Influence of deposition parameters on optical properties of TiO_2 films

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Abstract. Titanium dioxide is extensively used as high index material for multilayer optical thin film device applications operating in the visible and near infrared region. The performance (high reflectance/transmittance and laser-induced damage) of the device is decided by the absorption in the films. The refractive index and extinction coefficient of TiO_2 films is strongly influenced by the deposition parameters and stoichiometry of the evaporation material. In the present investigation, TiO_2 films have been deposited by reactive electron beam evaporation of TiO, Ti_2O_3, and TiO_2 in a neutral and ionized oxygen atmosphere. A Heitmann-type discharge source has been fabricated in the laboratory and used to ionize oxygen. Deposition parameters such as oxygen partial pressure (5×10^{-5} to 5×10^{-4} torr), rate of deposition (60 to 210 Å min^{-1}), and substrate temperature (25 to 250°C) were varied during the preparation of the films. The optical constants of TiO_2 films were estimated from the spectrophotometer data. *In-situ* optical monitoring of TiO_2 films with suboxides as the starting material showed the presence of considerable absorption in the films deposited in neutral oxygen, even under favorable deposition conditions. Postdeposition heating was necessary to reduce the absorption in the films. TiO_2 films with minimum absorption have been made using TiO_2 starting materials. Absorption-free films have also been obtained using ionized oxygen with the starting materials, even at higher substrate temperatures. The observed variation in optical properties has been explained on the basis of mismatches between the film growth and rate of oxidation. [DOI: 10.1117/1.1496489]

Subject terms: titanium dioxide films; optical properties; reactive evaporation; ionized oxygen; substrate temperature; dielectric films; optical coatings; high index thin films.

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1 Introduction

Titanium dioxide films have excellent properties (high optical transmittance, high refractive index, and better durability), which make them suitable for multilayer optical thin film device applications. Optical losses, structure, and chemical composition of the films depend on deposition conditions, which in turn affect the device performance. TiO_2 films are produced by a number of deposition techniques. Electron beam evaporation is the most common method for the deposition of TiO_2 films. Starting materials such as TiO, Ti_2O_3, and TiO_2 are evaporated in higher partial pressure of oxygen. Extensive studies have been made relating the optical properties of TiO_2 films with structure and preparation conditions.[1–18] A round-robin[16] study was conducted exclusively for TiO_2 films. In this, TiO_2 films were deposited by using six different techniques in different laboratories around the world. Wide variations were found in both the optical and physical properties of films even among films produced under nominally the same deposition conditions. A common observation in this study was that energetic ion beam and plasma-based processes produced denser and smoother TiO_2 films than conventional electron beam evaporated processes. However, ion- and plasma-based techniques have limitations, namely filament burnout in reactive atmospheres, a limited area of bombardment, difficult retrofitting in the existing systems, and high cost. It was also observed that the window region in which ion beam parameters can be varied to get absorption-free TiO_2 films is narrow.[7] The stoichiometry of TiO_2 films has been improved by using ionized oxygen instead of neutral oxygen.[4–6]

Rao et al.[9–11] observed that the substrate temperature has strong influence on the optical absorption in TiO_2 films deposited by electron beam evaporation of TiO in a neutral oxygen atmosphere. Recently, Macleod and coworkers[19] reported the optical properties of TiO_2 films deposited by reactive electron beam evaporation of Ti_2O_3 material. It was observed that partial pressure of oxygen and the substrate temperature influence the composition of the films, which in turn affects the absorption. This study also suggests that higher partial pressure of oxygen (5×10^{-4} torr) is required to deposit absorption-free films at

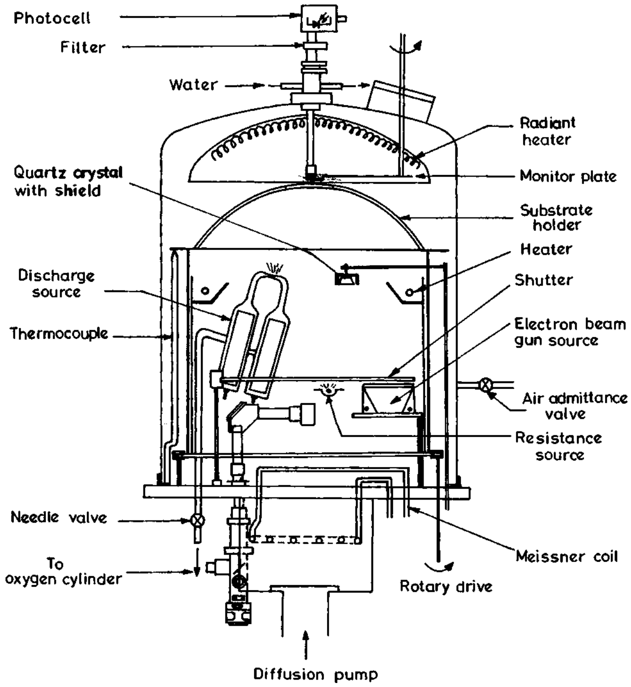

Fig. 1 Schematic diagram of the vacuum deposition system.

