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Surface degradation effects on laser damage in KU1 quartz glass windows for LIDAR applications

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Abstract

For LIDAR applications in fusion devices, surface degradation effects (erosion and deposition of a thin contaminating layer) on laser damage in KU1 quartz glass material has been assessed. To study surface quality effects, roughly polished samples have been examined. For surface deposition effects, thin gold layers were deposited by sputtering on to KU1 quartz samples in order to study the influence of the layer thickness on the laser damage probability. For the thinnest layer of 5 nm a decrease in threshold to produce laser damage by several orders of magnitude is observed, implying a serious risk of breakdown for the laser window from the onset of reactor operation.

1. Introduction

The light detection and ranging (LIDAR) diagnostic systems for 'Next Step' fusion devices such as ITER will employ high power laser pulses which must pass through highly transparent windows. The window material used to transmit the laser beam must not only be highly transparent but also highly radiation resistant. If the laser intensity is too high the window material may suffer dielectric breakdown and as a consequence the window may break. Laser damage in transparent materials does not exhibit a sharp threshold with laser intensity, but rather the sensitivity to damage is well characterized by curves representing the probability of damage as a function of laser beam intensity [1]. Fig. 1 illustrates this for common glass, UV grade sapphire, and KU1 quartz glass [2].

The study of the radiation damage in these materials has been divided into four stages: ionizing radiation in-beam effects, accumulated dose effects, surface erosion, and surface contamination. The first two have been reported previously [2], the last two are the subject of this paper. KU1 quartz glass showed an excellent radiation resistance in terms of in-beam and accumulated dose effects. However, it was observed that surface degradation, and particularly thin conductive layer growth, seriously reduced the threshold for laser damage.

It is anticipated that the vacuum face of optical windows will degrade because of erosion and thin contaminating layer deposition due to both sputtering and contamination processes in the vacuum vessel of the reactor. This degraded surface will absorb part of the laser beam and as a consequence the temperature within the interface will increase during the pulse and may induce laser damage/breakdown within the insulator (window). This has been confirmed for mechanical erosion and by the observation that the growth of a thin layer of gold on KU1 quartz glass may decrease the intensity threshold to produce laser damage by several orders of magnitude.

2. Experimental procedure

To simulate the effect of a thin contaminating layer which may deposit with time within the vacuum vessel of a fusion reactor, thin gold layers (5, 15 and 45 nm) were deposited by sputtering on samples of optically polished KU1 quartz glass (provided by the Russian Federation within the ITER project). The samples, 16 mm diameter

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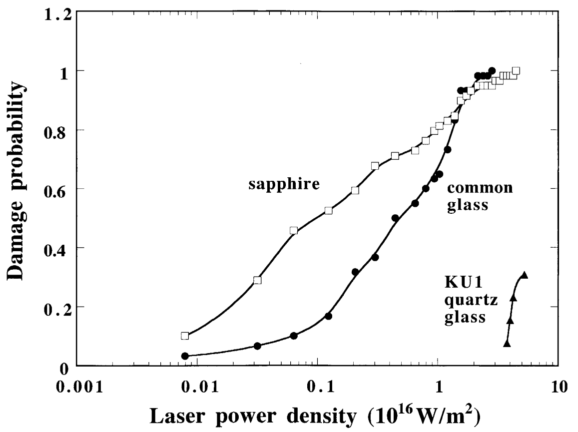

Fig. 1. Damage probability as a function of laser power density for sapphire, common glass and KU1 quartz glass.

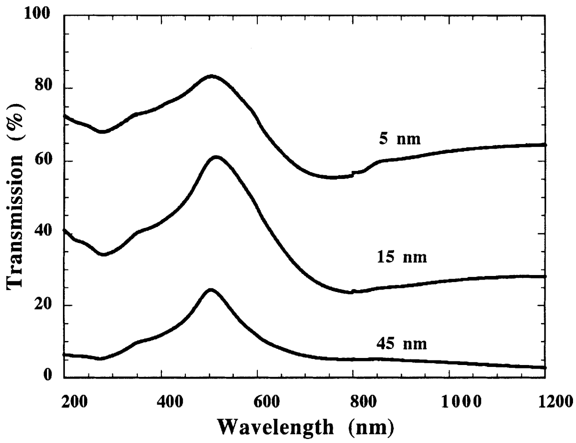

Fig. 2. Optical transmission spectra for 5, 15 and 45 nm thick layers of gold on KU1 quartz glass.

and 1 mm thick, were mounted in a holder which could be moved vertically and horizontally in the focal plane of a lens, the position was determined to about 0.1 mm. The laser beam direction was normal to the surface and the light was focused, using a 50 mm focal lens, in the exit surface layer of the sample. The thickness of the deposited layer was determined by a surface profiler DEKTAK. In the same way, to study surface quality (erosion) effects, samples with a rough face produced by grinding (100 μm diamond) have been examined.

