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Interactions of high current pulsed electron beam with phosphate laser glass

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Impact of electron beam bombardment on the surface of Nd^{3+} doped P_2O_5–B_2O_3–Al_2O_3–BaO laser glass was investigated. Physical properties of the bombarded glass were measured by 3D laser roughometer, microhardness tester, UV/VIS spectrometer, EDS and contact goniometer. Low beam energy had no significant impact on glass surface morphology and other properties. High beam energy increased glass surface roughness and decreased micro-hardness, UV/VIS transmittance and wetting angle. Thermal stress generated by high energy electron beam bombardment expanded the Griffith flaws and increased glass surface roughness.

Key words: *pulsed electron beam; phosphate glass; laser; micro-cracks; surface morphology*

1. Introduction

High energy electron beam was first used for simulation of nuclear explosion and X-ray radiograph by Bernesein and Champney in 1973 [1, 2]. Since then high energy electron beam has been widely used for modifying properties of materials to improve hardness, strength and anticorrosion and wear resistance [3–6]. Phosphorite bioglass was irradiated with electron beam to improve wetting properties to increase glass compatibility with biologic cells and to prevent dew formation on the glass surface [7]. The energy intensity of pulse electron beam applied to modify metallic materials

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is normally up to 10^8–10^9 W/cm^2 [8] while the corresponding energy intensity applied to glass surface modification is relatively low [7]. When soda lime silicate glass was bombarded with electron beam with energy intensity of 10^{12} W/cm^2, micro-flaws were formed on the glass surface due to a high thermal stress [9]. In this paper, we report on the impact of electron beam bombardment on properties of the surface of commercial Nd^{3+} doped P_2O_5–B_2O_3–Al_2O_3–BaO laser glass.

2. Experimental

Nadezhda-2 type pulsed high current electron beam developed by Proskurovsky et al. [10, 11], was used in this study. The beam energy and peak current were between 10–40 keV and 10^2–10^3 A/cm^2, respectively. Pulse duration was between 0.8 and 2 μs, beam area was 30 cm^2 and energy intensity was between 1 and 6 J/cm^2. The Nd_2O_3 doped phosphate glass for this study contained 67.29 wt. % of P_2O_5, 4.50 wt. % of B_2O_3, 3.40 wt. % of Al_2O_3 and 24.81 wt. % of BaO. Glass batch was melted in a platinum crucible and then cast to flat sheet, annealed, polished, and cut into the plate samples (10×10×1 mm^3). The glass plates were washed with tap water, ethanol and de-ionized water, dried in a vacuum chamber and then irradiated with electron beam at 19.869, 23.807, 26.85 and 28.64 keV, respectively.

Glass surface morphology was examined by a Zygo 5022 3D Laser roughometer. Surface hardness was measured with a Matsuzawa DMH-2LS microhardness tester. A Perkin Elmer LAMBDA 35 UV/VIS spectrometer was used to record UV/VIS spectra. An Oxford Instruments INCA energy disperse spectrometer was used to analyze glass surface composition. Wetting angle was measured by a JY-B type contact goniometer.

3. Results

As shown in Fig. 1, glass surface morphology is about the same after irradiation with electron beam at 19.869 keV (Fig. 1b). When beam energy is 23.807 keV (Fig. 1c), some arborization flaws consisting of stem flaws and offshoot flaws are formed on the glass surface. These flaws propagate when beam energy is increased to 26.85 keV (Fig. 1d). Concave and protruding annular concentric flaws are formed when beam energy is 28.64 keV (Fig. 1e). The dependence between the surface roughness and electron beam accelerating voltage is shown in Fig. 2. Compared to the starting glass sample, there is no change in the mean square roughness (Rms) and the average roughness of (Ra) after bombardment with electron beam at 19.869 keV. The roughness increases sharply when the beam energy is increased to 23.807 keV. At 28.64 keV, Rms increases to 410 nm. Microhardness as a function of beam energy is

shown in Fig. 3. It can be seen that microhardness decreases with increasing beam energy with pronounced decreasing rate between beam energy of 23.807 keV and 26.85 keV. As shown in Fig. 4, the wetting angle decreases with increasing beam energy.