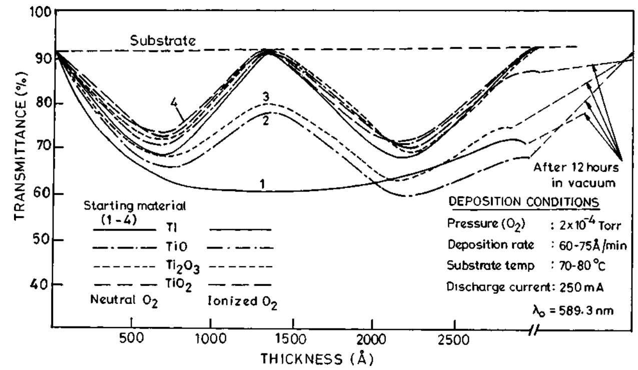

Fig. 2 *In-situ* optical transmittance of TiO_2 films with thicknesses for different starting materials.

200°C. Hence, there is a further scope for the study of influence of deposition parameters in conventional reactive evaporation on optical properties of the TiO_2 films, as electron beam evaporation is extensively used for the fabrication of multilayer thin film devices.

We report the preparation and characterization of single layer TiO_2 films by reactive electron beam evaporation of TiO, Ti_2O_3, and TiO_2 in neutral and ionized oxygen. The influence of deposition parameters such as oxygen partial pressure, rate of deposition, substrate temperature, and postdeposition heating in air on the optical properties of the film have been studied.

2 Experimantal Techniques

Titanium dioxide films were deposited in a conventional high vacuum deposition unit evacuated by a diffusion pump and rotary pump combination. The base pressure of 5×10^{-6} torr is routinely obtained in two hours. The starting materials TiO, Ti_2O_3, and TiO_2 (Balzers, 99.8%) were evaporated using an electron beam gun (ESV-6, Leybold Hereaus). The titanium metal was also reactively deposited from a tungsten boat. The desired oxygen pressure was maintained by using a needle valve and measured with a hot cathode ionization gauge. The Heitmann[4]-type discharge source has been fabricated in the laboratory, which was used to ionize oxygen. The evaporation source and discharge source were mounted opposite each other and symmetrical to the center of the substrate holder. The schematic of the deposition system is shown in Fig. 1. The substrates used were well polished, fused quartz plates of 25 mm diam and 2 mm thick. These were mounted on a spherical work holder and rotated to get uniform film thickness. The substrates were heated prior to and during deposition using radiant heaters, and the required temperature in the range 25 to 250°C was maintained within ± 5°C. Film thickness and the rate of deposition were monitored using a quartz crystal monitor (FTM 3, Edwards), whereas an optical monitor (OMS 2000, Leybold Hereaus) was used to monitor the *in-situ* film transmittance of the films.

The spectral transmittance of the films in air was recorded using a HITACHI 330 model UV-VIS-near IR double beam spectrophotometer. The refractive index, extinction coefficient, and thickness of the films were calculated by an envelope technique using the transmission spectra of the films.[20]

3 Results and Discussion

3.1 *In-situ Optical Monitoring of TiO_2 Films*

In the absence of absorption or inhomogenity, dielectric thin films show a transmittance that is equal to that of the substrate transmittance at a halfwave optical thickness. *In-situ* optical monitoring of TiO_2 films using different starting materials such as Ti, TiO, Ti_2O_3, and TiO_2, by keeping all the deposition parameters same and using both neutral and ionized oxygen, has been studied and is shown in Fig. 2. With titanium metal as the starting material, the films deposited under neutral oxygen show higher absorption. Though using both TiO and Ti_2O_3 films show oscillatory behavior in their transmittance with thickness, the maximum transmittance does not reach that of the substrate transmittance.

However, with TiO_2 as the starting material, the behavior of the film is normal as expected for that of dielectric films. The first maximum coincides with the substrate transmittance, but there is a slight deviation in the second maximum. When the suboxides are evaporated, the peaks are quite broad and hence there is always an uncertainty in monitoring quarterwave layers. This directly influences the reproducibility of multilayer devices.

It can be seen from Fig. 2 that in the presence of ionized oxygen, for all the starting materials (Ti, TiO, Ti_2O_3, and TiO_2), the films showed periodicity in transmission with thickness, and the transmittance maximum is equal to that of the substrate transmittance within the instrumental accuracy (± 0.5%). From these observations, it can be concluded that the film growth and reaction rate are not matched in the case of either metal or suboxide starting

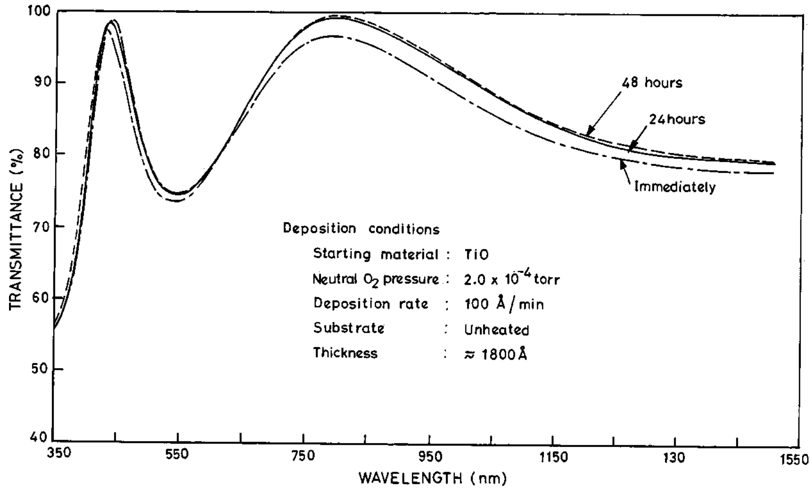

Fig. 3 Spectral transmittance of TiO_2 films at different stages of aging in air.

materials when neutral oxygen is used. However, by using ionized oxygen, the reaction is complete and the films are essentially absorption free.

