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Extremely High Resistance of Thin Flexible Glass against Thermal Stress Induced by Ultra-rapid Annealing

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Abstract

We have successfully crystallized amorphous silicon films on 100-μm-thick flexible glass by micro-thermal-plasma-jet (μ-TPJ) without any crack, while a lot of cracks were observed in 500-μm-thick conventional glass. Numerical analysis shows the threshold value for crack generation is estimated as 54 MPa, and the maximum residual tensile stress in flexible glass was 43 MPa. It was clarified that the ratio of surface densified layer thickness and thickness of glass plays an important role in the magnitude of residual tensile stress.

1. Introduction

Recently, flexible glass is attracting much attention because it could be applicable to curved or foldable displays. Conventional flat panel displays are fabricated on rigid glass with the typical thickness of ~500 μm. By thinning the glass to ~100 μm, it become flexible, but mechanically weak and easy to break. For thin film transistors (TFTs) fabrication on flexible glass, ultra-rapid thermal annealing (URTA) used for crystallization of amorphous silicon (a-Si) is one of the key process technologies. However, the effect of URTA on the residual thermal stress in the glass surface has not been clarified yet. In this work, we examine the resistance of thin flexible glass against thermal stress based on experimental and analytical investigations.

2. Experimental

After wet chemical cleaning of a 100-μm-thick flexible glass and 500-μm-thick conventional glass substrates, 100-nm-thick a-Si films were deposited by plasma-enhanced chemical vapor deposition (PECVD) using SiH_4 and H_2 at 250°C. Dehydrogenation was carried at 450°C in N_2 ambient for 1 h. Micro-thermal-plasma-jet (μ-TPJ) was generated by DC arc discharge under atmospheric pressure by supplying power (P) from 1.3 to 1.7 kW between a copper (Cu) anode and a tungsten (W) cathode under Ar gas flow rate (f) of 1.0 L/min (Fig. 1). μ-TPJ was generated by blowing out the thermal plasma through an orifice with its diameter (ϕ) of 600 μm. The distances between the plasma source and glass substrates (d) were fixed at 1.0 mm and the substrates were linearly moved by a motion stage in front of the μ-TPJ with scanning speed (v) of 450 to 2200 mm/s.

For the measurement of transient temperature variation in the glass, transient reflectivity during μ-TPJ annealing was measured by irradiating bare conventional glass substrate with a He-Ne laser (632.8 nm) from the back surface. Details of the non-contact temperature measurement technique have been reported in the reference [1].

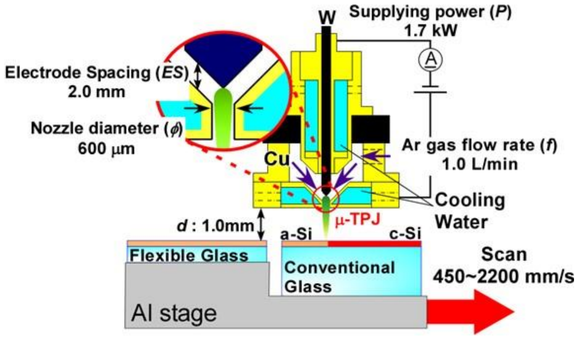

Fig. 1. Schematic diagram of μ-TPJ irradiation to conventional and flexible glass substrates on linear motion stage.

3. Results and discussion

Microscope images of crystallized Si films on conventional and flexible glass substrate are shown in Fig. 2. Laterally grown large Si grains are confirmed in both samples and the width of melt and regrowth regions was ~220 μm. Since the heat penetration depth in glass under the present μ-TPJ irradiation condition is estimated as ~17μm, which is much smaller than the substrate thickness, the maximum surface temperature is not dependent on glass thickness. After the melting and regrowth of a-Si, many cracks were observed in conventional glass. It has been reported that OH bonds in SiO_2 desorbed as H_2O molecules to form the cross-linked Si-O-Si network during URTA, which cause densification near the glass surface [2]. Residual tensile stress is generated by the densification and cracks occur when the glass surface can't endure the stress. On the contrary, to our surprise, no crack was observed in flexible glass as shown in Fig. 2. We performed crystallization under various μ-TPJ irradiation conditions and almost no crack was observed in flexible glass. This result suggests that thin flexible glass has high resistance against thermal stress.

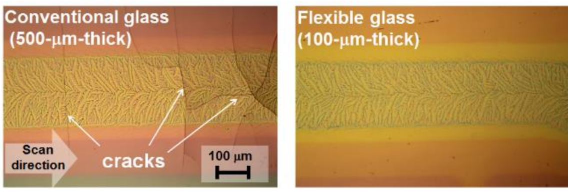

Fig. 2. Typical examples of surface microscope image taken after μ-TPJ crystallization of a-Si films on 500-μm-thick conventional glass (left) and 100-μm-thick flexible glass (right).

