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MECHANICAL PROPERTIES OF SILICON-BASED MEMBRANE WINDOWS APPLIED FOR A MINIATURE ELECTRON BEAM RADIATION SYSTEM

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Abstract: This paper presents the mechanical properties of silicon-based membranes windows applied for miniature electron beam radiation system. The membranes were used for the physical separation between the vacuum and atmosphere, and used as an EB-permeable membrane window. We used MEMS technologies to fabricate the thin Si-based membrane window structure. The size of each window is 6 mm in length and 2 mm in width. Four different types of membrane windows were fabricated to compare the mechanical properties. Residential stress, Young's modulus, and breakage pressure were evaluated by using bulge test technique. $SiN/SiO_2/Si$ membrane showed the highest breakage pressure and operated more than one thousand hours.

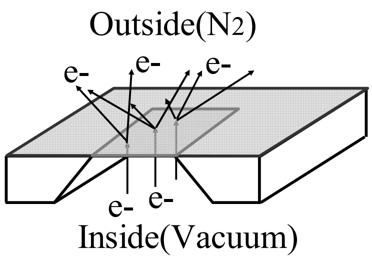
Keywords: Silicon, SiN, SiC, Membrane, Electron Beam, Residential Stress, Young's Modulus

1. INTRODUCTION

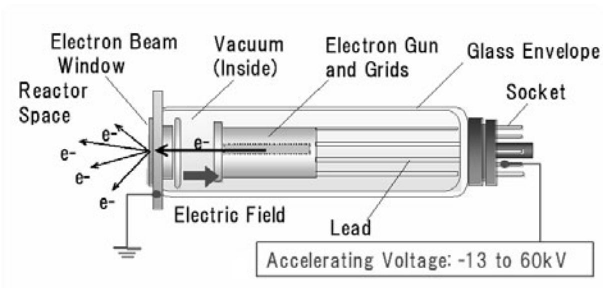
We previously purposed the Si membrane structure for irradiating the low energy electron beam (EB) in order to minimize the electron penetration depth into electrolyte film [1, 2]. Fujita el. al., applied it for curing the 500 nm thick methylsilsesquioxane (MSQ) low-k dielectric film, and improved its mechanical strength. The process also has the advantage that it is able to drastically shorten the processing time compared to the conventionally used thermal curing [3].

Si-based membrane is used for the physical separation between the vacuum and atmosphere, and also used as an EB-permeable membrane window. EB generated inside the vacuum tube is extracted to the atmospheric outside by penetrating Si membranes as shown in Figs. 1 and 2. The miniature EB tube with electron permeable Si-based membranes is shown in Fig. 1(b). The tube diameter and length are 50 mm and 130 mm, respectively. Electrons generated at gun in the vacuum are accelerated by high electrical field, and penetrate Si-based thin membrane to the outside for the EB radiations. The large-sized thin Si membrane is required to obtain high EB radiation power output and efficiency. However, it has to mechanically withstand the pressure difference under high temperature conditions. The temperature at the window becomes up to 500K because of heating by the EB penetration.

This time, we therefore evaluated the mechanical properties of the large-sized thin Si-based membrane windows to realize the miniature EB radiation system.



(a) Magnification of membrane and Electron Beam Penetration.



(b) Schematic of miniature electron beam.

Figure 1. Miniature electron beam tube with electron permeable silicon-based membrane.

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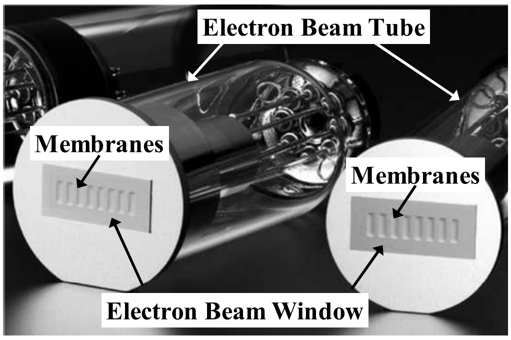
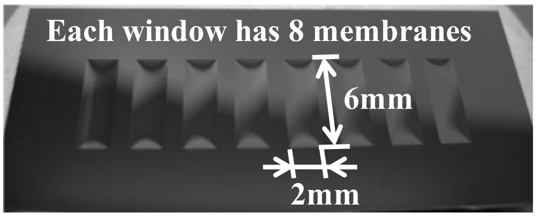
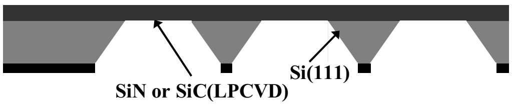


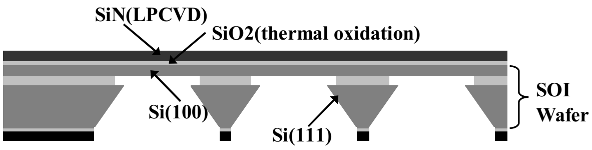
Figure 2. Photograph of miniature electron beam tube.



