ultimately, our findings demonstrating the possibility of analysing thin layers of Ta_2O_5 thin films contribute beneficial to understanding the physical and optical properties of tantalum pentoxide, especially for advanced optical coatings and optoelectronic devices suitable for military applications. Our methodology, procedure and experimental data and processed results may provide inspiration for future research and industrial processes, allowing for more accurate control in the production of thin films and the prevention of unwanted defects. Future refinement of the model used could further develop our understanding of the processes associated with thin films analysis, especially for applications that are directly related to use in the military.

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