Since the reaction is not complete in the case of films in neutral oxygen, changes can occur with time, and the same is seen in Fig. 2. The transmittance increased even when the film is in a vacuum. These films showed improvement in transmittance over a period of 12 h in a vacuum, although it never reached the maximum value. While venting the chamber to the ambient atmosphere, the transmittance of the films further increase in a short period (2 to 3 min) and afterward the increase was negligibly small.

Figure 3 shows the transmittance spectra of the titanium oxide films exposed to an ambient atmosphere. Spectra taken immediately in air show the presence of considerable absorption in the films, whereas those of the films exposed for a 24-h interval to an ambient atmosphere show greatly improved transmittance. At wavelengths corresponding to halfwave thickness, the transmittance was observed to be the same as that of the substrate transmittance. The transmission spectrum of the films was also recorded after 48 h of exposure to an ambient atmosphere, and the spectra are essentially the same as the one that was exposed for 24 h.

The stability of TiO_2 films was also studied by carrying out accelerated aging, that is, postheating the films in air at various temperatures. The results are shown in Fig. 4. Films heated to 75°C in air were found to be free from absorption. Further heating to 125 and 175°C resulted in a decrease in transmittance at wavelengths corresponding to halfwave thickness.

It is to be noted that the transmittance spectra of the films were recorded in Figs. 3 and 4 by keeping the uncoated substrate in the reference beam of the double beam spectrophotometer.

3.2 *TiO_2 Films with TiO as Starting Material*

The influence of deposition parameters such as partial pressure of oxygen, rate of deposition, and substrate temperature on optical properties has been investigated. The variation of the optical transmittance at $\lambda_0 = 589$ nm during film deposition as a function of thickness for the variation in the rate of deposition and partial pressure of oxygen is shown in Fig. 5. These films are all deposited in neutral oxygen, the starting material is TiO, and substrates are not heated. Though the reactively deposited TiO_2 films show oscillatory behavior, the film transmittance does not reach the value of the substrate transmittance. The difference between these two increased with either an increase in the rate of deposition or decrease in the partial pressure of oxygen. Similar behavior has been observed in the spectral transmittance of the films.

The analysis of the residual gases present in the vacuum chamber showed that oxygen was the major constituent followed by nitrogen. The partial pressure of the nitrogen is 1 order less than that of oxygen. The partial pressures of the atomic species are higher than their molecular counterparts

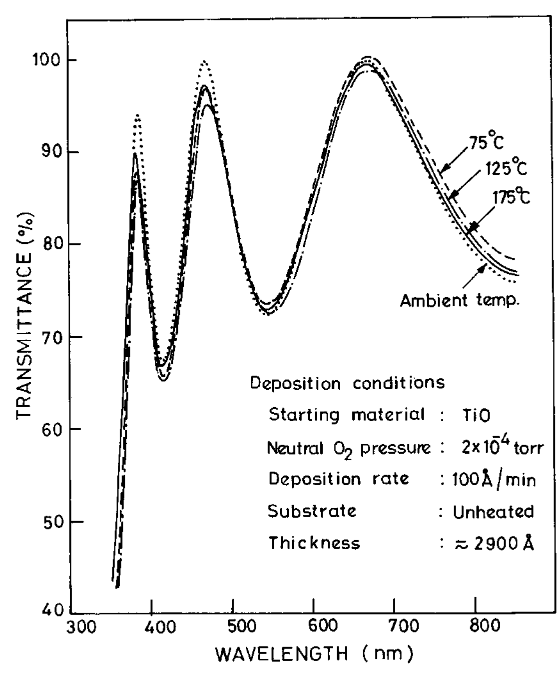

Fig. 4 Spectral transmittance of TiO_2 films with postdeposition heating in air at different temperatures.

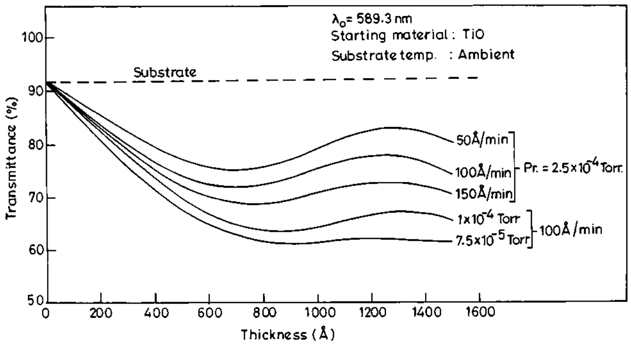

Fig. 5 *In-situ* optical transmittance of TiO_2 films with thicknesses at various pressures (neutral oxygen) and deposition rates.

in both the gases. Water vapor content is low. There was not much variation in the constituents during the successive depositions.

