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KU1 and KS-4V quartz glass lenses for remote handling and diagnostic optical transmission systems

A. Moroño *, R. Vila, E.R. Hodgson

Euratom/CIEMAT Fusion Association, Avenida Complutense 22, 28040 Madrid, Spain

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Abstract

Radiation resistant KU1 and KS-4V quartz glasses are candidate ITER materials for remote handling and diagnostic optical transmission components such as windows, lenses, and optical fibres. ^{60}Co gamma irradiations at different temperatures have been carried out to study ionizing radiation effects on refractive index, optical absorption, and the quality of lenses made from KU1 and KS-4V. No effect has been observed on the refractive index of KU1 for irradiations up to 100 MGy and temperatures up to 170 °C. Lenses made from both materials show acceptable quality before and after irradiation. Irradiation induced absorption is confined to the blue and UV region, however, KS-4V shows anomalous behaviour with irradiation temperature. In situ 1.8 MeV electron irradiations have been used to clarify this anomalous absorption.

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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 widows, lenses, and optical fibres to enable visual inspection and control to be carried out during any in-vessel operation. These components will be expected to maintain their transmission properties under high levels of ionizing radiation (≈5 Gy/s) during hundreds of hours. For such applications, radiation induced optical absorption is the main limitation. It is therefore necessary to study the optical degradation of suitable candidate materials, to assess the system lifetime. Requirements for diagnostic systems are more severe due to the higher radiation levels (tens to hundreds of Gy/s). For all these applications radiation resistant KU1 and KS-4V quartz glasses are candidate ITER materials [1–4]. In the work reported here gamma and high energy electron irradiations have been used to further characterize the two materials for optical component applications.

2. Experimental procedure

The KU1 and KS-4V quartz glass materials used in these experiments have been kindly provided by the Russian Federation within the ITER programme. Gamma irradiations were made between 35 and 170 °C in flowing nitrogen gas, at 11 Gy/s in a ^{60}Co pool facility [4]. Measurements were made pre- and post-irradiation. 1.8 MeV electron irradiations were performed in a high vacuum chamber mounted in the beam line of a Van de Graaff accelerator at 700 Gy/s and temperatures between 20 and 300 °C [5]. In this case measurements were made in situ of optical absorption.

Planar-convex lenses were prepared from 35 mm diameter KU1 and KS-4V quartz glasses. The lens parameters are as follows: diameter 29.94 ± 0.02 mm, centre thickness 3.93 ± 0.02 mm, focal length 100 ± 3 mm. These were then gamma irradiated to 100 MGy (about 100 days), at 35 and 170 °C, and characterized for optical absorption and quality. Refractive index was

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[*] Corresponding author. Tel.: +34-91 346 6204/6774; fax: +34-91 346 6124.

E-mail address: morono@ciemat.es (A. Moroño).

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examined for gamma irradiation at 50 and 170 °C also to 100 MGy, using 15 mm diameter 10 mm thick KU1 disc samples. For the in situ optical absorption measurements during 1.8 MeV electron irradiation, $6\times6\times1$ mm^3 samples were irradiated at seven temperatures between 30 and 300 °C. Possible density changes for the lens samples were determined using an immersion technique.

Pre- and post-irradiation optical absorption measurements from 200 to 3000 nm were made for the lenses and refractive index samples using a Varian CARY 5 spectrophotometer. Optical absorption measurements during electron irradiation were made in situ from 200 to 800 nm using a home made system, to examine KS-4V samples. For lens image formation quality, the MTF (Modulation Transfer Function) curve was obtained using the so-called 'Knife-edge Method'. The image of a knife edge object is collected by a refrigerated CCD Cohu Camera and transferred to a computer. The line profile of the edge is then extracted and treated by Fourier transform software to obtain the MTF for the lens.

3. Results

3.1. Refractive index

The results show no significant change in KU1 refractive index for gamma irradiation to 100 MGy at 50 and 170 °C. Measured values were $n = 1.4578$ for unirradiated, and 1.4575 and 1.4578 for irradiations at 50 and 170 °C, respectively.

