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Reduction of Reflectivity of glass surface of solar photovoltaic modules through chemical means

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***Abstract:** In crystalline silicon solar cell module, the main losses of power due to reflectance of photon from the module glass surface. Generally, it's reflecting 8% to 9% of photon which affected the overall solar cell efficiency. So, our endeavor is to develop economically low-cost anti reflection coating on glass substrate and reduce the reflection losses or improves the transmittance of solar module glass subtract. After chemical treatment and environment impact overall achieved approximate 2% -3% increment of transmittance of solar module glass substrate.*

***Key words:** Wavelength, Refractive Index, Reflectivity, Transmission*

I. INTRODUCTION

One of the main loss mechanisms that any kind of Photovoltaic module is subjected to is the loss from the glass aperture on the entrant side. This is applicable for both conventional Si based module as well as thin film-based cell/module; in addition solar heating modules are also subjected to these losses. As much as 8% of the incident light can be lost due to frontal reflection. Thus, one of the aims of Photovoltaic industry has been to find out an effective and economical way to improve the transmission profile of glass used in existing production process. Broadly speaking, there are two kinds of techniques that are available for increasing in transmission of glass; 1) interference technique, achieved by deposition of anti reflection coating on glass surface and 2) developing a graded refractive index profile at the surface of glass. In the first method one needs multiple layers for making a broadband transmission window; also the increase in transmission is inversely proportional to incidence angle and decreases drastically at lower angle of incidence. The method is also expensive to produce and lastly and very important from Solar application point of view, this method suffers from environmental degradation severely. The second method, property of which was first enunciated by Lord Rayleigh [1] involves chemical action on the surface of a glass, which causes selective etching/leasing of ions in the glass to cause a porous structure on the surface. The structure thus formed is non-uniform so that the refractive index formed is not linear but takes on a graded form and this causes a reduction in reflectance from the surface. This technique also has the potential to be cost effective from the point of view commercial manufacturing of solar panels.

The detail of this process was first described by Kinoshita [2] and has been subsequently improved upon by various and researchers such as Nakajima [3] and Mader [4]. However, the above method and process described by all these authors are general in nature and does not address the key issue of developing a stable process for application in the solar industry. Considering the fact that process stability is one of the crucial factors for any type of photovoltaic application, we decided to relook this technique specifically from this viewpoint and developing a dependable process set which could be used for reliable prototype samples. The paper describes results of experiments that we have conducted to study the change in transmission properties of glass over the entire visible wavelength range after chemical etching and also describes the effect of annealing on such chemically treated glass.

The paper is arranged as follows. In the first section, we describe the basic theory as to how reflection losses are reduced by modification of refractive index. In the second section, chemical action on glass surface is described. In the third section the salient features of this method are explained and in the fourth section, effects of process parameter are described. The fifth section describes the actual work performed. This is followed by description of result obtained and comparison with the theoretical prediction and discussion.

II. BASIC PRINCIPLE

Light, when incident from one medium (of RI n1) to another medium (of RI n2), is partly reflected and partly transmitted. Assuming a non-magnetic media, the reflection and transmission coefficient at near normal incidence is given by eq. (1)

$$R = R_s = R_p = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \quad (1)$$

For a common glass R is about 4%. However, when reflection from top and bottom surfaces are considered the total reflection is 2R/(1+R).

Now, from eq. (1) it is clear that in order to reduce R we need to reduce the difference between n1 & n2. Technically this is achievable by a having a layer of RI in between n1 & n2. There are various ways to achieve the same such as by chemical etch-leach process, sol-gel method and other process5. In the first process of chemical-etch leach, which we have followed, the surface of glass is chemically treated in such a way that some tens of nanometers of the surface of the glass is leached/etched away to make a porous structure having a RI lying between that of air and glass. Thus, difference between the RI is reduced resulting in reduction in the Reflection coefficient. In reality, the RI of the porous layer is not uniform but is graded which further enhances the anti reflection property. This is shown schematically below in fig 1:

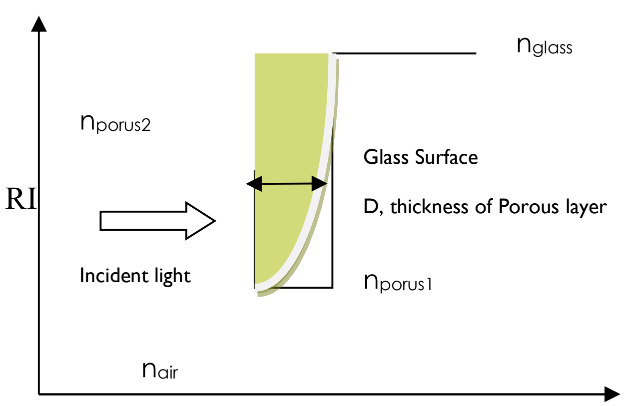


Fig 1

Assuming an actual case where the porosity formed is non-isotropic along the direction of the incident light, the reflection coefficient R is linked to the wavelength2,3 assuming normal incidence

$$R = 1 - \frac{4N_g N_a N}{(N_a N_g + N^2)^2 - (N_a^2 - 1)(N^2 - N_g^2)\sin^2(\frac{\delta}{2})} \quad (2)$$