Figures 6 and 7 show the spectral transmittance characteristics of titanium oxide films deposited by varying the pressure as well as the rate of deposition. It can be seen that the transmittance maximum for all the films is less than the substrate transmittance except for the film deposited at a pressure of 2.5×10^{-4} torr. The deviation from substrate transmittance increased either on decrease of pressure or on increasing the rate of deposition, thus exhibiting the deficiency of oxygen in these films. These films were post-

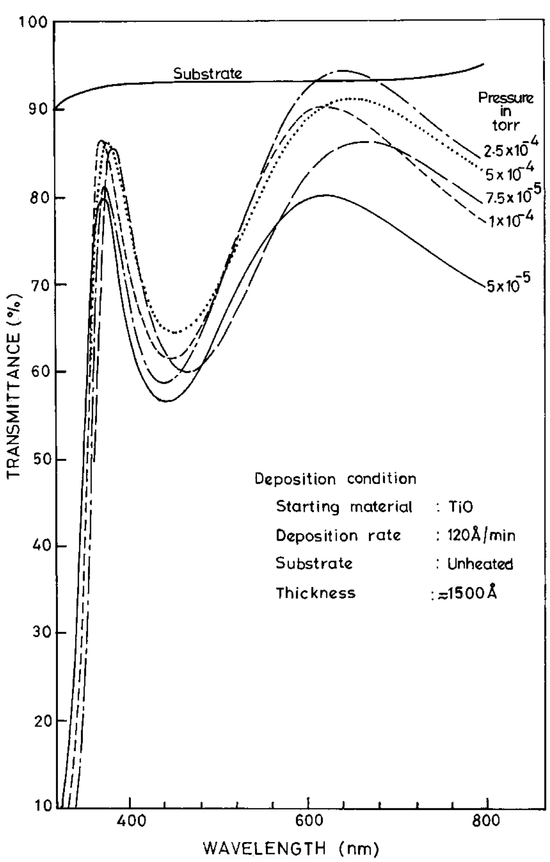

Fig. 6 Measured spectral transmittance characteristics of TiO_2 films for different oxygen pressures in neutral oxygen.

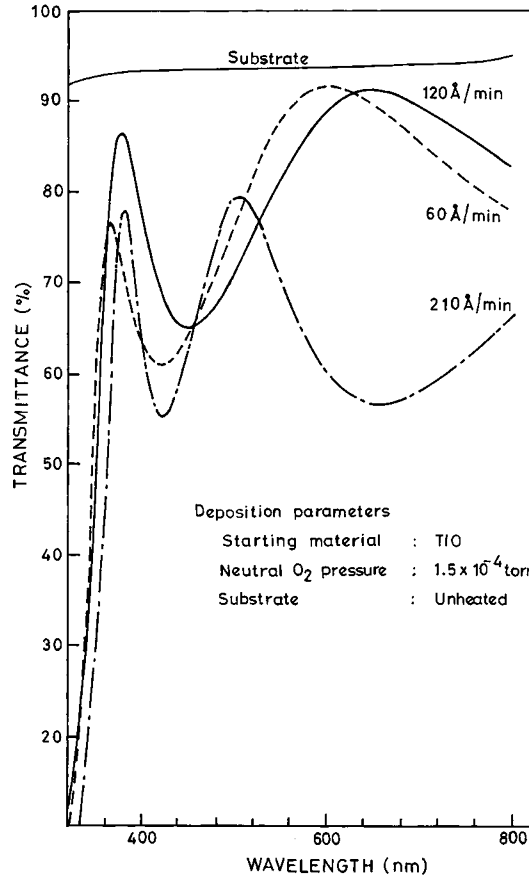

Fig. 7 Measured spectral transmittance characteristics of TiO_2 films at different rates of deposition.

heated in air in the temperature range 25 to 225°C, and optical constants of the films were estimated.

Figure 8 shows the variation in **n** and **k** as a function of postdeposition heating temperature. The refractive indices of films deposited at a higher rate of deposition and lower oxygen pressure are higher. Ritter[2] and Pulker[3] have also observed similar variations in refractive index with oxygen pressure as well as rate of deposition. Postdeposition heat treatment resulted in a negligible change in the index of the films.

Films deposited at lower pressures and higher rates of deposition have higher values of extinction coefficients. The extinction coefficient decreased with postheating in air in all cases. The minimum extinction coefficient was obtained around 125°C. The as-deposited films are oxygen deficient and absorbs sufficient oxygen from the ambient atmosphere on postdeposition heating, which results in a reduction in the extinction coefficient.

The refractive index as a function of wavelength for these films subjected to postdeposition heat treatment in air at 125°C is shown in Fig. 9. The refractive index is higher for the films deposited either at higher rates of deposition (210 Å/min) or at low partial pressure of oxygen (5×10^{-5} torr). This is mainly due to the improved packing density of the films as the gas incorporation in the films is less.

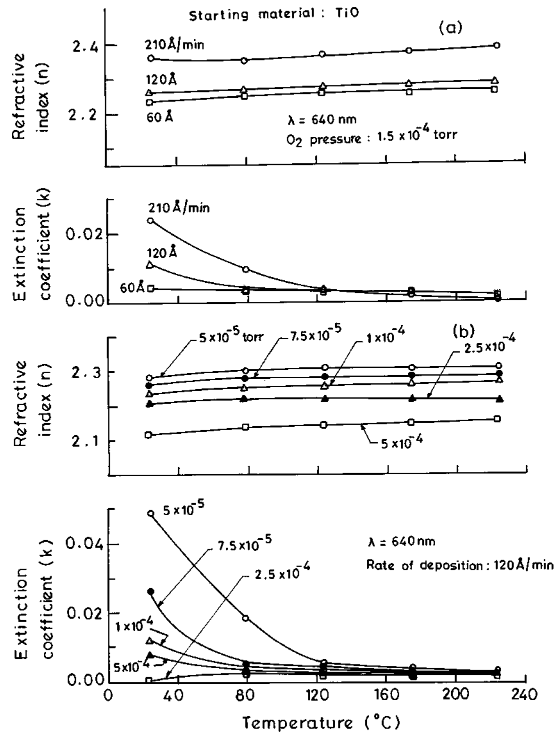

Fig. 8 Calculated optical constants (**n** and **k** at 640 nm) of TiO_2 films deposited in neutral oxygen as a function of postdeposition heating temperature for: a) different deposition rates and b) different deposition pressures.