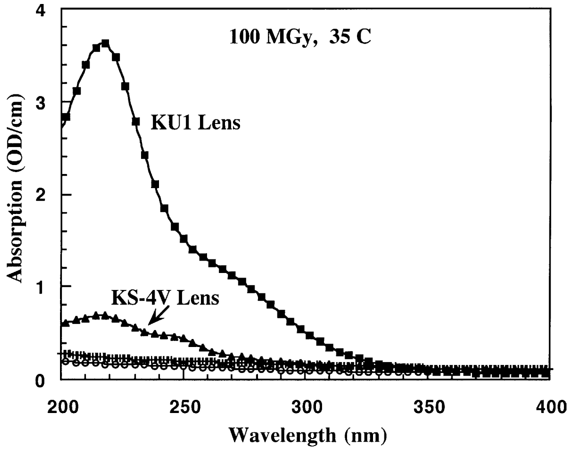

Fig. 1. Optical absorption spectra for KU1 and KS-4V lenses before (KS-4V crosses and KU1 circles) and after gamma irradiation to 100 MGy at 35 °C.

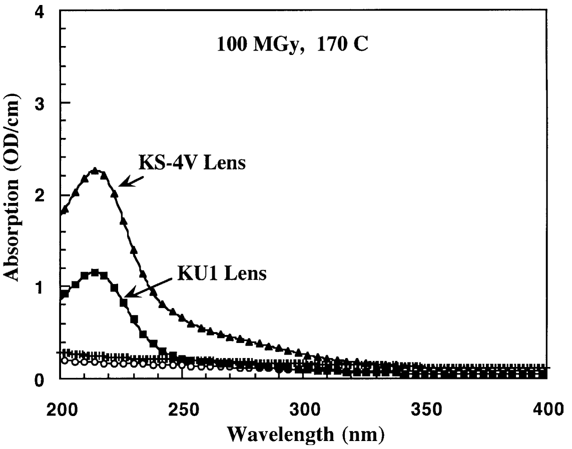

Fig. 2. Optical absorption spectra for KU1 and KS-4V lenses before (KS-4V crosses and KU1 circles) and after gamma irradiation to 100 MGy at 170 °C.

3.2. Optical absorption

Figs. 1 and 2 show the optical absorption spectra for KU1 and KS-4V lenses, gamma irradiated at 35 and 170 °C to 100 MGy. Both lenses show enhanced absorption only in the UV region due to the E' band at 215 nm and to the oxygen deficiency centre band at 245 nm. Above 400 nm no change is observed, the only difference between the two materials being the well known OH band at about 2700 nm in KU1 [1]. At 35 °C the 215 nm absorption in KS-4V is about four times less than in KU1. However, the results at 170 °C are disturbing. The behaviour of the KU1 absorption is as expected, i.e. reduced for higher temperature irradiation. However, the KS-4V shows anomalous behaviour with the 215 nm band absorption increasing for the higher temperature irradiation. This result was then checked using electron irradiations to reduce the necessary time. These irradiations confirmed this abnormal behaviour. Further electron irradiations were then performed at temperatures between 30 and 300 °C to study this phenomenon. Fig. 3 gives the electron irradiation results for the 215 nm band production efficiency as a function of irradiation temperature, where one may see that the production efficiency passes through a maximum at about 120 °C, and that at 170 °C the efficiency is considerably larger than at 35 °C.

3.3. Density changes

The densities of the lens samples irradiated at 35 °C were also measured to check its contribution to the refraction index. A value of 2.2008 ± 1 g/cc was obtained for irradiated KU1 compared with 2.1986 ± 1 g/cc for the unirradiated control sample, a change of 0.1%. No change was found in the density of KS-4V irradiated at 35 °C.

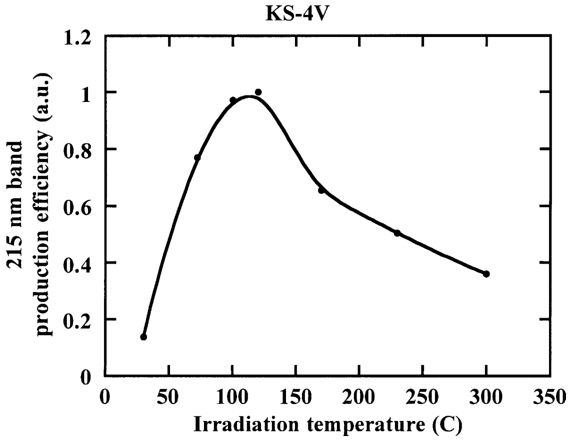

Fig. 3. Rate of growth of the 215 nm optical absorption band for electron irradiated KS-4V as a function of irradiation temperature.