Where $\delta = 2\pi(Na + Ng)D/\lambda$, N being the RI of glass, Na = RI of outer surface of coating, Ng = RI of glass interface, λ the wavelength of light & D is coating thickness.

At the point of minimum reflection

$$D = \lambda_{-min} / 2(N_a + N_g) \quad (3)$$

λ_{-min} is the wavelength where minimum reflectance (or maximum transmittance) occurs

Thus, $\lambda_{-min} \propto$ path length $\equiv \lambda_{-min} \propto D$

If λ_{-min} & N_a & N_g are known from experimental data then D can be calculated.

We have simulated the transmission spectra of the treated glass and studied its dependence on refractive index of the glass and on coating thickness. While the refractive index of the glass was used for this plot were the standard values, the data given in ref(2) was used for the other parameters. The result is shown in Fig 2. For comparison we have included the transmission spectra of an untreated glass also as shown in Fig 3.

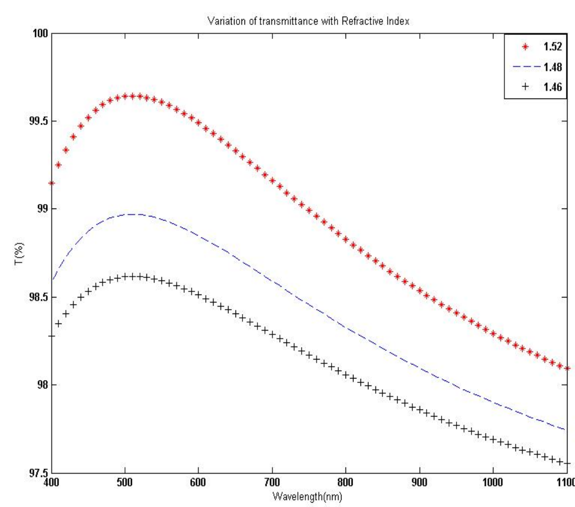


Fig 2

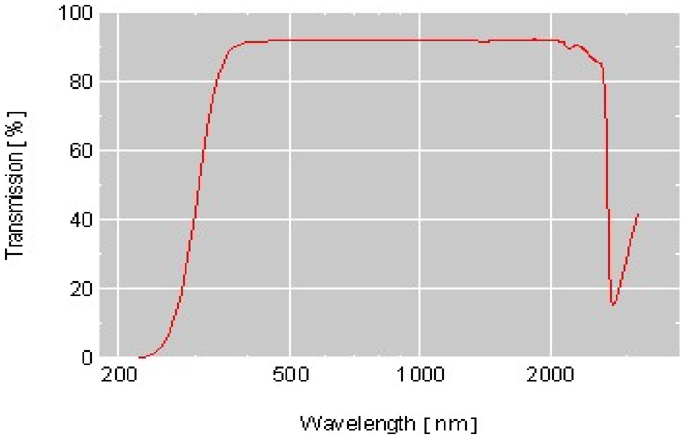


Fig 3

Fig 2 shows the variation of the spectra with refractive index (BK-7 crown glass RI=1.52, Fused silica R=1.46 and LEBW Low expansion Borosilicate glass RI=1.48). The nature of the profile remains the same for all types of glasses however, there is change in transmittance, especially the peak transmittance, which is different for different type of glasses. Although, the difference is small (~ 1%) for certain applications such as those related to Photovoltaic related this change can be significant. Thus, it indirectly implies change in transmittance will vary from glass to glass.

Fig 4 shows the surface plot of transmittance spectra as a function of etch depth.

