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KU1 quartz glass for remote handling and LIDAR diagnostic optical transmission systems

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Abstract

KU1 quartz glass, a radiation-resistant material, is being considered for use in different fusion applications such as remote handling optical transmission components and diagnostic windows. Gamma (^{60}Co) and 1.8 MeV electron irradiations have been carried out to study the ionizing radiation-induced optical absorption in this material. The results show that while the optical absorption induced by irradiation in the KU1 silica is acceptable for the remote handling optical transmission components, this is not the case with diagnostic window applications, where background absorption may pose a problem for LIDAR. However, this disadvantage may be minimised by pre-irradiation at about 200°C. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Due to the high residual radiation levels inside future fusion devices such as ITER, remote maintenance and inspection will be necessary. The so-called remote handling systems will require the use of optical transmission components in the form of windows, lenses, and optical fibres to enable visual inspection and control to be carried out during any in-vessel operation [1]. These components will be expected to maintain their transmission properties under high levels of ionizing radiation ($\approx$5 Gy/s) during hundreds of hours. For such applications, radiation-induced optical absorption imposes a severe limitation. It is therefore necessary to study the optical degradation of suitable candidate materials, to assess the system lifetimes.

The requirements for diagnostic windows are even more severe as they will be required to operate under much higher levels of radiation (10 to several hundred Gy/s, and about 10^{-10} dpa/s), where not only absorption but also radioluminescence will be of concern [2]. In particular, LIDAR diagnostic windows will require extremely high transmission over the range of 500–1000 nm as a consequence of the use of high power lasers [3]. In this case, transmission loss of only a few percent may have serious consequences. To assess this problem it is necessary to employ in-beam techniques not only to determine such small losses, but also short-lived transient radiation-induced absorption. Such effects, associated with the electronic excitation, are due to the ionizing component of the radiation field, and will occur in the initial stages of irradiation well before the influence of displacement damage becomes important.

A type of silica glass at present being examined within the ITER diagnostics programme, KU1 quartz glass [1] and known to be radiation-resistant [2], has been studied under conditions expected for the remote handling systems. i.e., temperatures below 200°C and purely ionizing radiation at about 5 Gy/s, in order to assess its possible use in remote handling applications. The same material has been irradiated with 1.8 MeV electrons in a Van de Graaff accelerator and optical absorption measurements have been made in situ to study the radiation-induced absorption. At the present time, in situ, and in-beam experiments in particle accelerators are the

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most reliable ways to study the small possible unstable changes in optical absorption, and in particular, the high-energy electron irradiation provides a good simulation of the expected ionization-induced changes.

The results show that KU1 quartz glass may be used for remote handling optical transmission components at temperatures between 20°C and 200°C, for total doses up to at least 10 MGy with very little loss in transmission, from 400 to 2600 nm. The lower limit could be extended down to 300 nm, if loss by a factor of 10 in transmission is acceptable. Furthermore, the results show that operation at higher temperatures markedly improves the UV transmission. However, the use of this material as a high-power transmission diagnostic window is questionable.

2. Experimental procedure

Radiation-induced optical absorption in KU1 quartz glass has been studied as a function of irradiation dose and temperature to assess the possible use of this material for remote handling optical transmission components. The irradiations have been carried out in the CIEMAT Náyade ^{60}Co irradiation pool facility. The sample chamber contains a sample holder and a small thermocoax heater. In this way, samples of approximately $5 \times 5 \times 1$ mm^3 have been irradiated in air at 20°C, 100°C and 200°C, from 1 to 500 h, at a dose rate of approximately 5 Gy/s. Post-irradiation measurements of optical absorption were performed at room temperature in a Cary 5 E spectrophotometer over the range of 195–3000 nm, the data being taken at 1 nm intervals. An initial spectrum was taken for every sample before each irradiation and following different irradiation times and temperatures to study the induced absorption.