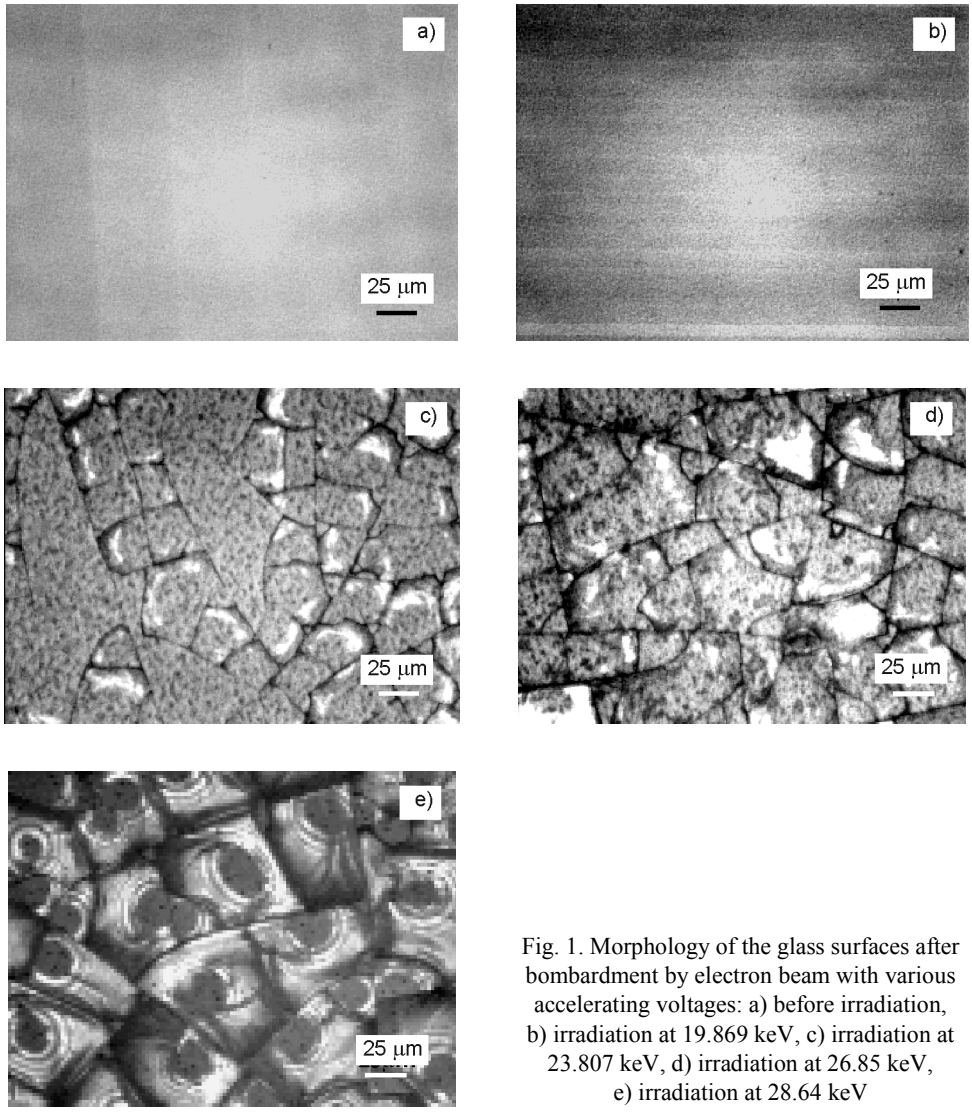

Fig. 1. Morphology of the glass surfaces after bombardment by electron beam with various accelerating voltages: a) before irradiation, b) irradiation at 19.869 keV, c) irradiation at 23.807 keV, d) irradiation at 26.85 keV, e) irradiation at 28.64 keV

Figure 5 shows UV/VIS spectra of the electron beam bombarded sample. The absorption peaks can be attributed to Nd^{3+} electron transitions between various energy levels. Peaks at 350, 356, 430, 476, 511, 524, 582, 682, 746, 802, 874 nm correspond to ^4D, $^4D_{5/2}$, $^2P_{1/2}$, $^{3/2}G_{9/2}$, $^4G_{9/2}$, $^2K_{13/2}$, $^2G_{5/2}$, $^4F_{9/2}$, $^4F_{7/2}$, $^4F_{5/2}$, $^4F_{3/2}$ energy level transitions, respectively. These results are slightly different from the results reported in ref-

erence [12] due to different substrate glass compositions. The transmittance decreases with increasing beam energy with no shift in peak positions.

