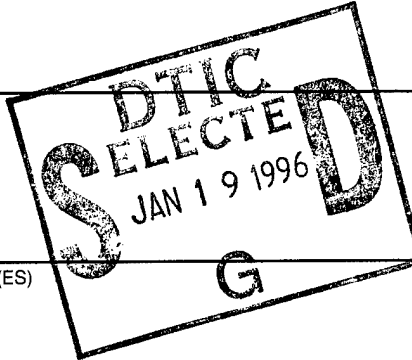


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DEFECT FORMATION IN FUSED SILICAS DUE TO PHOTON IRRADIATION AT 5 AND 50 eV

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Abstract

We have compared the paramagnetic defect formation in two types of pure fused silica glass irradiated with intense photon fluxes at 5 eV (KrF laser) and 50 eV (undulator beam from Aladdin Synchrotron Light Source), using electron paramagnetic resonance spectroscopy with a frequency of 9.7 GHz and sample temperatures of 110 and 300K. The 5 eV photons produce approximately  $10^{-14}$  paramagnetic defects per photon and the 50 eV photons produce approximately  $10^{-5}$  defects per photon. The ratio of E' centers to oxygen related centers is ~10 times greater for 5 eV photons than for 50 eV photons in type III silica.

## Introduction

Intrinsic defects in silicas have drawn considerable attention since Weeks initially identified and characterized the E' center in 1956.<sup>1</sup> This attention results from increased understanding of the scientific and technological importance of defects in a wide variety of materials. Many questions about defects in SiO<sub>2</sub> have not been resolved. Defects affect several important applications of silicas. These include optical fibers, both core and cladding regions, and VLSI's (Very Large Scale Integrated Circuits) in which SiO<sub>2</sub> functions as an insulator or passivating layer.

Many interesting phenomena have been discovered with improvements of brightness, pulse duration and the wavelength-tunability of light sources. Stathis and Kastner<sup>2</sup> reported that different defects are created in silicas by 5.0, 6.4, and 7.9 eV photons from excimer lasers whose energies are all smaller than the bandgap energy of silica, which is almost 10 eV.<sup>3,4</sup> They found that 5.0 eV photons are the most efficient in producing E' centers.<sup>3</sup> They also observed that 7.9 eV photons introduced different defects in dry and wet silicas.

The purpose of this work was to determine the relative and absolute efficiency of 5 and 50 eV photons in producing intrinsic defects in silicas. Five eV photons were produced by a KrF excimer laser and the 50 eV photons were produced by the undulator beamline of Synchrotron Radiation Center at Madison, Wisconsin.

## Experimental Procedure

The silica samples consisted of Type III and IV<sup>5</sup> high-purity synthetic silicas, specifically Suprasil W1 (dry), which contains about 5 ppm OH by weight, and Suprasil I (wet), which contains 1200 ppm OH. Total metallic impurities were of the order of 1 ppm.

Samples were cut from a 30 mm diameter and 1 mm thick disk to the dimensions 5 mm x 18 mm x 1 mm. The samples were cleaned, mounted on a sample holder attached to a manipulator, and inserted into an UHV (Ultra High Vacuum) chamber for the 50 eV irradiations. Several samples were mounted on the same holder. The same optical geometry for each sample was achieved by changing the height of the sample holder inside the UHV chamber. The experimental setup is shown in Fig. 1. The vacuum was kept at 10<sup>-9</sup> torr during the 50 eV exposure at room temperature. For the 5 eV exposure, 50 mJ/cm<sup>2</sup> unfocused KrF excimer laser beam was used to expose the sample in air at room temperature. The total number of shots was 10<sup>10</sup>.

The types and concentrations of paramagnetic defects produced by 5 and 50 eV light were measured by electron paramagnetic resonance spectroscopy (Bruker ESR 200 at 9.7 GHz). The E' centers (singly charged oxygen vacancies) and oxygen-related centers were monitored at room temperature and 110K, respectively. The number of defects in silica was determined by comparison with a standard sample (a Bruker strong pitch secondary standard) whose paramagnetic state concentration was known. The error in the relative numbers of paramagnetic defects was ± 10%. The absolute numbers of paramagnetic centers has an error estimated at ± 100%.

The flux of 5 eV photons incident on a sample was determined through calculations based on measurements of power density and total number of pulses. The total number of 50 eV photons was also calculated from the exposure time and the photon flux. The photon flux was calculated from measurements of current produced in a calibrated gold diode and the photoelectric yield on gold.<sup>6</sup> The flux of 50 eV photon was  $(1.1 \pm 0.1) \times 10^{18}$  photons per 1mm diameter spot per minute.

The irradiated volume was calculated from the 1/e penetration depth of 50 eV photons in silica and the beam diameter. The 1/e penetration depth was assumed to be 3.2 μm<sup>7</sup> and the beam diameter was 1 mm. Seven to fourteen spots were irradiated on each sample. We estimate the uncertainty of the diameter of the beam size as ± 30% when the distribution of photons across the beam is taken into account. The photon energy is lower than the bandgap energy in the case of the 5 eV photons; hence, the irradiation volume is the entire sample.

## Results

Paramagnetic resonance spectra of E' centers and oxygen related (OR) centers, including peroxy radicals<sup>8</sup> and non-bridging oxygen hole centers<sup>9</sup> were detected in both 5 and 50 eV irradiated silicas. The concentrations of defects of each type in each sample were calculated from measurements of the number of defects and the irradiated volume. The defect formation rate per photon was obtained by dividing the total number of defects by the total number of photons.