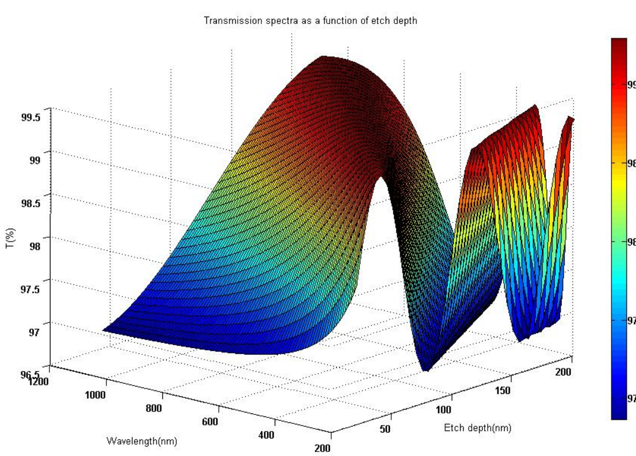


Fig 4

This result indicates that peak transmittance is a function of etch depth and that transmittance peaks only for a particular set of wavelengths and etch depth combination. This means, that depending upon the requirement at which peak transmission occurs, etch depth requirement will change and hence process conditions has to be changed accordingly.

We now describe below the basic chemical process that takes place on the glass surface.

III. CHEMICAL PROCESS

This section briefly describes the mechanism, which results in the formation of the porous layer when suitably treated. Glass, those used for optical purposes, typically contains SiO2 (65-75%), Alkali metal oxide (5-20%), Alkali earth metal oxide (0-15%) & other elements (0-5%) by wt. When treated suitably, the surface of the glass becomes porous upto a depth of hundreds of nanometers. In addition the glass surface may actually be etched out depending upon the process condition. As described earlier, in order to have a layer of intermediate refractive index we need to have a porous layer only. Also, from application point of view this layer needs to be physically stable. Lastly, the porous layer should exhibit antireflective behavior for a very broad wavelength range.

Two effects contribute to the formation of the overall effect:

A) *Leaching process:* This is formed when Protons in aqueous solutions replaces alkali ions in glass so as to form a Aoyake layer as shown

---Si----O----R + H_2O → ---Si---OH + R^+ + OH^- where R = Na, K Li etc

B) *Etching process:* The Si-O bond in the glass forming the skeleton, is destroyed and the glass is slowly dissolved.

----Si----O-----Si + OH^- →----Si----OH + ----Si-----

Depending upon the process condition, either of the process can be dominant. However, the porosity cannot be increased sufficiently if the leaching process is dominant so that the Refractive Index cannot be lowered sufficiently so as to obtain a really low Reflectivity. For the reverse case when etching process becomes dominant, again Refractive Index cannot be lowered sufficiently as dissolution of glass takes place resulting in weak formation porous layer. For satisfactory performance, these two processes should be roughly equal.

IV. SALIENT OPTICAL PROPERTIES OF GLASS THAT CAN BE MODIFIED BY THIS TECHNIQUE

The most important glass properties that we would like to address thorough this process are (i) minimum value of reflectivity (ii) absolute range of the wavelength (iii) λ_{min} corresponding to R_{min}.

(i) *Minimum value of reflectivity:* The minimum reflectivity depends upon the degree of leaching. In theory, if all the metal ions were leached out one can have the minimum reflectivity. In practice, this is not possible as this means un-acceptably long treatment time. However, lab scale experiments have reported reflectivity as low as 0.1%[3]. As we will show in the result section we have achieved (for a particular wavelength), transmission > 99.5%.

(ii) Wavelength range: It has been shown by theoretical modeling[2,3] that the wavelength range in which the reflectance is lowest is the combined effect of the leached metals.

(iii) *Minimum wavelength:* Consider the expression for reflectivity as defined in Equation 3. λ_{min} is a function of D and the intermediate Refractive Indices N_a and N_g(which are function of glass composition). Thus, the treatment time and glass composition will determine the value of λ_{min}. This also means that each type of glass will have different process conditions in terms of say treatment time, for having a particular λ_{min}.

V. CRITICAL PROCESS CONTROL PARAMETERS FOR OPTIMIZING THE OPTICAL CHARACTERISTICS OF GLASS

Concentration, temperature, pH, time and Surface to Volume ratio(S/V) are some of the important parameters that affect the process. Amongst this S/V ratio and process time are the critical parameters from the application point of view that we are looking into.

a) *Glass Surface area treated to Volume of treating solution ratio(S/V):* As reported by Mader[3] this is a very important parameter for the growth of porous layer. Mader reports that S/V ratio must be suitably selected so that the growth rate of the porous layer will be sufficiently slow so as to make the layer durable and uniform and make the process reproducible and controllable and according to him typical S/V ranges between 1/1000 cm^2/cm^3 upto 1/1 cm^2/cm^3.

b) *Treatment time:* This determines the wavelength at which reflection coefficient becomes minimum. This is because the thickness of the porous layer is proportional to the wavelength of minimum reflectance, which is in turn proportional to treatment time. Using the data of Nakajima[2] we have plotted a graph showing the variation of wavelength with time and time with S/V ratio is shown below in Fig 5 :