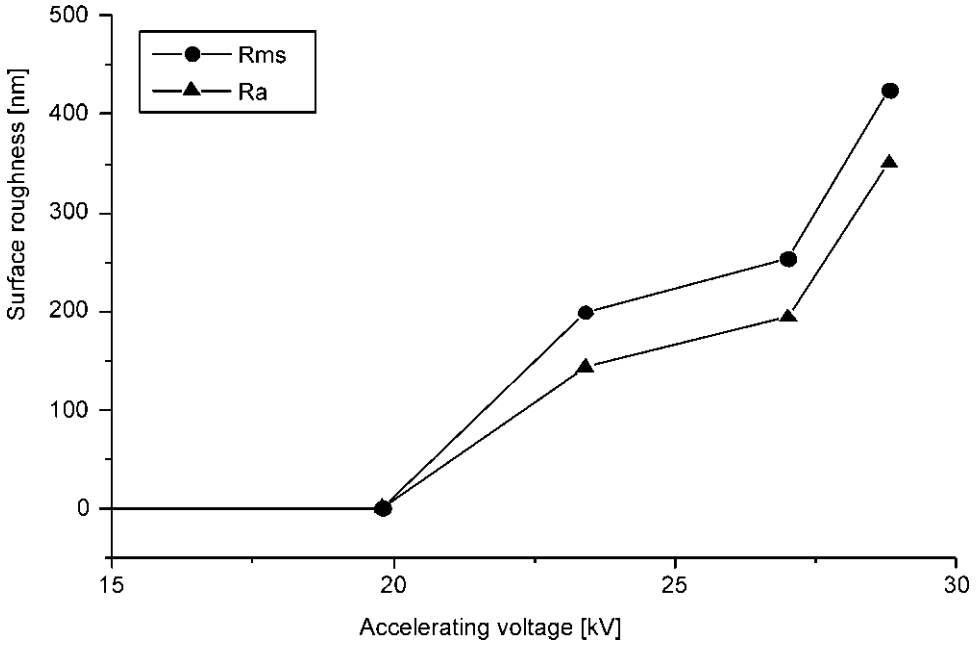

Fig. 2. Roughness of glass surface as a function of the accelerating voltage of electron beam

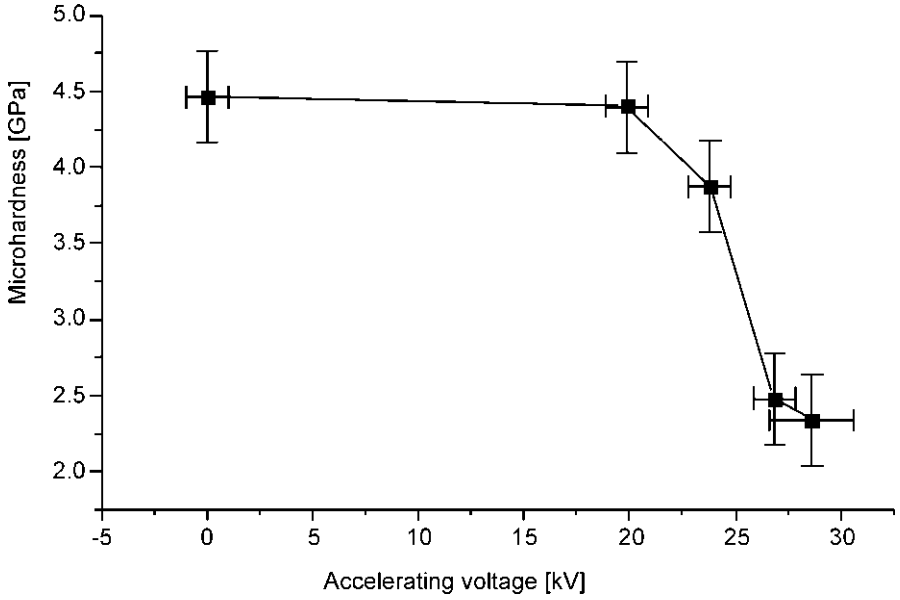

Fig. 3. Dependence of glass microhardness on the accelerating voltage of electron beam