(a) Top view of silicon-based membrane windows.



(b) SiN or SiC membrane.



(c) SiN/SiO2/Si membrane

Figure 3. Fabricated silicon-based membrane window.

2. MANUFACTURE OF MEMBRANE WINDOWS

We used MEMS technologies to fabricate the large-sized thin Si-based membrane window structures. Figure 3 shows the fabricated membrane windows. The size of each window is 6 mm in length and 2 mm in width as shown in Fig. 3(a). We fabricated four different types of membrane windows. The thickness and materials used at layers are shown in Figs. 3(b) and 3(c), and Table 1.

A standard {100} oriented Si wafer was used as a substrate for fabricating SiN, SiC, and SiN/SiC membrane windows. These materials were formed on the Si surface by deposition process.

Table 1 Configuration of membrane windows.

Type of Window	Configuration of Window	
	Layer of Membrane	*Substrate*
SiN	SiN(1.1um)	Standard Si Wafer
SiC	SiC(1.1um)	
SiN/SiC	SiN(0.3um)/SiC(0.8um)	
$SiN/SiO_2/Si$	$SiN(0.3um)/SiO_2(0.05um)/Si(1.0um)$	SOI

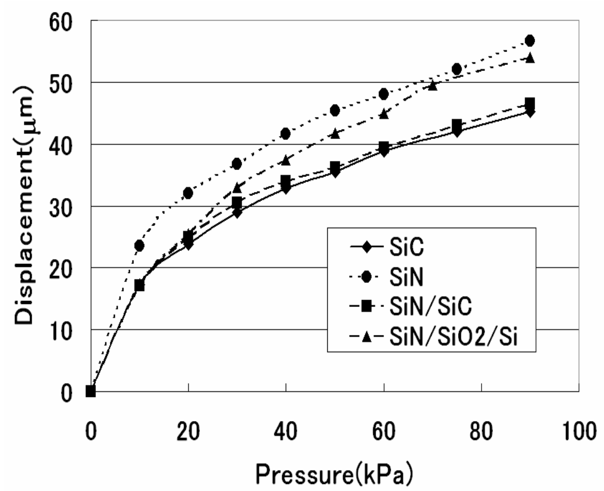


Figure 4. Membrane deformation against loading pressure.

KOH anisotropic wet etching was used to form the diaphragm structures. We used SOI wafer as a substrate to precisely control the thickness of Si layer at the $SiN/SiO_2/Si$ membrane. The thickness of each membrane was designed to obtain the same electron transmission efficiency.

3. MEASUREMENT OF MECHANICAL PROPERTIES

We evaluated three mechanical properties, residual stress, Young's modulus, and breakage pressure, by using bulge test technique [4, 5]. The displacement versus pressure, as a function of the window types, is shown in Fig. 4.

We calculated the Young's modulus and residual film stresses by using the graphs in Fig. 4, and showed them in Fig. 5. The followings are obtained results.

(1) Young's modulus of the SiC and SiN membranes were 431GPa and 255 GPa, respectively.
(2) The residual stresses of SiC, SiN/SiC, and

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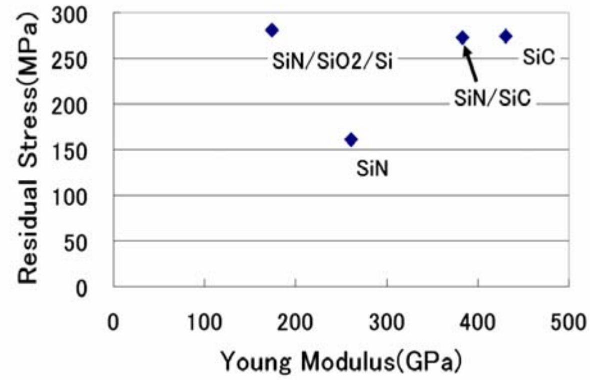

Figure 5. Young's modulus and residual stress of membranes.

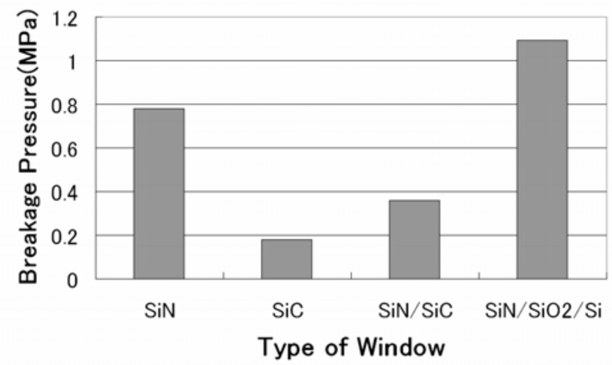

Figure 6. Breakage pressure of window type.