A second set of experiments were devoted to the possible use of the KU1 quartz glass for diagnostic windows, in particular, in LIDAR applications. This part of the work was performed in the beam line of a 2 MeV Van de Graaff accelerator, in which samples were irradiated with 1.8 MeV electrons at 700 Gy/s, 10^{-10}dpa/s. The samples were approximately $16 \times 8 \times 3$ mm^3 in size and were irradiated on one of the 16×8 mm^2 faces, while the other 16×8 mm^2 face was held in thermal contact with an oven. A 3×1 mm^2 window mask placed on one of the 16×3 mm^2 faces enabled in situ measurements of optical absorption to be made perpendicular to the irradiation direction in the 8 mm direction at a distance of 1–2 mm behind the irradiated face. This increased thickness (8 instead of 1 mm) greatly enhanced the measurement sensitivity as the optical absorption depends exponentially on sample thickness [4]. The in-beam optical spectrometer employs two monochromators and signal chopping to enable absorption and luminescence to be separated and measured with and without radiation. In this way, two samples were irradiated at 40°C and 200°C. Optical absorption spectra at the irradiation temperatures were taken in situ at different irradiation times.

3. Results

For the ^{60}Co irradiations, Fig. 1 shows the initial and final absorption spectra for irradiation at 20°C to 11 MGy. The unirradiated sample shows essentially good transmission over the range from about 250 to 2600 nm. Below 250 nm, the absorption increases to about 1 in optical density (i.e., transmission drops to 10%). Above 2600 nm, the well-known OH absorption at about 2700 nm dominates the spectrum. Irradiation-induced oxygen vacancy-related defects cause an increase in the absorption below about 400 nm. This absorption is given in more detail in Fig. 2. It is clear from Fig. 1 that no

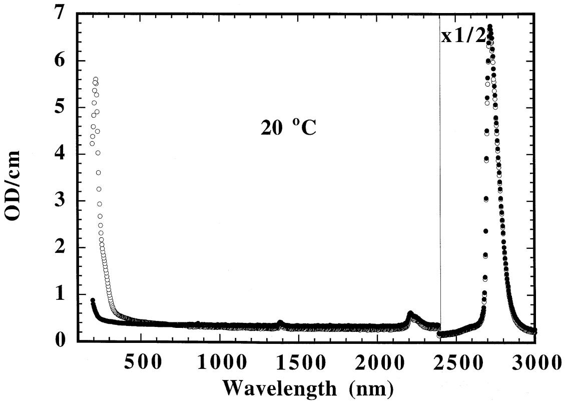

Fig. 1. Optical absorption spectra for KU1 before irradiation (closed circles) and after irradiation with ^{60}Co gamma rays up to 10.8 MGy at 20°C (open circles).

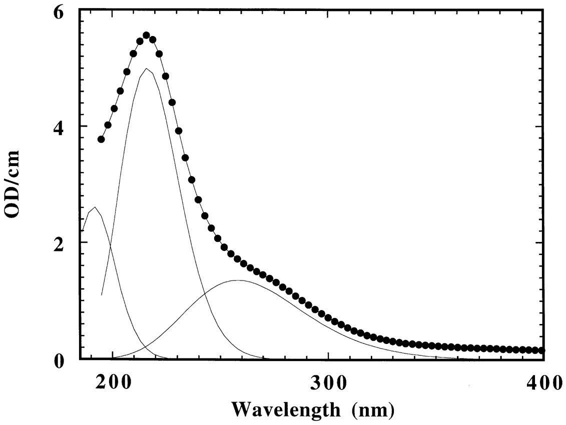

Fig. 2. Details of the three gaussian band fit of the 190–400 nm region of the irradiated spectrum shown in Fig. 1 at 20°C.

other significant changes occur in the spectrum. The spectrum from 190 to 400 nm can be fitted very well by three gaussian bands with maxima at 194 (6.4 eV), 215 (5.7 eV) and 260 nm (4.8 eV) and widths (FWHM) of 0.8, 0.7 and 1.1 eV, respectively, as may be seen in Fig. 2. The 215 nm, the so-called E$'$ band is by far the most important and is associated with oxygen vacancies [5]. The evolution with irradiation time of the optical absorption at 215 nm at different irradiation temperatures is given in Fig. 3. The absorption reaches saturation, more rapidly at higher temperatures. It is interesting to note that the initial rate of growth increases on increasing the temperature. Fig. 4 shows the absorption spectra from 190 to 400 nm once saturation is reached, for irradiations at 20°C, 100°C, and 200°C.