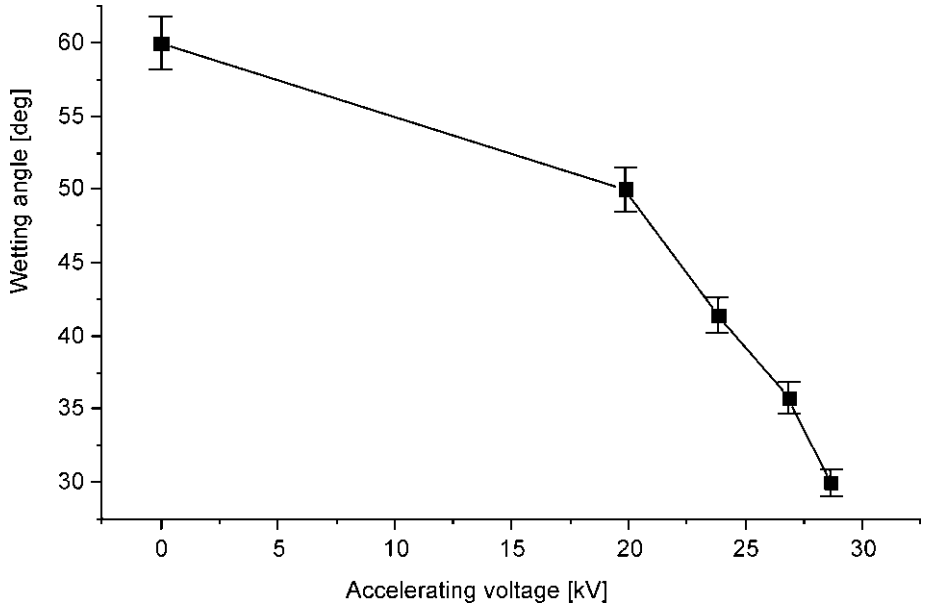

Fig. 4. Dependence of glass surface wetting angle on the accelerating voltage of electron beam

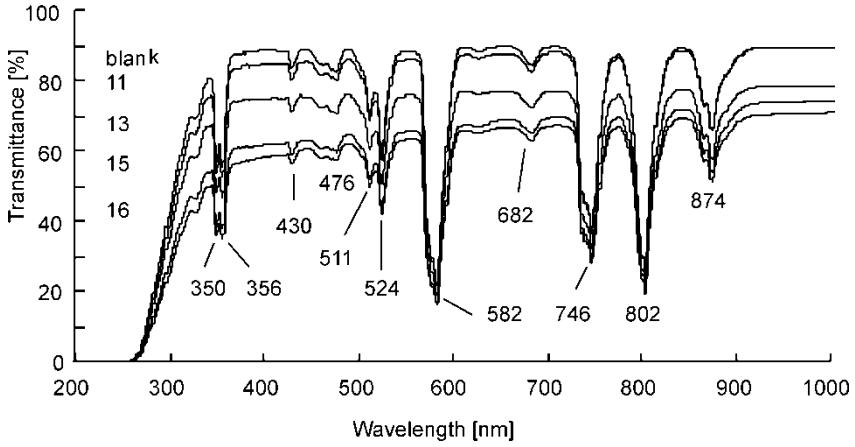

Fig. 5. UV/VIS transmittance spectra of glass after bombardment by electron beam with various accelerating voltages

Glass surface compositions (at. %) of O, P, Ba and Al as a function of accelerating voltages are shown in Figs. 6–9, respectively. When electron beams irradiate the glass surface, oxygen atoms are sputtered from the surface. Therefore, the oxygen concentration decreases with increasing beam energy. Other atoms with higher atom weight such as P and Ba are difficult to be sputtered so the concentrations of these atoms increase with the beam energy. The aluminium concentration appears to increase with

increasing beam energy probably due to the abnormal fluctuation in EDS measurement.