This study reveals that the films deposited at optimum deposition conditions (2×10^{-4} torr, 100 Å/min., ambient or 75°C) have high transparency as seen from Fig. 4. These films are free from absorption due to either aging or heating in air at 75°C. However, during deposition all the films were absorbing (from *in-situ* transmittance) even under favorable deposition conditions when neutral oxygen was used.

These observed results can be explained on the basis of the incorporation of oxygen molecules in the films, which

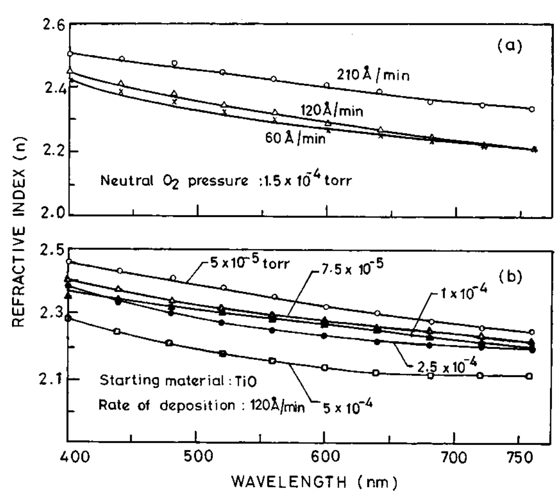

Fig. 9 Refractive index versus wavelength of TiO_2 films after subjecting them to postdeposition heating in air at 125°C.

Table 1 Calculated optical constants (**n** and **k** at 640 nm) of deposited TiO_2 films using TiO as starting material in neutral and ionized oxygen.

Substrate temperature in °C	t=140 nm				t=280 nm			
	neutral		ionized		neutral		ionized	
	n	**k**	**n**	**k**	**n**	**k**	**n**	**k**
Ambient	2.21	0.003	2.22	0.001	2.21	0.001	2.20	0.001
100	2.22	0.007	2.22	0.001	2.26	0.001	2.27	0.001
175	2.25	0.021	2.24	0.001	2.31	0.003	2.31	0.001
250	2.31	0.012	2.30	0.002	2.45	0.004	2.34	0.001

is determined by the oxygen pressure and the rate of deposition. TiO_2 films contain considerable absorption when the films are grown even under favorable deposition conditions. This is due to the poor match between the film growth and reaction rate between suboxide vapor and oxygen molecules.

The influence of substrate temperatures in the range 25 to 250°C on optical properties was also studied by maintaining the optimized parameters of pressure and rate of deposition using both neutral and ionized oxygen. The substrate temperature has a strong influence on optical absorption in the films. The absorption in the films increased with the increase of substrate temperature when neutral oxygen was used, whereas it has only marginal influence when ionized oxygen was used. The influence of film thickness was also studied.

The refractive index and the extinction coefficient of deposited films with substrate temperatures for neutral and ionized oxygen are given in Table 1. It can be seen from Table 1 that the refractive index increased steadily with substrate temperature in both cases of neutral and ionized oxygen. It is also seen that the thicker films showed higher refractive index than the thinner ones. The very high value of index (2.45) observed for a thicker film deposited at 250°C in neutral oxygen might be due to the film exhibiting a higher value of extinction coefficient (0.004). This is due to the presence of suboxide phase (TiO) as observed in electron spectroscopy for chemical analysis (ESCA) spectra.[11] The refractive index with the increase of substrate temperature might be due to the improved packing density of the films. The extinction coefficient, in general, increased with the increase of substrate temperature, the increase being small for thicker films. However, thinner and thicker films showed lower extinction coefficient even at elevated substrate temperatures when ionized oxygen was used in comparison with neutral oxygen. This is mainly due to the higher reactivity of oxygen in an ionized form. Similar behavior has been observed by Kuster and Ebert.[5] The lower values of **k** observed in the case of thicker films might be due to further oxidation during prolonged deposition. These observations and the earlier discussions indicate that the films deposited under favorable conditions contain required oxygen but they need adequate time or a kind of activation for the stabilization of the films. This instability also influences device performance, such as laser coatings. Instability of extinction coefficients of TiO_2 films with the film thickness was also reported by Bovard

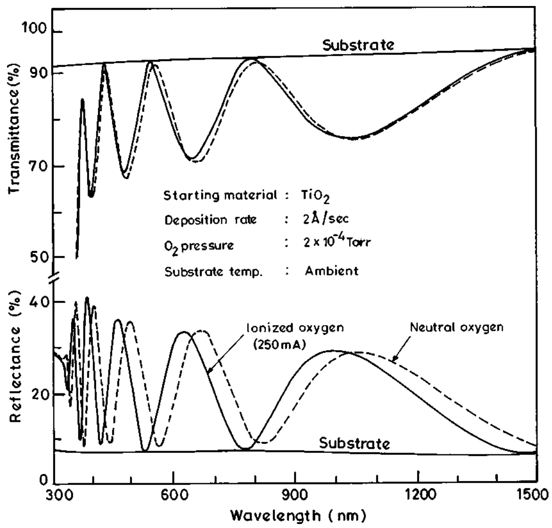

Fig. 10 Measured spectral transmittance and reflectance characteristics of TiO_2 films in neutral and ionized oxygen.