For the LIDAR application study, irradiations have been carried out with 1.8 MeV electrons at 40 and 200°C. Fig. 5 shows the optical absorption spectrum for irradiation at 40°C, and is very similar to that obtained at 20°C with ^{60}Co gamma rays. The in situ measurements allow one to reliably observe small changes in optical absorption in the visible range. This is shown in Fig. 6 for the 40°C irradiation, where a flat optical

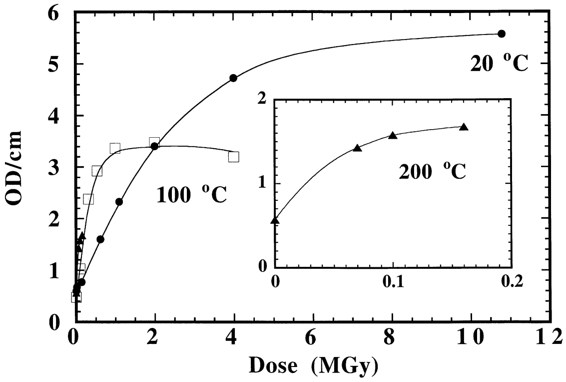

Fig. 3. Evolution with dose of the optical absorption at 215 nm for samples irradiated with ^{60}Co gamma rays at 20°C, 100°C and 200°C.

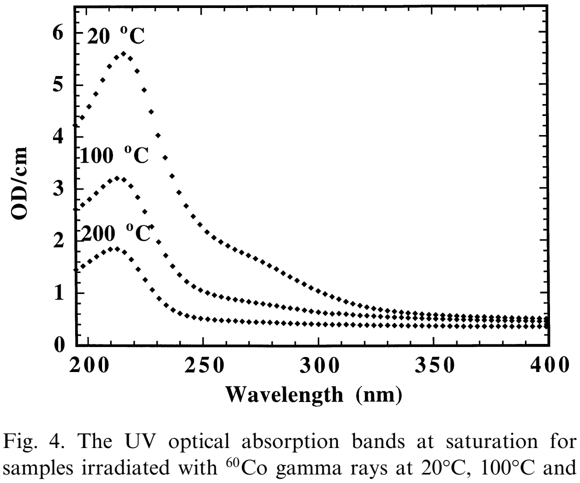

Fig. 4. The UV optical absorption bands at saturation for samples irradiated with ^{60}Co gamma rays at 20°C, 100°C and 200°C.

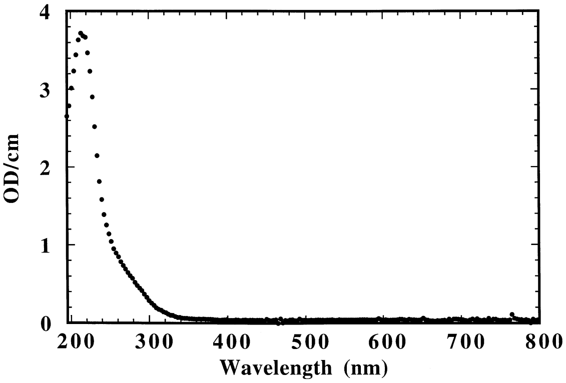

Fig. 5. Optical absorption spectrum of a sample irradiated with 1.8 MeV electrons up to 41 MGy at 40°C.

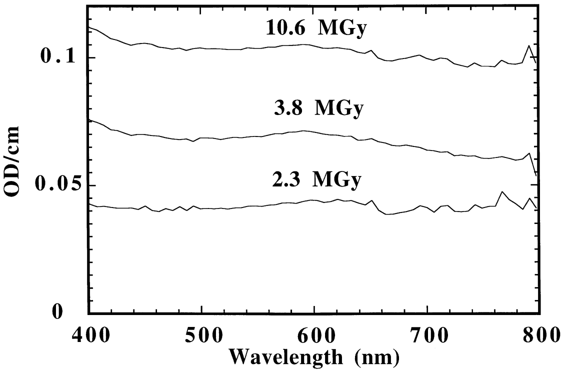

Fig. 6. Optical absorption increase in the visible region of a sample irradiated with 1.8 MeV electrons at 40°C.