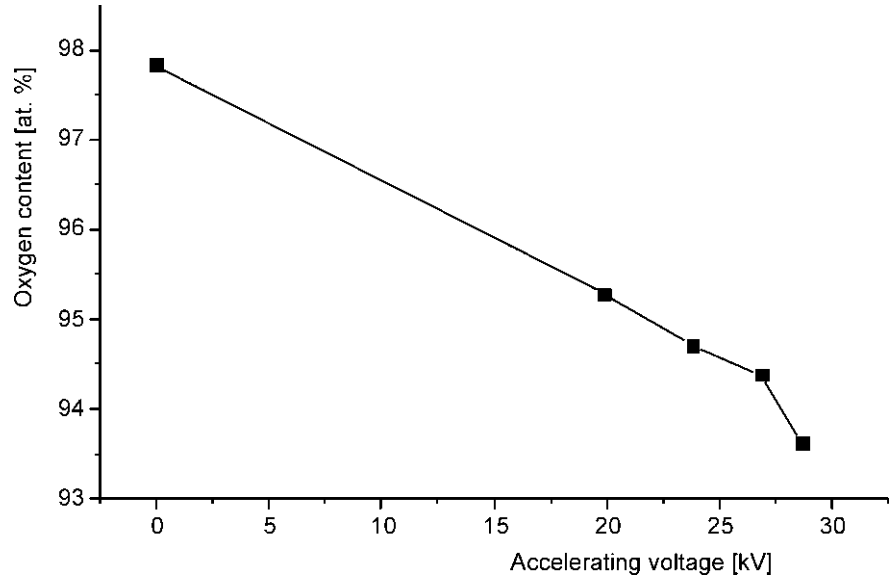

Fig. 6. Oxygen contents (at. %) on the glass surface after bombardment by electron beam with different accelerating voltages

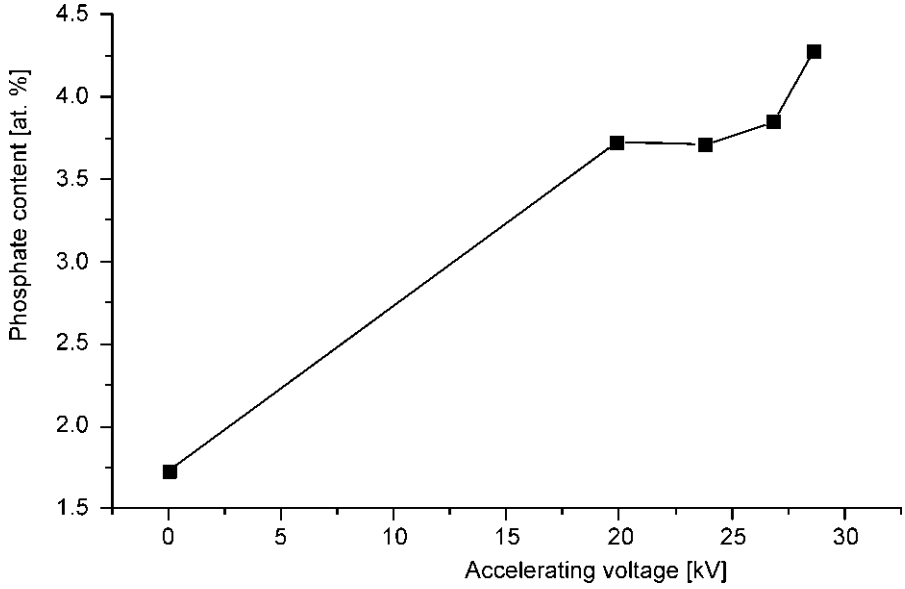

Fig. 7. Phosphate contents [at. %] on the glass surface after bombardment by electron beam with various accelerating voltages