In order to better understand the experimental results, direct measurement of glass temperature during μ-TPJ irradiation and numerical calculations on residual stress were carried out. As the v becomes slower, the maximum surface temperature increases and heat penetration depth becomes larger. We assumed a bilayer model which has densified layer and remained glass layer as illustrated in Fig. 3(a). The shrinkage of glass surface was calculated according to previous report [3]. Then, the densified layer was expended with virtual external force and attached to the under layer (Fig. 3(b)). After the external force is released, two cases, namely, free deformation and constraint conditions are considered. For the former case, the amount of deformation as curvature radius is given by the following equations:

$$\frac{1}{R} = \frac{6t(L-l)}{(h_d^3+h_r^3)\left(\frac{l}{h_d}+\frac{L}{h_r}\right)+3(h_d l+h_r L)} \quad (1),$$

where R is radius of curvature, t is the total thickness of glass (100 μm or 500 μm), h_d and h_r are the thicknesses of densified and remained layers, respectively. L and l are the length of remained and densified layer under free shrinkage, respectively, as shown in Fig. 3 (a). We calculated residual tensile stress under the free deformation condition (eq. (2)) and constraint condition (eq. (3)).

$$\sigma_{d(free\ deformation)} = \frac{E(h_d^3+h_r^3)}{6h_d tR} \quad (2),$$

$$\sigma_{d(constraint\ condition)} = \frac{E(L-l)}{l+\frac{h_d}{h_r}L} \quad (3),$$

where E is Young's modulus. In order to verify the validity of this model, the amount of deformations of the conventional and flexible glass substrates after μ-TPJ irradiation was calculated based on Eq. (1) and compared with experimentally obtained displacement measured by a stylus. The calculated deformations reproduce the measured results well. This result indicates the present stress model is acceptable.

On the basis of present model, residual tensile stresses of conventional and flexible glass substrate under constraint condition are calculated and the result is shown in Fig. 4. We observed cracks in conventional glass beyond the residual

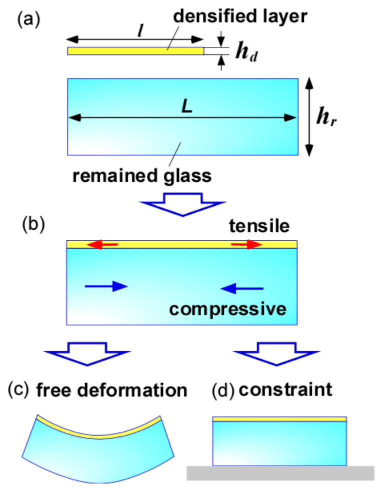

Fig. 3. Schematic illustration of physical model describing the calculation of residual tensile stress at the glass surface. Two final conditions of free deformation and constraint are considered.

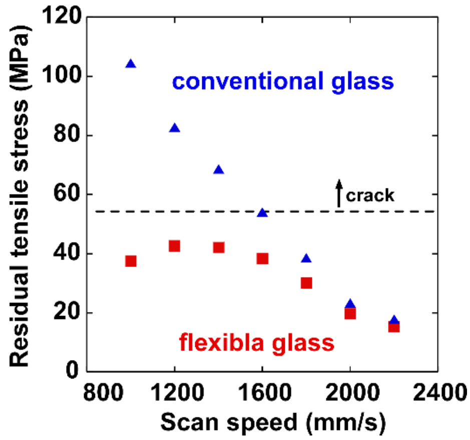

Fig. 4. Residual tensile stress at the glass surface under constraint condition calculated for conventional and flexible glass.

stress threshold of 54 MPa. (In general, fracture strength of glass is about 50 – 100 MPa [4].) On the other hand, the maximum residual tensile stress was 43 MPa in flexible glass. Residual tensile stress of flexible glass does not exceed the threshold value and no crack occur. In the experiment, the glasses are fixed on the stage, and the residual stress should be explained based on the constraint model (eq. (3)). With decreasing v, the glass surface temperature increases and heat penetration depth increases as well. Therefore, l becomes smaller and h_d/h_r also becomes smaller. The numerator of eq. (3) is the same for both conventional and flexible glass for same v. On the contrary, the h_d/h_r term in the denominator is much different in conventional and flexible glass, because the flexible glass thickness is 5 times smaller. This tells us that the ratio of densified and remained layer thickness is the key factor that determine the residual stress value. This is because the two layers balances the shrinkage force and resistive force against as shown in Fig. 3(b). Since the resistive force of flexible glass is small because of small remained layer thickness. As the result, the maximum residual stress saturates as shown in Fig. 4.

4. Conclusions

We have clarified the mechanism of extremely high resistance of thin flexible glass against thermal stress induced by URTA on the basis of experimental and analytical approaches. Thin flexible glass is useful for device fabrication.

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