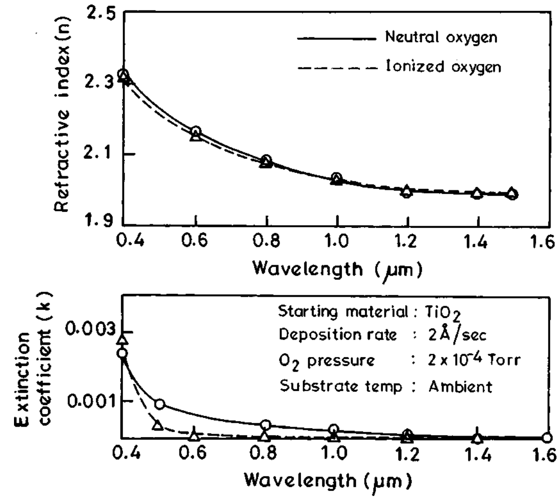

Fig. 11 Optical constants: a) refractive index and b) extinction coefficient of TiO_2 films using TiO_2 as starting material.

et al.[21] The chemisorption of oxygen at elevated temperatures is low, consequently it affects the stoichiometry of films.

3.3 *TiO_2 Films with TiO_2 as Starting Material*

Figure 10 shows the measured spectral transmittance and reflectance characteristics of TiO_2 films deposited in neutral and ionized oxygen. The reflectance of the films was measured using a 6-deg angle of incidence specular reflectance attachment in the Hitachi 330 model UV-VIS-near IR spectrophotometer. For reflectance measurement, 100% baseline was achieved by placing two identical plane front surface aluminum mirrors in sample and reference beams. The sample reflectance was then measured by replacing the sample side mirror with the substrate coated with TiO_2 film. The thickness of the films is estimated to be 371 and 368 nm, respectively. Both the films are fairly transparent and the transmittance and reflectance of the film deposited using ionized oxygen are the same as the substrate values at all the wavelengths corresponding to halfwave optical thicknesses. Films deposited using neutral oxygen marginally deviated from the substrate.

The optical constants are also estimated and are presented in Fig. 11. The refractive index is almost the same for both the films except at shorter wavelengths. The refractive index is 2.20 at 550 nm. The extinction coefficient was also low (<0.001) for both the films. Films deposited using ionized oxygen had extinction coefficients as low as 5×10^{-4} at 550 nm.

TiO_2 films were also deposited at elevated substrate temperatures using neutral oxygen and their optical properties were studied. The measured spectral transmittance characteristics of TiO_2 films deposited at different temperatures are shown in Fig. 12. The thickness of the films is about 160 nm. It can be seen from Fig. 12 that the transmittance of the ambient deposited film is the same as the substrate transmittance at maxima corresponding to halfwave optical thicknesses. The deviation increased with the increase of substrate temperature, indicating the absorption in films. Films deposited at 290°C had a deviation of 3%.

Figure 13 shows the dispersion characteristics of TiO_2 films prepared at different temperatures. It is observed that the refractive index increased steadily from 2.19 to 2.32 at 550 nm when the substrate temperature varied from ambient (75°C) to 250°C and the extinction coefficient was also increased from 0.0005 to 0.003 at 550 nm in the same intervals of temperature. Films deposited at 290°C had an extinction coefficient of 0.006. Further studies on these films with increased thickness (3000 Å) indicates the low extinction coefficient (<0.001) even at 250°C. Some of these new results and structural properties of TiO_2 films will be reported later. However, it is observed that the increase of extinction coefficients is negligibly small until

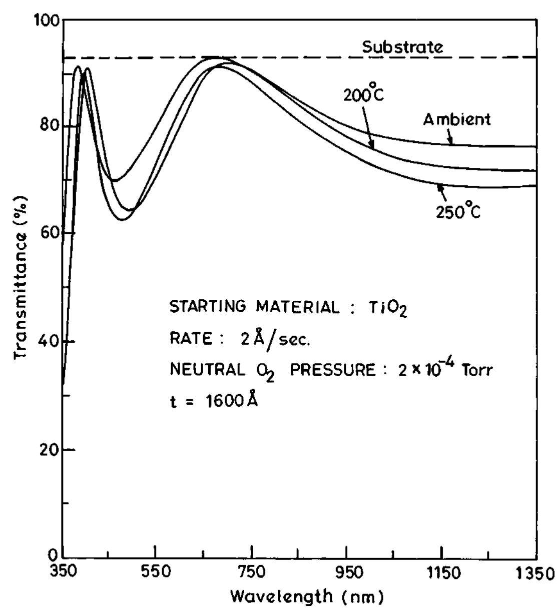

Fig. 12 Measured spectral transmittance characteristics of TiO_2 films deposited at different substrate temperatures.

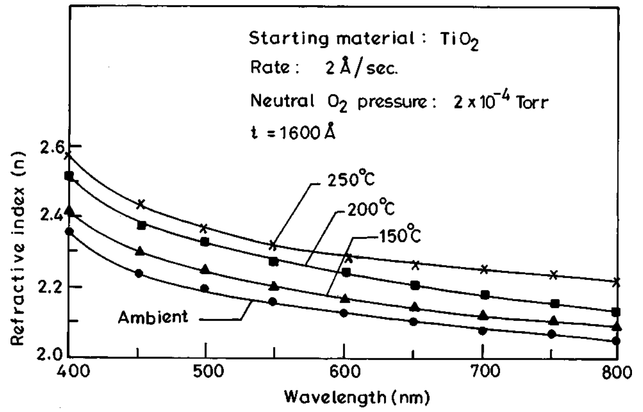

Fig. 13 Dispersion characteristics of TiO_2 films prepared at different substrate temperatures.