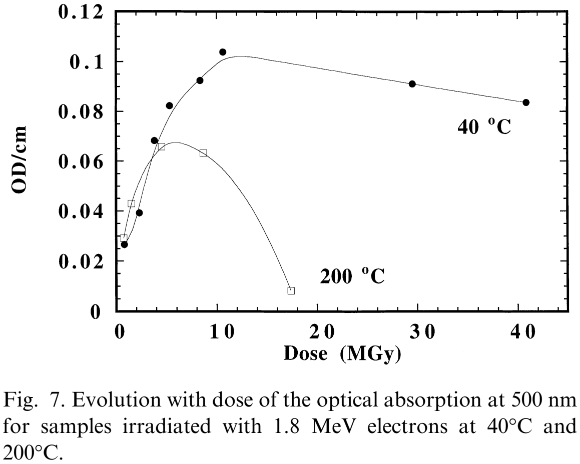

Fig. 7. Evolution with dose of the optical absorption at 500 nm for samples irradiated with 1.8 MeV electrons at 40°C and 200°C.

absorption increases with dose. No difference was observed between the absorption measured during irradiation and that recorded without radiation indicating that radiation-induced transient absorption is negligible. The evolution of the flat background for 40°C and 200°C is shown in Fig. 7, where the absorption at 500 nm is given as a function of dose. This absorption reaches a maximum, and then decreases, more rapidly at the higher temperature, where the absorption introduced by irradiation is almost removed by 18 MGy.

4. Discussion

The results obtained to assess the use of KU1 for remote handling applications (Figs. 1–4) show that this material can be used for optical transmission components (windows and lenses) for ionizing radiation doses up to at least 11 MGy and temperatures between 20°C and 200°C. The optical transmission between about 400 and 3000 nm does not degrade. In the region, 200 to 400 nm radiation-induced absorption bands rapidly reduce the transmission. In general, there is a clear advantage for components operating at and above 100°C where the saturated absorption is notably less than at 20°C. This is mainly due to the thermal instability of the 260 nm absorption band at the higher temperatures as may be seen in Fig. 4. The instability due to this component has also been observed in thermal annealing treatments for electron-irradiated KU1 [2]. However, for applications below 2 MGy it is clearly better to operate at 20°C, see Fig. 3.

The situation is very different for the case of diagnostic LIDAR window applications. The results shown in Figs. 6 and 7 indicate that in the region of interest the increase of the optical absorption is of the order of 0.1 cm^{-1}. It is important to note that no in-beam transient absorption has been observed, only a dose-dependent stable change. An increase of 0.1 cm^{-1} means that for a 1 cm thick window 25% of the power will be absorbed giving rise to material heating, which may prove to be critical. The evolution with irradiation time of this flat absorption is complex. The absorption first increases and then decreases more rapidly at a higher temperature. This kind of behaviour is very similar to the change in density observed in silica when irradiated [6,7]. It has been observed this change in density can modify the refractive index, and hence cause a decrease in transmission due to increased reflection. However, the reported change in the refractive index (≈0.5%) is too small to explain the decrease in transmission given in Figs. 6 and 7 (about 17–25%). The results obtained at 200°C indicate that pre-irradiation at this temperature may remove the potential problem of laser absorption.

5. Conclusions

One may conclude that the KU1 quartz glass is highly resistant to purely ionizing radiation and may be employed for remote handling optical components with no loss in transmission from 400 nm to about 2600 nm at temperatures between 20°C and 200°C to doses of at least 11 MGy. Operation even down to 300 nm is possible if a reduction in transmission to about 10% is acceptable. In the case of KU1 for LIDAR systems, an increase in the background absorption in the region of interest could lead to a 25% power loss in the window, however, pre-irradiation at about 200°C may avoid this problem.

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