Measurements of laser damage were carried out irradiating each sample with a series of laser pulses, one pulse per position in the sample, for seven different laser power densities (from 1×10^{14} to 6.7×10^{16} W/m^2) and at 25 different positions for each laser power density. After each laser pulse, the sample was moved 0.5 mm (or 1 mm depending on extension of damage site) horizontally in the focal plane of the lens, so that a new material zone could be used, and when necessary the sample could be moved vertically. Laser damage was manually monitored from the visible light emission and a clearly audible noise resembling a small explosion. Subsequent examination of the sample in an optical microscope indicated that the damage was in the form of craters and cracks ranging in size from about 0.1–1 mm. In regions where no light nor sound emission had been noted, no damage was visible.

The Q-switched Nd:YAG laser used in this work generates 1064 nm wavelength pulses of 7 ns duration with a maximum energy of 330 mJ. The focal spot size on target was 30 μm.

3. Results

The three metallized KU1 samples exhibited a greenish colour due to the gold layer. Fig. 2 shows the corresponding optical transmittance spectra. The transmittance around 500 nm exhibits a maximum which explains the green colour. One can see in the figure that the laser wavelength (1064 nm) is far from this maximum.

Fig. 3 gives the damage probability curves for the three metallized, the roughly, and the optically polished samples. The probability for laser damage is clearly increased in the case of the roughly polished sample. In the case of the metallized samples the change is far greater with a decrease of at least 3 orders of magnitude in the threshold power density for laser damage being observed. The probability for damage increases as the gold layer thickness decreases. This is clearly shown in Fig. 4 where damage probability is represented as a function of the gold layer thickness for a laser power density of 1.6×10^{13} W/m^2.

The possibility of 'in situ' laser cleaning was studied for the thin layers of gold deposited by sputtering. It was found that the layers were easily removed from the KU1 substrate by laser pulses with intensities below the damage threshold. Observations in the optical microscope confirmed that laser cleaned areas were not damaged. Hence periodic in situ cleaning may be possible.

4. Discussion

Previous work [2] has indicated that in-beam and accumulated dose effects do not produce a decrease in the threshold for laser damage in the case of KU1 quartz glass. Fig. 5 shows the damage probability curves taken from [2] where the combined effect of accumulated dose and surface erosion are given. However, the results obtained in the present work imply that surface degradation, particularly metal layer growth, will be a serious problem for LIDAR windows in future machines where

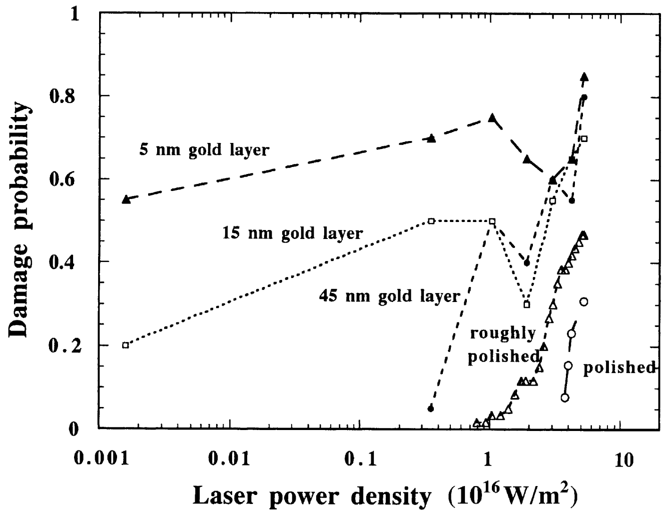

Fig. 3. Damage probability as a function of laser power density for a roughly polished, an optically polished, and three gold metallized KU1 quartz glass samples.

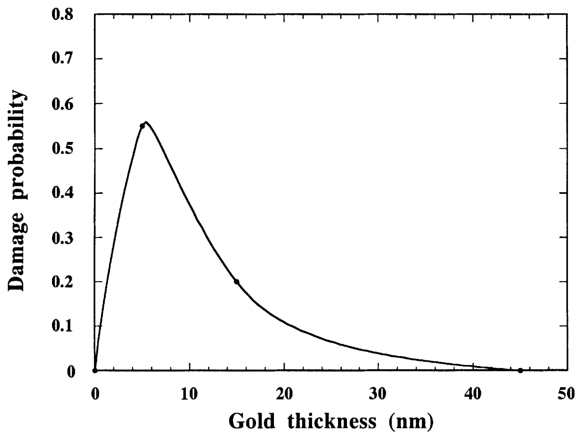

Fig. 4. Damage probability as a function of gold layer thickness for a laser power density of 1.6×10^{13} W/m^2.