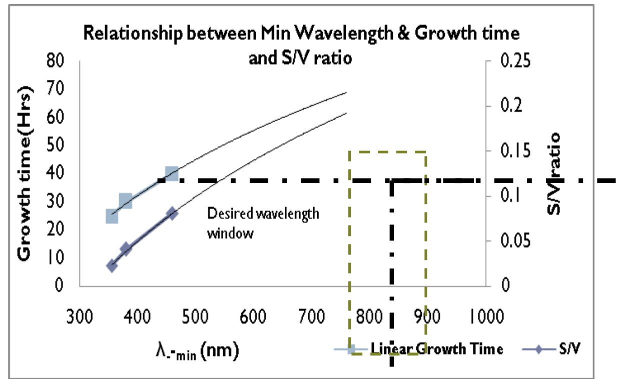
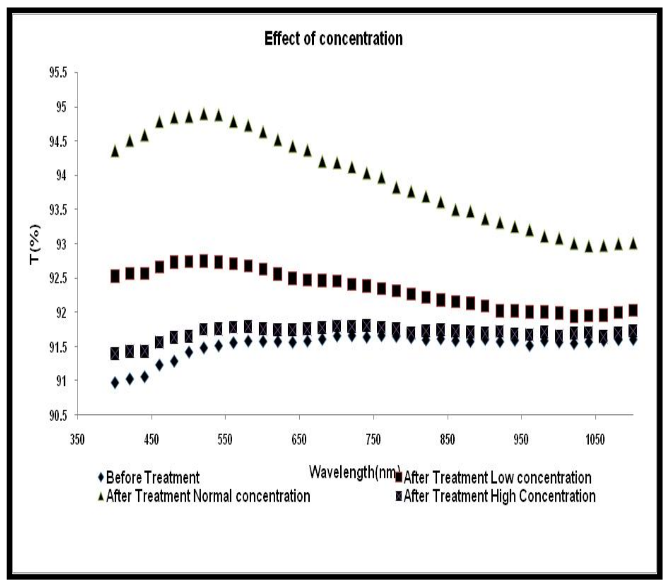


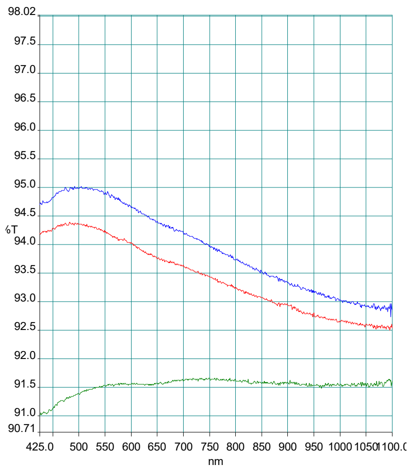
Fig 5

From this graph it is possible to deduce the process time required and the required S/V ratio to tune maximum transmittivity point at any desired wavelength .

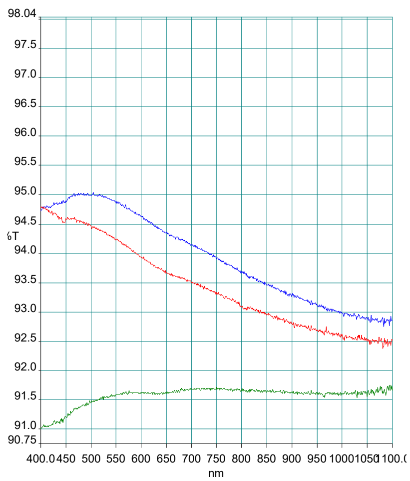
c) *Concentration* of *ARC solution* : Normal concentration of Al ions is required for increasing of transmittance, less concentration or higher concentration will be direct effect to process as look like as showing in graph



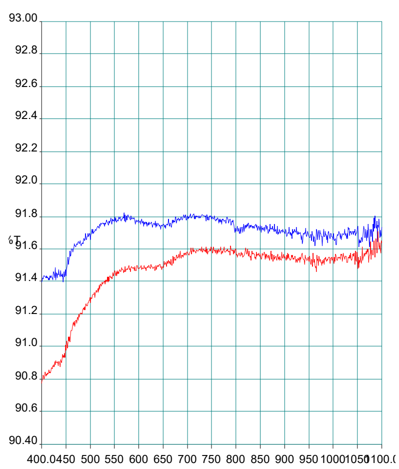
d) pH: pH also play important roll during process if experiment done with standard solution and constant treatment time following spectra indicates %T not increase in higher pH but in range of 7.0 to 8.3 pH it shows good result. We are not putting glass in lower pH because potassium silicate concentration variation.



pH=7.0



pH=8.20(Normally used)



pH=10.0

VI. EXPERIMENT

Having discussed the theory and the general process, we now describe in detail the experiments that we have conducted. The experiments were performed on toughen glasses(low iron glass). Conceptually, the experimental work can be divided up into following parts:

A. *Choosing a suitable form factor:* The form factor chosen was primarily dictated by the limitation of the testing devices ability to accept the required glass size. We have taken a form factor of 75mm x 25mm x 3.2mm for all our experiments.

