Process Analysis and Optimization on PECVD Amorphous Silicon on Glass Substrate

Yan Ying Ong\textsuperscript{1,2}, Bang Tao Chen\textsuperscript{2}, Francis E.H. Tay\textsuperscript{1,2} and Ciprian Iliescu\textsuperscript{2}

\textsuperscript{1} Department of Mechanical Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260
\textsuperscript{2} Institute of Bioengineering and Nanotechnologies, 31 Biopolis Way, The Nanos, #04-01, Singapore 138669

Email: btchen@ibn.a-star.edu.sg

Abstract: In this paper, depositing of low stress Amorphous Silicon (\(\alpha\)-Si) with high deposition rate by using a plasma-enhanced chemical vapour deposition (PECVD) system (STS, Multiplex Pro-CVD) was studied. The influence of the process parameters, such as power, frequency mode, argon flow rate, temperature and pressure, on these objectives have been studied and optimized. RF modes (13.56 MHz and 380 kHz) have obvious influence on the deposition rate of amorphous silicon, which revealed that high RF mode provide higher deposition rate, but not certain on the residue stress. The power has a proportional relationship to the deposition rate, and also, is proportional to stress induced at high RF mode, so low power is preferred for low stress film. At high RF mode, the deposition rate decreases with temperature while stress increases. By increasing the gas flow rate of argon, the film stress is found to decrease for both RF modes, while the deposition rate decreases for the low RF mode. Lastly, at high RF mode, pressure is also proportional to deposition rate and stress (compressive). The proper process conditions were optimized to get the low stress \(\alpha\)-Si. The application of \(\alpha\)-Si sacrificial layer in the glass etching process is also briefly highlighted and illustrated at the end of this paper.

Keywords: amorphous silicon; PECVD; low stress; deposition rate

1. Introduction

Amorphous silicon layers (a-Si:H) are used in diverse application such as image sensors [1] and solar cells [2], active matrix displays [3], electrophotography [4]. The deposited a-Si:H films are often used as sacrificial and masking layer on glass substrate due to its resistance towards HF based solution [5]. In other applications, a-Si:H films serve as a very competent sacrificial layer because of its easy removal by well-developed technology such as wet etching in alkaline solution (TMAH or KOH) or, to avoid stiction problem, dry etching (using XeF\textsubscript{2} or SF\textsubscript{6} gas).

There are three well-established methods for silicon thin film deposition: chemical vapor deposition (CVD), plasma enhances chemical vapor deposition (PECVD) and physical vapor deposition (PVD). The CVD methods assure a conformal deposition under the condition where the growth is limited by the surface reaction. For this reason a high temperature is necessary for a high deposition rate. The application of this method to glass is somehow limited by the annealing point of the glass (usually 500-600\(^\circ\)C), which is in a similar range with the deposition of polysilicon layer in...
low-pressure CVD systems. PVD system presents poor sidewall coverage due to the large distance between the source and the substrate, while the deposition is made at room temperature, usually with a low deposition rate. On PECVD reactors, the a-Si:H films are deposited at a relatively low temperature (around 300°C). The films present a good adhesion, good step coverage, high deposition rate and also a high quality.

Previous studies regarding PECVD a-Si:H layers reports high deposition rate on insulating Corning #7059 glass, diamond and sapphire substrates as compared to the conductive Al and Ge substrates [6]. In addition, Chung et al [7] reported an increased deposition rate of a-Si:H for both RF modes (380 KHz and 13.56 MHz). Besides deposition rate, defect density is also a very crucial property as it may affect the functionality and reproducibility of the devices. Not only so, it can also become a very crucial property especially when smooth MEMS microstructure is desired. Tsai et al [8] reported that minimum defect density was found when deposition is performed using pure SiH₄ gas and lower power. Stress induced during the deposition can also affect the sensitivity, accuracy, precision and functionality of the device, thus, in some applications, is important to ensure a low residual stress in the thin layer. The main methods for stress control in silicon layer are by doping or annealing [9,10].

In this paper, we have studied the influence of process parameters such as power, frequency mode, Argon flow rate, temperature and pressure, on the deposition rate and stress induced in the thin a-Si:H layer.

2. Experimental procedure

The deposition of a-Si:H layers were performed using a PECVD system (STS, Multiplex Pro-CVD, UK). A schematic diagram of the equipment is presented in [7]. A characteristic of the system is that the plasma can be activated in two RF modes: low frequency (LF) at 380 kHz and/or high frequency (HF) at 13.56 MHz. Another important characteristic of the equipment is that offer the opportunity of selecting the power in a large range: 0 to 600 W for HF and 0 to 1 kW for LF. The depositions of the layers were performed using pure SiH₄ and argon Ar.