3.4. Modulation transfer function

The final MTF curve for the two KU1 lenses, derived from the edge profile, as explained above, are shown in Fig. 4, and the final MTF curves for the two KS-4V lenses are given in Fig. 5. In these figures the MTF of a 'perfect' (without aberrations) lens with the same parameters is also shown for comparison, the observed differences between theory and the unirradiated lens are due to normal lens aberrations. The curves obtained are considered normal for good quality single material lenses.

4. Discussion

The results for the testing of unirradiated and irradiated KU1 and KS-4V lenses show that, for the visible region, high quality lenses can be made from both materials. Irradiation up to 100 MGy produces almost no degradation in quality, as expected from the negligible changes in absorption, refractive index and density, which control the image formation. This is in contrast with other silicas where changes of volume/density and refraction index after irradiation are well documented [6,7], and confirms the high radiation resistance of KU1 and KS-4V previously reported [2–4]. From the changes of MTF (Figs. 4 and 5), KS-4V appears to be marginally better than KU1.

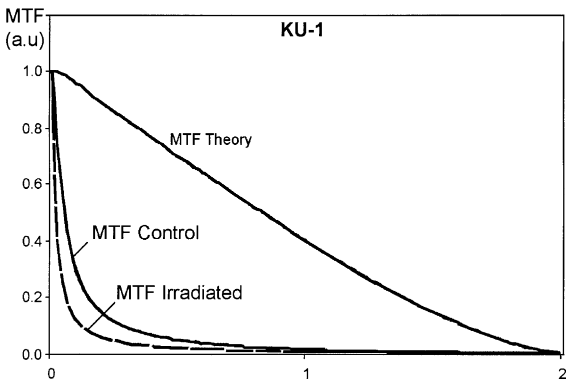

Fig. 4. MTF plots obtained for KU1 before and after (dashed line) gamma irradiation at 35 °C. The theoretical MTF of a 'perfect' (without aberration) lens of the same characteristics is also shown for comparison.

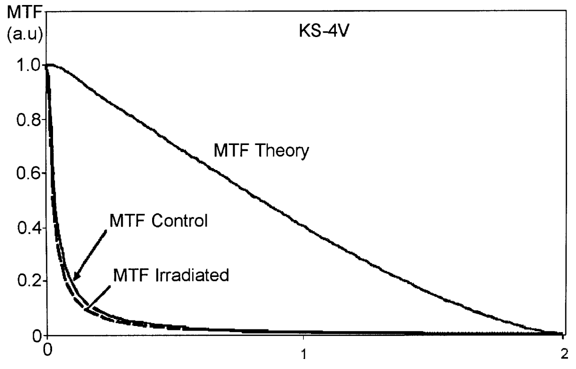

Fig. 5. MTF plots obtained for KS-4V before and after (dashed line) gamma irradiation at 35 °C. The theoretical MTF of a 'perfect'(without aberration) lens is also shown for comparison.

Optical degradation does, however, occur in the UV region. The prominent absorption band at about 215 nm is associated with E' centres, oxygen vacancies produced by ionizing radiation [8–10]. Moreover the temperature behaviour of the UV optical absorption for KS-4V is anomalous. The accepted model for coloration curves in alkali halides based on interstitial trapping [11], also successfully used for Al_2O_3 [5], implies that the height of the radiation induced optical absorption band associated with anion vacancies should be lower for higher irradiation temperatures. This model is in general agreement with the KU1 results here and in [4], but does not describe the results obtained for KS-4V where the 215 nm absorption increases for the higher irradiation temperature (Figs. 1 and 2). The results obtained from the electron irradiations show that the efficiency curve for the E' band production as a function of irradiation temperature for KS-4V passes through a maximum at about 120 °C (Fig. 3). The efficiency at 170 C is about four times higher than at 35 C, in agreement with the gamma irradiation results for the KS-4V lenses. Similar efficiency curves have been observed for the alkali halides at low temperatures, and the behaviour is related to competitive processes for stable vacancy production, where irradiation temperature plays a role not only in the vacancy–interstitial recombination process, but also in the defect production itself [12].

5. Conclusions

One may conclude that both KU1 and KS-4V are highly suitable for optical components in remote handling and diagnostic systems up to at least 100 MGy. Windows and high quality stable lenses can be made from both materials. In the visible region they are both more than adequate. In the IR region the low OH KS-4V material should be used. For applications towards and including the UV the final choice of material will depend on the temperature of operation. For operation below about 50 °C the KS-4V material will show less absorption in this region, however, above this temperature KU1 is to be preferred. Further theoretical and experimental work is necessary to understand radiation damage processes in KS-4V, and possibly exploit its low temperature advantage.

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