175°C. It is possible to decrease the extinction coefficient at elevated temperatures using ionized oxygen.

The increase of absorption in the films with increased substrate temperatures has been explained by taking the fact that the chemisorption of oxygen decreases at elevated substrate temperatures, which was also observed by Ritter and others.[2,9,10,19]

In-situ optical monitoring of TiO_2 films with suboxides as the starting material showed the presence of considerable absorption in the films deposited in neutral oxygen (Fig. 2). This is mainly due to the mismatch between the film growth and the rate of oxidation. However, with ionized oxygen all the materials Ti, TiO, Ti_2O_3, and TiO_2 gave absorption-free films. This shows that the stability (optical) of the films with ionized oxygen is good.

The extinction coefficient of the films increased with the increase of the substrate temperature (Table 1 and Fig. 12) with neutral oxygen when TiO and TiO_2 were used. This is due to the decrease of chemisorbed oxygen at elevated temperatures. However, by using ionized oxygen the films are stoichiometric (as observed in ESCA Spectra),[11] even at 250°C for a film deposited with TiO as a starting material. Though there could be slight loss of oxygen due to the substrate temperature, even in the case of ionized oxygen, oxygen present in the film is sufficient to give stoichiometric films as it is highly reactive. Kuster and Ebert[5] also observed the increase of extinction coefficients with substrate temperatures for TiO_2 films deposited with and without ionized oxygen using TiO and Ti_2O_3, as starting materials. They have attributed this to the disassociation of titanium-oxygen compounds at higher substrate temperatures. By carefully observing the results in Table 1, thicker films are more stable (by comparing the extinction coefficient) compared to thinner ones at elevated temperatures. Substrate temperature brings stability to films at higher thicknesses (prolonged deposition as is the case with the multilayers), but our observation is that the films deposited under neutral oxygen are nonstoichiometric, especially with the suboxides TiO and Ti_2O_3 as starting materials.[11]

Hence, elevated substrate temperatures adopted to improve the durability of films should be chosen after careful optimization of deposition parameters. However, activated reactive evaporation helps in improving the stoichiometry of films even at elevated substrate temperatures.

Further, it was also observed that TiO_2 and Ti_2O_3 materials have to be degassed thoroughly prior to deposition by heating and melting in a vacuum. It is also observed that these materials spatter during deposition, especially in the case of TiO_2. The process appears to be erratic. After a few evaporations it was found that TiO_2, which is initially black in color, turns brownish, where as Ti_2O_3, which is initially brown becomes darker. This agrees with the observations made by Pulker, Paesold, and Ritter[3] that these two materials tend to form Ti_3O_5, which is stable on successive evaporations.

Evaporation of TiO by electron beam gun is found to be easy compared to the evaporation of other starting materials. The deposition rate can be controlled to any desired extent without spattering. If the rate of deposition is low (2 to 3 Å/sec) and it is maintained constant, reproducible films can be obtained and the color (golden yellow) of the starting material remains same in successive evaporations. The only problem with this material is that the reaction of TiO with oxygen is incomplete during deposition and results in higher optical absorption in films. It needs either postdeposition heating or a kind of activation using ionized oxygen to reduce the absorption in films.

3.4 *UV and IR Characteristics of TiO_2 Films*

Figure 14 shows the IR transmission characteristics of TiO_2 films with TiO and TiO_2 as starting materials in neutral and ionized atmospheres. The transmission decreased with the increase of substrate temperature. However, TiO_2 films deposited under varied deposition conditions did not show any significant variation in characteristics (absorption peaks) except that the intensity of water vapor absorption peaked at $3300\ cm^{-1}$. The films were deposited on polished NaCl substrates. These characteristics are found to be very similar to the characteristics exhibited by the bulk rutile TiO_2 material.[22] The variation in the short wavelength absorption edge is also negligible (375 to 380 nm) for various films.

4 Conclusions

Single layer TiO_2 films have been deposited by conventional reactive electron beam evaporation using starting materials TiO, Ti_2O_3, and TiO_2. The deposition parameters have influenced the extinction coefficient of the films significantly when either metal or suboxide is used as starting material. The films are not stable and require postdeposition heating to reduce the extinction coefficient of the films. However, absorption-free TiO_2 films have been obtained by using TiO_2 as starting material. Low loss films of TiO_2 are also prepared using ionized oxygen with either metal or suboxide as starting material even at elevated substrate temperatures. Refractive index and extinction coefficients of the films increased with decrease of oxygen pressure, increase of rate of deposition, and substrate temperature.