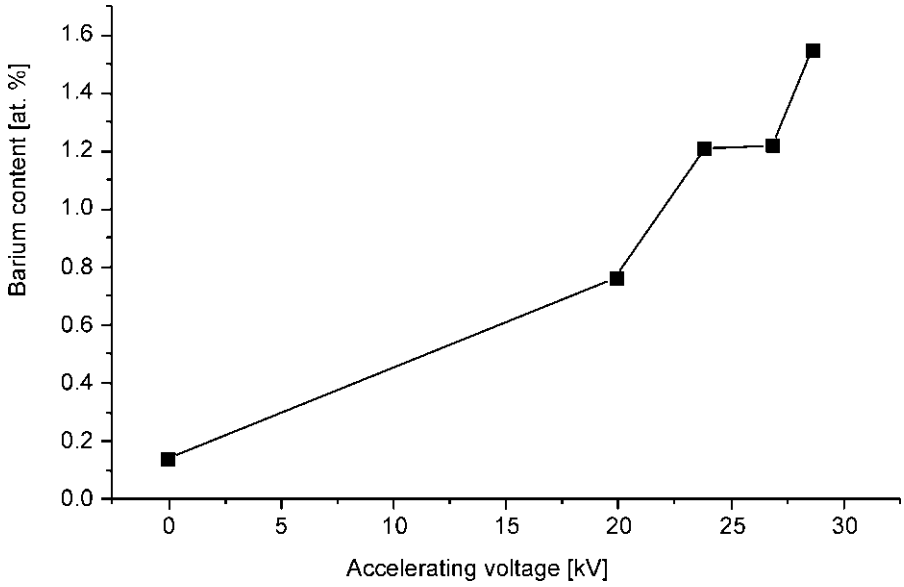

Fig. 8. Barium contents [at. %] on the glass surface after bombardment by electron beam with various accelerating voltages

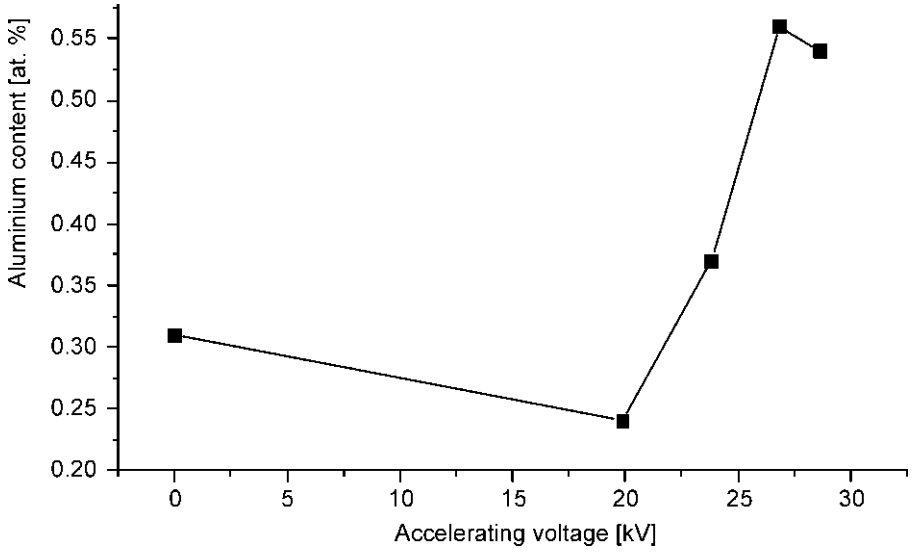

Fig. 9. Aluminium contents [at. %] on the glass surface after bombardment by electron beam with various accelerating voltages

4. Discussion

When high energy electron beams bombard glass surface, excitation and ionization of the surface atoms occurs. A large amount of energy concentrates on a small

area of the glass surface (the maximum energy intensity is up to 10^{12} W/cm^2) and the local temperature rapidly increases. Since the temperature of other areas on the glass surface is relatively low, a temperature gradient is formed to cause strong thermal expansion. The thermal stress expands the Griffith flaws to form more microflaws. These microflaws propagate with increasing beam energy.

When glass surface is bombarded with high current pulsed electron beams, the first pulsed electron beam bombardment forms stem flaws and then offshoot flaws. The second pulsed electron beam bombardment forms pulse stress. The transmitting rate of pulse stress is higher than the diffusion of offshoot flaws. Interaction between pulse stress and offshoot flaws changes the diffusion direction of the flaws to form annular ripples as shown in Fig. 1e).

After bombardment with electron beams, microflaws formed on the glass increase surface roughness and decrease microhardness. The contact area between water and glass increases due to rougher surface. This will decrease the wetting angle and improve wetting property. The dispersion of visible light on the glass surface increases with increasing surface roughness and this leads to low transmittance.

5. Conclusions

High pressure and temperature gradients generated by high current pulsed electron beam bombardment on the phosphate glass surface produce high stress. This stress expands the Griffith flaws to form arborization flaws and cross flaws. The micro flaws propagate with increasing electron beam energy and annular ripples are formed at a high beam energy. The roughness of glass surface increases, and micro hardness, visible light, ultra violet transmittance and wetting angle decrease with increasing beam energy.

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