APPENDIX A

ERROR ANALYSIS

Consider Z as a known function of several quantities A, B and C,

$$Z = Z(A,B,C) \qquad \text{...(A0.1)}$$

Then the standard error in Z, ΔZ is given by [1]

$$(\Delta Z)^2 = (\Delta Z_A)^2 + (\Delta Z_B)^2 + (\Delta Z_C)^2 \qquad \text{...(A0.2)}$$

where
$$\Delta Z_A = \left(\frac{\partial Z}{\partial A}\right)\Delta A \qquad \text{...(A0.3)}$$

$$\Delta Z_B = \left(\frac{\partial Z}{\partial B}\right)\Delta B \qquad \text{...(A0.4)}$$

$$\Delta Z_C = \left(\frac{\partial Z}{\partial C}\right)\Delta C \qquad \text{...(A0.5)}$$

and ΔA, ΔB, ΔC are the standard error in variables A, B and C respectively.

A1 Error of Refractive Index, Δn

From equation 4.6, the refractive index of the film is given by

$$n = \sqrt{N + \sqrt{N^2 + n_s^{\ 2}}} \qquad \text{...(A1.1)}$$

where
$$N = \left(\frac{n_s^{\ 2} + 1}{2}\right) + 2n_s\left(\frac{T_{\max} - T_{\min}}{T_{\max}T_{\min}}\right) \qquad \text{...(A1.2)}$$

Considering the refractive index of the substrate, n_s as a constant, equation A6 is a function of two variables

$$n = n(T_{\max}, T_{\min}) \qquad \text{...(A1.3)}$$

Therefore the standard error in n, Δn can be stated as

$$(\Delta n)^2 = (\Delta nT_{\max})^2 + (\Delta nT_{\min})^2 \qquad \text{...(A1.4)}$$

where $$\Delta nT_{\max} = \left(\frac{\partial n}{\partial T_{\max}}\right)\Delta T_{\max} \qquad \text{...(A1.5)}$$

$$\Delta nT_{\min} = \left(\frac{\partial n}{\partial T_{\min}}\right)\Delta T_{\min} \qquad \text{...(A1.6)}$$

However it is quite arduous to evaluate $\left(\frac{\partial n}{\partial T_{\max}}\right)$ and $\left(\frac{\partial n}{\partial T_{\min}}\right)$. For this reason an alternative method [2] which is less laborious and has equivalent accuracy is used. From equation A1.5, $\Delta nT_{\max}$ indicates the value of n when $T_{\max}$ changes by an amount $\Delta T_{\max}$ while $T_{\min}$ is a constant, hence

$$\Delta T_{\max} = n(T_{\max} + \Delta T_{\max}\,,\ T_{\min}) - n(T_{\max}\,,\ T_{\min}) \qquad \text{...(A1.7)}$$

and in the same way

$$\Delta T_{\min} = n(T_{\max},\ T_{\min} + \Delta T_{\min}) - n(T_{\max}\,,\ T_{\min}) \qquad \text{...(A1.8)}$$

$\Delta T_{\max}$ and $\Delta T_{\min}$ are then combined as in equation A1.4 to calculate the value of Δn. By taking $\Delta T_{\max}$ and $\Delta T_{\min}$ = 0.5%, the standard error in the refractive index values obtained for all samples, $\frac{\Delta n}{n} \leq 0.01$.

A2 Error of Film Thickness, Δ*d*

From equation 4.1,

$$d = \frac{m\lambda}{2n} \qquad \text{...(A2.1)}$$

therefore the standard error in the film thickness, Δd is given by

$$(\Delta d)^2 = \left[\left(\frac{\partial d}{\partial m}\right)\Delta m\right]^2 + \left[\left(\frac{\partial d}{\partial \lambda}\right)\Delta\lambda\right]^2 + \left[\left(\frac{\partial d}{\partial n}\right)\Delta n\right]^2 \qquad \text{...(A2.2)}$$

where Δm, $\Delta\lambda$ and Δn are the standard error in order of the fringes, the wavelength and the refractive index of the film respectively.

the standard error in the wavelength can be calculated as

$$\Delta\lambda = \sqrt{\frac{\sum_{i=1}^{N}(\lambda_i - \lambda_{Avg})^2}{N(N-1)}} \qquad \ldots(A2.3)$$

$\frac{\Delta d}{d}$ values for all samples are less than 0.07.