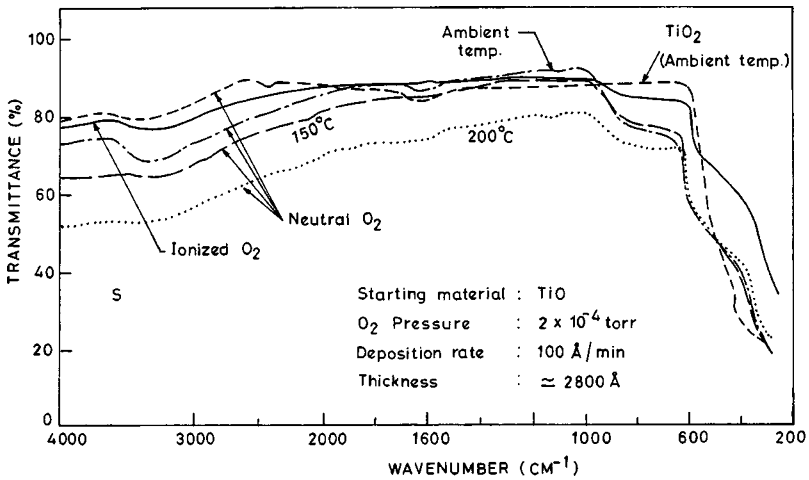

Fig. 14 Infrared transmission characteristics of TiO_2 films prepared under varied deposition conditions.

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References

1. M. A. Auwarter, "Process for the manufacturer of thin films," US Patent No. 2920002 (1960).
2. E. Ritter, "Deposition of oxide films by reactive evaporation," *J. Vac. Sci. Technol.* **3**, 225–226 (1966).
3. H. K. Pulker, G. Paesold, and E. Ritter, "Refractive indices of TiO_2 films produced by reactive evaporation of various titanium: oxygen phases," *Appl. Opt.* **15**, 2986–2991 (1976).
4. W. Heitmann, "Reactive evaporation in ionized gases," *Appl. Opt.* **10**, 2414–2418 (1971).
5. H. Kuster and J. Ebert, "Activated reactive evaporation of TiO_2 layers and their absorption indices," *Thin Solid Films* **70**, 43–47 (1980).
6. T. H. Allen, "Properties of ion assisted deposition of silica and titania films," *Proc. SPIE* **325**, 93–100 (1982).
7. J. R. Mcneil, G. A. Al-Jumaily, K. C. Jungling, and A. C. Barron, "Properties of TiO_2 and SiO_2 thin films deposited using ion assisted deposition," *Appl. Opt.* **24**, 486–488 (1985).
8. H. Demiryont and J. R. Sites, "Effects of oxygen ion-beam sputter deposition of titanium oxides," *J. Vac. Sci. Technol. A* **2**(4), 1457–1460 (1984).
9. K. Narasimha Rao, M. A. Murthy, and S. Mohan, "Optical properties of electron-beam evaporated TiO_2 films," *Thin Solid Films* **176**, 181–186 (1989).
10. K. Narasimha Rao and S. Mohan, "Optical properties of electron-beam evaporated TiO_2 films deposited in ionized oxygen medium," *J. Vac. Sci. Technol. A* **8**(4), 3260–3264 (1990).
11. K. Narasimha Rao and S. Mohan, "Chemical composition of electron-beam evaporated TiO_2 films," *J. Vac. Sci. Technol. A* **11**(2), 394–397 (1993).
12. N. Ozer, H. Demiryont, and J. H. Simmons, "Optical properties of sol-gel spin-coated TiO_2 films and comparison of the properties with ion-beam-sputtered films," *Appl. Opt.* **30**(25), 3661–3666 (1991).
13. K. Bange, C. R. Ottermann, O. Anderson, U. Jeschkowski, M. Laube, and R. Feile, "Investigations of TiO_2 film deposited by different techniques," *Thin Solid Films* **197**, 279–285 (1991).
14. K. Balasubramanain, X. F. Han, and K. H. Guenther, "Comparative study of titanium dioxide thin films produced by electron-beam evaporation and by reactive low-voltage ion plating," *Appl. Opt.* **32**(28), 5594–5600 (1993).
15. F. Varnier, "Ion assisted deposition effects on the surface structure of a TiO_2 thin film," *J. Vac. Sci. Technol. A* **8**(3), 2155–2159 (1993).
16. J. M. Bennett, E. Pelletier, G. Albrand, J. P. Borgogno, B. Lazarides, C. K. Carniglia, R. A. Schmell, T. H. Allen, T. Tuttle-Hart, K. H. Guenther, and A. Saxer, "Comparison of the properties of titanium oxide films prepared by various techniques," *Appl. Opt.* **28**, 3303–3317 (1989).
17. Z. L. Wu and K. Bange, "Comparative photo thermal study of reactive low-voltage ion plated and electron beam evaporated TiO_2 thin film," *Appl. Opt.* **33**(34), 7901–7907 (1994).
18. Hans W. Lehmann and K. Frick, "Optimization of electron beam evaporated TiO_2 films," *Appl. Opt.* **27**(23), 4920–4924 (1988).
19. S.-C. Chiao, B. G. Bovard, and H. A. Macleod, "Repeatability of the composition of titanium oxide films produced by evaporation of Ti_2O_3," *Appl. Opt.* **37**(22), 5284–5290 (1998).
20. R. Swanepoel, "Determination of thickness and optical constants of amorphous silicon," *J. Phys. E* **16**, 1214–1222 (1983).
21. B. G. Bovard, F. J. Van Milligen, M. J. Messerly, S. G. Saxe, and H. A. Macleod, "Optical constants derivation for an inhomogeneous thin film from in-situ transmission measurements," *Appl. Opt.* **21**, 4020–4029 (1982).
22. K. G. Geraghty and L. F. Donghaey, "Preparation of sub-oxides in the TiO system by reactive sputtering," *Thin Solid Films* **40**, 375–383 (1977).

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