The concentrations of defects, the defect formation per photon, the ratio of E' center to OR centers, and the total number of photons used in exposure are all listed in Table I and II.

The 50 eV light created about  $10^{15}$  E' centers per  $\text{cm}^3$  and about  $10^{13}$  OR centers per  $\text{cm}^3$  in both dry and wet silicas. The formation rate of E' and OR centers are  $10^{-4}$  and  $10^{-5}$  per photon respectively. The ratio of E' center to OR center is three times higher in wet silica than dry silica.

The 5 eV photons introduced about  $10^{16}$  E' centers in both samples. These photons induced approximately 30 times higher concentration of OR centers in dry silica ( $6.0 \times 10^{14}$ ) than in wet silica ( $1.7 \times 10^{13}$ ). The formation rate of E' center is about  $10^{-12}$  per photon in both silicas, and  $6 \times 10^{-13}$  and  $1.6 \times 10^{-15}$  OR center per photon in Suprasil W1 and Suprasil 1, respectively. The E'/OR Center ratio is 50 times higher in wet silica than dry silica and has the same trend as in 50 eV irradiated silicas.

## Discussion

A flux of  $10^{18}$  50 eV photons create the same order of magnitude of E' and OR centers as  $10^{26}$  5 eV photons. The absorption coefficient for the 5 eV photons in silica is about  $7 \times 10^{-3} \text{ cm}^{-1}$ ,<sup>10</sup> while all the 50 eV light is absorbed. Taking this difference in absorptivity into account, the 50 eV light produces  $\sim 10^5$  to  $10^6$  more defects than the 5 eV light.

Three possible reasons may explain this difference in defect formation per photon between the 5 and 50 eV photons. First, E' center formation by 5 eV photons may be due to a two photon process.<sup>11</sup> If this is the case, the low absorptivity for a two photon process, which is  $2 \times 10^{-3} \text{ cm}^{-1,12}$  would result in an absorptivity of  $\sim 10^{-5} \text{ cm}^{-1}$ . Thus, the ratio absorptivities for 5 eV and 50 eV photons is approximately  $10^{-10}$ . The ratio of paramagnetic states produced by 5 eV to 50 eV photons is  $\sim 10^{-12}$ . Thus, the 50 eV photons produced  $\sim 100$  times more paramagnetic defects than did the 5 eV photons. Second, Arai et al.<sup>11</sup> suggested that the E' center induced by 5 and 6.4 eV light is through hole capture at precursor sites. At a flux of  $10^{21}$  6.4 eV photons  $\text{cm}^{-2}$  the onset of saturation of E' centers was observed. This saturation effect may also occur for  $10^{26}$  5 eV photons  $\text{cm}^{-2}$ . In addition, the 50 eV photons may produce new E' and OR centers by Si--O bond breaking. The threshold energy for Si--O bond breaking is about 8.5 eV;<sup>13</sup> hence, in case of 50 eV photons we assume that their energy is sufficient to break Si--O bonds. Bond breaking process may well explain why 50 eV light produces 2 or 3 orders more defects in silica than 5 eV light.

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Table I Silicas Irradiated by 50 eV Light from Synchrotron

Silicas	E'(cm <sup>-3</sup> )	ORC(cm <sup>-3</sup> )	E'/Photon	ORC/Photon	E'/ORC	Total Photons
Sup W1	1.1x10 <sup>15</sup>	6.4x10 <sup>13</sup>	3.0x10 <sup>-4</sup>	1.8x10 <sup>-5</sup>	17	3.7x10 <sup>18</sup>
Sup I	3.3x10 <sup>15</sup>	6.7x10 <sup>13</sup>	4.5x10 <sup>-4</sup>	0.9x10 <sup>-5</sup>	49	7.4x10 <sup>18</sup>
Error	(±40%)	(±40%)	(±50%)	(±50%)	(±20%)	(±10%)

5.3x10<sup>17</sup> photons per 5 mins per 1 mm dia. beam size

The penetration depth for 50 eV photon in silica is 3.2 μm

Table II 5 eV (248 nm) KrF Excimer Laser Irradiated Silicas

Silicas	E'(cm <sup>-3</sup> )	ORC(cm <sup>-3</sup> )	E'/Photon	ORC/Photon	E'/ORC	Total Photons
Sup W1	6.8x10 <sup>15</sup>	6.0x10 <sup>14</sup>	6.0x10 <sup>-13</sup>	6.0x10 <sup>-14</sup>	10	7.8x10 <sup>26</sup>
Sup I	8.5x10 <sup>15</sup>	1.7x10 <sup>13</sup>	8.0x10 <sup>-13</sup>	1.6x10 <sup>-15</sup>	500	7.8x10 <sup>26</sup>
Error	(±40%)	(±40%)	(±50%)	(±50%)	(±20%)	(±10%)

50mJ per cm<sup>2</sup> per shot, total shots 10<sup>10</sup>, total photons on .5 x .5 x .3 cm<sup>3</sup> = 7.8x10<sup>26</sup>

The absorption coefficient of 5 eV photon in silica is about 7.0 x 10<sup>-3</sup> cm<sup>-1</sup>

Oxygen Related Centers (ORC) include Peroxy Radicals (POR) and Non-Bridging Oxygen Hole Centers (NBOHC)

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