A3 Error of Optical Energy Gap, ΔE_g

From equation 4.27, the strong absorption region in an amorphous semiconductor can be expressed as

$$\alpha E = A(E - E_g)^2 \qquad \ldots(A3.1)$$

hence the E_g value can be calculated from a Tauc's plot of $\sqrt{\alpha E}$ versus E

$$E_g = \frac{c}{m}$$

where c and m are the intercept and gradient of the graph respectively.

Therefore, the standard error in E_g is

$$\frac{\Delta E_g}{E_g} = \sqrt{\left(\left(\frac{\Delta c}{c}\right)^2 + \left(\frac{\Delta m}{m}\right)^2\right)} \qquad \ldots(A3.2)$$

It is found that the standard error in E_g as determined from the Tauc's plot, $\frac{\Delta E_g}{E_g} \leq 0.02$ for all samples.

A4 Error of Hydrogen Content, ΔH%

To calculate the error of hydrogen content in the film, other standard error need to be calculated such as $\Delta\omega_o$, ΔS_{band}, ΔI and ΔN_H, which are correspond to standard error in the wavenumber, the S_{band}, the integrated intensity and the atomic density of hydrogen respectively.

The error of wavenumber, $\Delta\omega_o$:

$$\Delta\omega_o = \sqrt{\frac{\sum_{i=1}^{N}\left(\omega_i - \omega_{Avg}\right)^2}{N(N-1)}} \qquad \ldots(A4.1)$$

The error of S_{band}, ΔS_{band} can be calculated from equation 4.35,

$$S_{band} = \frac{A\sqrt{\pi}}{\sqrt{B}} \qquad \ldots(A4.2)$$

therefore

$$\frac{\Delta S_{band}}{S_{band}} = \sqrt{\left(\left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta B}{B}\right)^2\right)} \qquad \ldots(A4.3)$$

A, ΔA, B and ΔB can be calculated by using equation 4.38,

$$\ln(y) = \ln(A) - B(\omega - \omega_o)^2 \qquad \ldots(A4.4)$$

where $\ln(A)$ and B are the intercept and slope of the plot $\ln(y)$ versus $(\omega - \omega_o)^2$ respectively. The value of A, ΔA, B and ΔB can be acquired from the regression of the plot at the selected region.

The error of integrated intensity, ΔI can be determined from equation 4.40,

$$I = \frac{S_{band}}{\omega_o} \qquad \ldots(A4.5)$$

hence

$$\frac{\Delta I}{I} = \sqrt{\left(\left(\frac{\Delta S_{band}}{S_{band}}\right)^2 + \left(\frac{\Delta\omega_o}{\omega_o}\right)^2\right)} \qquad \ldots(A4.6)$$

The error of the atomic density of H, ΔN_H can be distinguished from this equation,

$$N_H = I \times \left(1.60 \times 10^{19}\right) \qquad \ldots(A4.7)$$

so

$$\Delta N_H = \Delta I \times \left(1.60 \times 10^{19}\right) \qquad \ldots(A4.8)$$

The hydrogen content, $H\%$ in the a-Si:H film can be determined from this expression

$$H\% = \left(\frac{N_H}{5 \times 10^{22}} \right) \times 100\% \qquad \text{...(A4.9)}$$

Hence, the error of hydrogen content, $\Delta H\%$ is

$$\Delta H\% = \left(\frac{\Delta N_H}{5 \times 10^{22}} \right) \times 100\% \qquad \text{...(A4.10)}$$

$\frac{\Delta I}{I}$ for all samples are between 0.07 and 0.16. So the values of $\frac{\Delta H\%}{H\%} \leq 0.2$ for all samples.