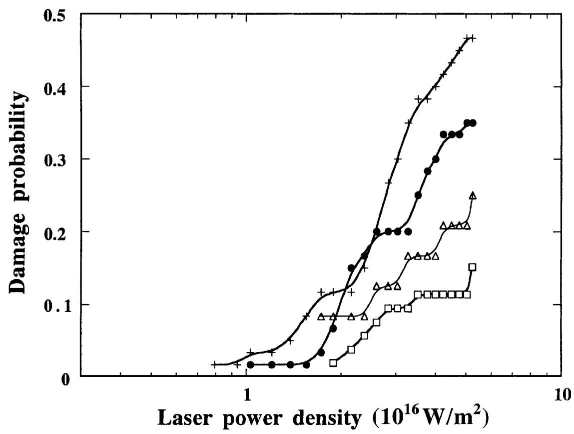

Fig. 5. Damage probability as a function of laser power for KU1 quartz glass in which the exit beam face was roughly polished. The curves are given for the unirradiated (crosses), irradiated up to 0.02 MGy (circles), 0.045 MGy (squares) and 20 h after irradiation (triangles).

sputtering and/or contamination processes will occur. An increase in sensitivity to laser damage of several orders of magnitude is observed, and what is more important is that the effect is more noticeable for the thinnest layer. This implies that in a relatively short reactor operation time the LIDAR window will become highly sensitive to laser damage.

The laser damage within the metal insulator interface occurs basically in the same way described in [3,4]: after passing through the insulator material the front part of the laser pulse is strongly absorbed within the metallic layer. The temperature within the interface rises to several thousand °C, then evaporation of the metal layer and excitation/ionization of metallic atoms occur. A small plasma is formed producing local UV and even X-ray emission. Before the end of the laser pulse electrons in the valence band of the insulator are excited to the conduction band due to both the sudden increase in temperature and the local UV/X-ray emission. The electrical conductivity of the insulator near the interface with the metal layer increases and then the remaining part of the laser pulse is readily absorbed within the insulator, damaging the surface region. In addition heating of metallic particles relative to the adjacent quartz glass produces stresses in the glass which can exceed its theoretical strength and result in mechanical failure.

It has been observed here that the sensitivity to laser damage increases as the metal layer decreases. Important physical parameters in this process are the thermal conductivity K and the specific heat capacity c_p of both materials [3]. The most probable reason for this inverse behaviour of laser damage is that the temperature reached within the metal layer depends inversely on the heat removed from the laser irradiated area which increases with the layer thickness. The thermal diffusivity of the material is $\chi = K/\rho c_p$, where ρ is the density. The scale length l_D for diffusion of heat during the laser pulse length τ is $l_D = (\chi\tau)^{0.5}$. Values for gold are [5]: $K_{Au} = 318$ $W\,m^{-1}\,K^{-1}$, $\rho_{Au} = 19.3 \times 10^3$ $kg\,m^{-3}$, $c_{p^{Au}} = 129$ $J\,K^{-1}$ kg^{-1} (at 25 °C and constant pressure). This gives $l_D = 9.4 \times 10^{-7}$ m which is much larger than the thickness of the gold layer ($0.5–4.5 \times 10^{-8}$ m), hence the thin gold layer is not capable of removing the heat generated during the laser pulse.

Laser cleaning was shown to be very effective. The gold layer was easily removed from the samples without damaging the surface at all. However, one must take into account that the reactivity of gold with the KU1 substrate is low which implies that the adhesion is low as well. In the case of other materials the adhesion will be different and hence laser cleaning may be more difficult. Other more relevant materials, in particular stainless steel, must be studied.

5. Conclusions

Surface erosion increases slightly the sensitivity to laser damage in KU1 quartz glass. However, the growth of a thin metallic layer on the vacuum (exit) face of LIDAR windows will have a dramatic adverse effect on the damage sensitivity. This is an unavoidable process due to sputtering and contamination, which will give rise to laser damage in the window after only a short fusion reactor operation time. Frequent laser cleaning seems to be a possible solution, however, other more relevant materials such as stainless steel should be studied to check this.

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