$SiN/SiO_2/Si$ were almost the same, and their value was 275 MPa. The SiN showed the lowest value of 160 MPa.

These values largely depend on their deposition conditions. We are now investigating the relationship between the deposition conditions and these values.

We then measured the breakage pressure value of each membrane by pressuring nitrogen gas. All type withstood the atmospheric pressure difference, as shown in Fig. 6. The $SiN/SiO_2/Si$ membrane had the highest value of over 1.0 MPa. The SiC one showed a relatively low value of less than 0.2 MPa because of rough surface whose roughness is about 40 nm as shown in Fig. 7. The rough surface easily promotes the slip along at the grain boundary. We think that we are able to increase breakage pressure values by improving the surface roughness at membrane.

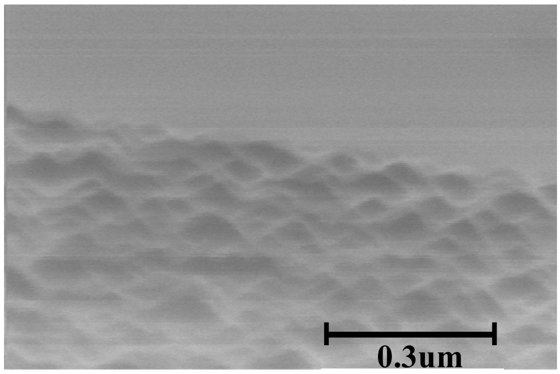

Figure 7. SEM image of SiC membrane surface.

4. EB OPERATION PERFORMANCE

We finally evaluated the actual operation performance by using SiN and $SiN/SiO_2/Si$ membrane, which showed high values of breakage pressure. The applied voltage, the current, and the outside pressure of the tube, were 13 kV, 0.3 mA, and 1.3 kPa nitrogen, respectively. The followings are obtained results.

(1) The SiN membranes were melted after 0.5 hour operation as shown in Fig. 8, because of its low thermal conductivity. We therefore calculated the temperature at the center part of the SiN membranes by the fine element method, and obtained the value of 2137K.

(2) The $SiN/SiO_2/Si$ membranes showed excellent stability, and operated more than 1,000 hour. On the other hand, the temperature value at the center was less than 594K in this case. This is because the high thermal conductivity of silicon material was used as a part of the membrane. The thermal conductivity of thin film of single crystal silicon is 150 W/mK [6]. The heart transferred from the center of the window can be broken into thermal-convection, -radiation, and -conduction. The value of the first one is smaller than that of the last one, because of the vacuum conditions. The second one is also relatively small in these temperature regions. Therefore, the heart conduction from the center to the window frame dominates the overall heat transfer. The ratio between thermal-convection, -radiation, and -conduction are 15, 5, and 80, respectively. We now think that it is important to use the materials having the high thermal conductivity to reduce the rise in the temperature at the membrane and to improve the lifetime. Less conductive material

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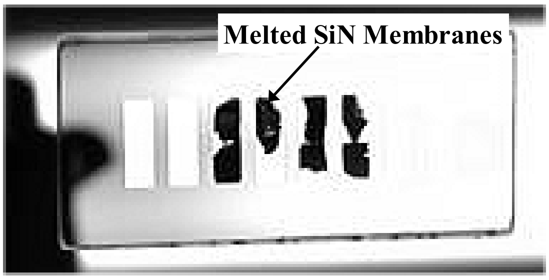

Figure 8. SiN membranes melted at the center position by overheating during operation of electron beam system.

such as SiN shows a steep temperature gradient over the membrane surface.

5. CONCLUSION

(1) Young's modulus of the SiC and SiN membranes were 431GPa and 255 GPa, respectively.

(2) The residual stresses of SiC, SiN/SiC, and $SiN/SiO_2/Si$ were almost the same, and their value was 275 MPa. The SiN showed the lowest value of 160 MPa.

(3) All type withstood the atmospheric pressure difference. The $SiN/SiO_2/Si$ membrane had the highest value of over 1.0 MPa. Breakage pressure of SiC and SiN/SiC membranes were too low.

(4) The $SiN/SiO_2/Si$ membranes showed excellent stability, and operated more than 1,000 hour in the life test.

We now concluded that the SiN/SiO2/Si multi-layer membrane is the most suitable for EB window, and will report the experimental result in detail at the conference.

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