For characterization of the deposited layers, 4” glass wafers (Corning7740) were used as the substrates. The wafer were initially cleaned in Pirhana (H₂SO₄:H₂O₂ in the ratio of 20:1) at 120°C for 20 minutes, rinsed in DI water and spin-dried. The stress characterization of the a-Si:H films was performed with a stress measurement system (KLA Tencor FLX-2320, USA). 100 nm-thick Al layer was deposited by sputtering in a LSVO- Unaxis system on the both surface of the wafer for the initial curvature measurement of the wafers. The stress measurement method of the thin layers deposited on glass wafer is presented in [5]. After the measurement of the wafer curvature the Al thin layer was removed in a classical Al etchant and the wafers were cleaned again. The thickness of the a-Si:H films, the uniformity and the refractive index was measured with a refractometer (Filmetrics F50, USA).

3. Experiments and discussion

3.1 Temperature influence

The first set of experiments was performed in order to understand the influence that the temperature of the substrate exhibits on residual stress and deposition rate for the two RF modes (HF and LF). For these experiments the conditions were: constant power at 300W, constant pressure at 900 MPa, SiH₄ flow rate of 120 sccm and Ar flow rate 700 sccm. The experiments were carried out at four different temperatures: 200°C, 250°C, 300°C and 350°C.

Figure 1 represented the stress and deposition rate for HF and RF modes at a deposition power of 300W, relatively similar variation was observed for the other value of power. For both RF modes the residual stress is compressive. While for LF mode the stress is in a wide range (between 320 and 450 MPa) with increased values at lower temperature, for HF mode a significant low stress value was achieved at 200°C. For this temperature at a power of 100W a tensile stress was generated in the thin
layer (40 MPa). For the deposition rate we can observe that the values for HF mode are sensitively increased comparing with LF mode due to a better dissociation of the SiH$_4$. Also, for LF mode the variation of the deposition rate is not very relevant, while for all the deposition performed at 200°C in HF mode a high deposition rates was noticed. Usually an increased temperature of the substrate improves the reaction on the substrate surface and a high deposition rate can be achieved. The decreasing of the deposition rate when the substrate temperature was increased from 200°C to 250°C. This can be explained by generation of the “microcrystalline” amorphous silicon (µc-Si) reported also in [6] and [11]. The presence of µc-Si can explain also the variation of the stress in HF mode, with an almost constant value at temperature greater than 250°C.

3.2 Influence of the deposition power

Another set of experiments was performed in order to understand the influence of the power. However, for these experiments the conditions were: constant temperature at 300 °C, constant pressure at 900 MPa; SiH$_4$ flow rate of 120 sccm and Ar flow rate 700 sccm.

As was expected, for an increased power, a high deposition rate is achieved for both RF modes. A high power can be associated with a high rate of gas dissociation, which leads for more reactive species in the plasma with direct effect on increasing of deposition rate. From Figure 2(a), we can observe that the deposition rate and stress (compressive) increases with the power for the HF mode. Meanwhile, for the LF mode (Figure 2(b)) there is a linear increasing of the deposition rate with the
power. The “strange” variation of the stress for this mode can be explain by the small stress band (the measurement errors presents a strong influence), so we can conclude that for this mode the stress is almost constant (is not influence by power). The strongly dependence of the deposition rate on the power can be explain by the increased dissociation of SiH₄. The relatively constant stress in LF mode is a result of ion bombardment that characterizes plasma at low frequency. At high frequency (more then 1 MHz) the ions cannot follow the frequency due to their inertial mass. For this reason deposition at LF is associated with a bombardment of the thin layer with effect on densification and stress.

3.3 Influence of Ar flow rate

The experimental conditions for these experiments are: constant power at 450 W, constant temperature at 300 °C, constant pressure at 900 mTorr and SiH₄ flow rate of 120 sccm. The depositions were performed for Ar flow rates of 0 sccm, 350 sccm and 700 sccm.

![Figure 3. Influence of the Ar flow rate for HF (a) and LF (b) modes with the intrinsic stress induced and the deposition rate](image)

From Figure 3(a), it can be observed that the Ar flow rate doesn’t have a strong influence on deposition rate and stress for the HF mode (somewhat normal, due to the fact that at this frequency the Ar ions are “froze” due to their inertial mass). Meanwhile for the LF mode an increased Ar flow rate has a negative effect on the deposition rate (ion bombardment and etching) while the stress value decreases significantly.

3.4 Influence of pressure

Lastly, the influence of the pressure in the reactor chamber was investigated. The experimental conditions were: constant temperature at 300 °C, constant power at 450 W, SiH₄ flow rate of 120 sccm and Ar flow rate 700 sccm. In this case, pressure is varied from 600-1000 mTorr with an interval of 100 mTorr.