A5 Error of Microstructure Parameter, ΔR

The microstructure parameter, R is given by this equation

$$R = \frac{I_{2090}}{I_{2090} + I_{2000}} \qquad \text{...(A5.1)}$$

So the error of microstructure parameter, ΔR is

$$\frac{\Delta R}{R} = \sqrt{\left(\left(\frac{\Delta I_{2090}}{I_{2090}} \right)^2 + \left(\frac{\Delta I_{2000}}{I_{2000}} \right)^2 \right)} \qquad \text{...(A5.2)}$$

where ΔI_{2000} and I_{2090} are the error of integrated intensity at 2000 cm^{-1} and 2090 cm^{-1} respectively.

$\frac{\Delta R}{R}$ are found to be less than 0.02 for all samples.

A6 Error of Dark-conductivity, Δσ

From equation 4.42,

$$\sigma = \frac{I}{V}\frac{L}{A} = (Slope)\frac{L}{t \times W}$$

Hence, the error of dark-conductivity, $\Delta\sigma$ is

$$\left(\frac{\Delta\sigma}{\sigma}\right)^2 = \left(\frac{\Delta Slope}{Slope}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta W}{W}\right)^2$$

The values of $\frac{\Delta\sigma}{\sigma} \leq 0.07$ for all samples except for the sample with He:$SiH_4 = 5$ where the $\frac{\Delta\sigma}{\sigma}$ value is quite big.

References:

1. E. Armitage, "Practical Physics in SI", John Murray (1983).
2. G. L. Squires, "Practical Physics", McGraw-Hill Book Co., 2/e (1976) 36-37, 50-52.

APPENDIX B

PARAMETERS DETERMINED FROM FTIR SPECTROSCOPY

Parameters	He:SiH$_4$					
	0	1	2	3	4	5
ISiH (±5)	44	62	56	49	44	31
ISiH$_2$ (±4)	57	19	16	16	12	9
H% (±2)	7	13	12	12	10	7
R (±0.004)	0.564	0.232	0.223	0.242	0.219	0.211

APPENDIX C

PARAMETERS DETERMINED FROM AFM SPECTROSCOPY

Parameters	He:SiH_4					
	0	1	2	3	4	5
Surface Roughness on glass substrate (±0.5)	13.9	6.6	11.6	9.2	3.9	5.9
Surface Roughness on c-Si substrate (±0.5)	12.8	13.8	8.7	6.9	2.9	4.3

APPENDIX C

PARAMETERS DETERMINED FROM AFM SPECTROSCOPY

Parameters	He:SiH_4					
	0	1	2	3	4	5
Surface Roughness on glass substrate (±0.5)	13.9	6.6	11.6	9.2	3.9	5.9
Surface Roughness on c-Si substrate (±0.5)	12.8	13.8	8.7	6.9	2.9	4.3

APPENDIX D

PARAMETERS DETERMINED FROM OPTICAL SPECTROSCOPY

Parameters	He:SiH$_4$					
	0	1	2	3	4	5
Deposition rate on glass substrate (±0.9)Å/s	1.4	4.1	3.5	3.7	2.5	2.7
Deposition rate on c-Si substrate (±1.5)Å/s	10.0	12.5	11.2	11.7	9.9	9.1
Refractive Index (n±0.02)	2.46	2.76	2.97	2.99	2.76	2.59
Optical Energy Gap (E_g±0.03)eV	2.10	1.79	1.77	1.75	1.78	1.79
Non-silicon Atom Content (I%±3)	28	23	13	11	15	12
Urbach Energy Gap (±0.002)eV	0.088	0.043	0.039	0.041	0.055	0.038

APPENDIX E

PARAMETER DETERMINED FROM I-V MEASUREMENT

Parameter	He:SiH_4					
	0	1	2	3	4	5
Dark-conductivity $(\sigma\pm1)\times10^{-7}\ \Omega^{-1}cm^{-1}$	5.7	1.3	1.9	6.5	14.0	1.1