From Figure 4(a), deposition rate presents a maximal point for 900 mTorr for HF mode while the induced stress is reduced for low values of pressure. When the pressure increases, the reactant gases, charged and energetic species are packed more closely together. Thus, the probability of their colliding onto one another also increases. This will hence increase the number of effective collision, association and dissociation too. As a result, in a first phase the deposition rate increases. In a second phase, if the pressure continues to be increased the number of collisions continues to increase but not their reaction with the substrate as a result the deposition rate can decrease after an optimal value of pressure. For the LF mode the optimal frequency for a high deposition rate is 700 mTorr, while relatively low values of stress can be achieved at high pressure.
4. Application in glass wet etching

In MEMS devices fabrication, glass is the second most widely used material, after silicon. Among all the available glass etching processes, the wet chemical etching using hydrofluoric-based solutions remains one of the most low-cost and effective solutions. The masking layer depends on the application and the "thermal budget" of the fabrication process of the device. There are three major groups of masking materials: photoresist, metal and silicon. Photoresist and metal mask are restricted by the poor resistance in HF solution and generally used for glass etching of less than 100 µm [12, 13]. Silicon is an inert material in HF-based solutions. It also has the advantage of being a hydrophobic material. Hence, the penetration of etchant through the small impurities of the mask is relatively difficult. The amorphous silicon masking layer presents the advantage of deposition at low temperatures PECVD, but as we analyzed in [14], the high value of compressive stress induced in this layer (400-600 MPa) limits its application of deep glass etching, which will induce the pinholes and notch defects in the glass. Our study has optimized the PECVD amorphous silicon layer with low stress, and can be used for the glass deep etching of 100 µm above. Figure 5 and figure 6 showed the glass wet etching with amorphous silicon mask, etching for 100 and 150 µm, respectively. To get deeper etching of glass substrate without defects, other material will be needed. For example, with combination of amorphous silicon and silicon carbide layer, the glass can be etched up to 1 mm deep without significant defects [15].
5. Conclusions

The properties of amorphous Silicon films are often affected by the process parameters and conditions. In the present work we analyze the influence of the deposition parameters on the deposition rate and the stress for a-Si:H layers. The conclusions of the investigation can be summarized as:

For LF mode
- The residual stress in the a-Si:H depositions highly compressive (usually 320-400 MPa, but also values greater than 500 MPa were achieved).
- The power and the temperature of the substrate have no influence (due to the densification of the layer caused by ion bombardment).
- The dilution with Ar decreases the deposition rate but reduces the stress.

For HF
- a-Si:H depositions at HF generate a high deposition rate due to the high dissociation of SiH₄.
- The depositions of low temperature (200°C) generate a low stress layer with a good deposition rate.
- Increasing the power the deposition rate and also the stress increase.
- The optimal pressure in the chamber can be considered to be around 800 mTorr.

We can conclude that for a low stress a-Si:H layer with a good deposition rate the recommended temperature of the chuck is 200°C, pressure in the chamber 800 mTorr, at a Power of 100 W, a SiH₄ flow rate of 120 sccm and Ar flow rate of 350 sccm, in high RF mode.

References

[1] K.S. Karim, P. Servati, N. Mohan, A. Nathan, J.A. Rowlands 2001, IEEE Int. Symp. On Circuits and Systems, vol. 5, 479-482.
[2] Senft, Donna Cowell, *Journal of Electronics Material*, 2005.
[3] Kuo, Y., Okajima, K., Takeichi, M., *IBM Journal of Research and Development*, Jan-Mar 1999.
[4] A.C. Tam, R.D. Balanson, “Lasers in Electrophotography”.
[5] C. Iliescu, J.M. Miao, F.E.H. Tay 2005, *Surface and Coatings Technology*, vol. 192/1, 42-47.
[6] Kondo M, Toyoshima Y, Matsuda A and Ikuta K 1996, *J. Appl. Phys.* vol 80, 6061-6063.
[7] C. Chung, M.Q, Tsai, P.H. Tsai and C. Lee 2005, *J. Micromech. Microeng.* 15 136-142.
[8] C.C. Tsai, J.C. Knights, G. Change and B. Wacket, *J. Appl. Phys.*, 59 B2998-3001.
[9] L. Chen, J. Miao, L. Guo, R. Lin 2001, *Surface and Coatings Technology*, vol. 141/1, 96-102.
[10] C. Iliescu, J.M. Miao, F.E.H. Tay 2005, *Sensors and Actuators A*, vol. 117/2, 286-292.
[11] A. Madan 2005 “Amorphous Silicon – from doping to multi-billion dollar applications” *Proc. ICANS21*, Lisbon, Portugal, 2005.
[12] D.C.S. Bien, et al, Characterization of masking materials for deep glass micromachining, *J. Micromech. Microeng.*, 13, S34-40, 2003.
[13] S. Shoji, H. Kikuchi and H. Torigoe, Low-temperature anodic bonding using lithium aluminosilicate-β-quartz glass ceramic, *Sensors and Actuators A*, 64, 95-100, 1997.
[14] E. Belloy, et al, The introduction of powder blasting for sensors and microsystem application, *Sensors and Actuators A*, 84, 330-337, 2000.
[15] C. Iliescu, B. Chen, et al, Characterization of deep wet etching of glass, *Proceedings of SPIE* 6037, 60370A, 2005.