B. *Cleaning of glass substrates*: Standard procedure was used for cleaning the substrates and includes sonicating with IPA & Acetone.

C. *Chemical* processing of substrate: Clean 1000 ml plastic beaker fitted with magnetic stirrer and pH meter. Add 500 ml DI water in the beaker. start magnetic stirrer and add accurate 2.5gm acetate salt after dissolve it add 2.5gm Hypophosphite salt . Prepared freshly 25ml 0.25M Al ions solution and take 1.5ml from stock and add in to plastic beaker solution and stirrer for 15 minute. After 15 minutes add weak base 'P' drop wise and adjust pH 7.0 to 8.20.After adjust pH, filtered the solution and check pH again if found less than 7.0 then maintain it with weak base. Prepared solution marked as solution –(1).Then start water bath and kept solution- (1) and maintain temperature 85'C.

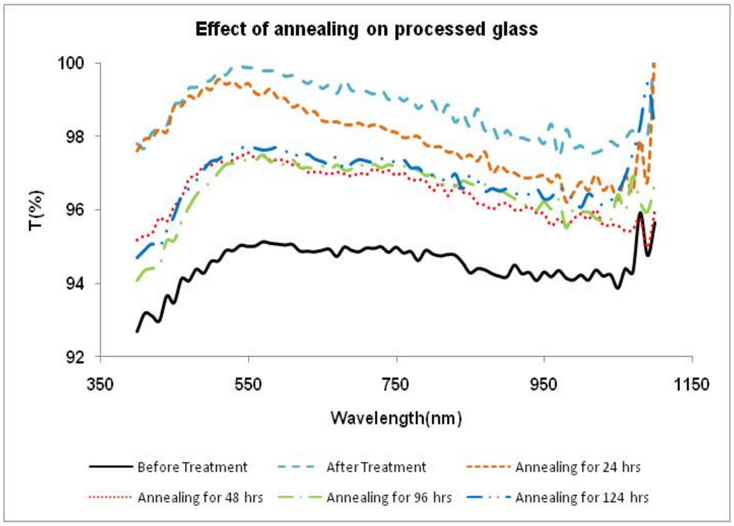
Pretreatment of glass (low iron glass)- First we measure surface area of glass, according it find out volume of solution- (1) by the *ratio* of S (surface)/V (volume)=0.2, According to said ratio we taken volume of solution for chemical treatment of glass.

Clean glass as per SOP and dry it with wipe. Start UV-VIS Spectrometer instrument and check % transmittance as a blank & save value for further analysis.

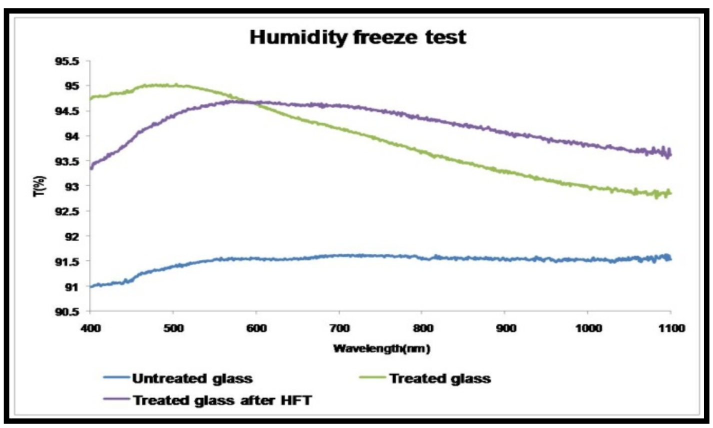
After measure blank transmittance then kept glass in dilute nitric acid for 20 minute at 80-95'C temperature. After 20 to 30 minute remove glass from nitric acid solution then cool it at room temperature then clean it with DI water. After clean with DI water pretreatment glass kept in to plastic beaker solution- (1) which lying in water bath at 85'C temperature for 48 Hrs.After 48 Hrs. remove glass from plastic beaker solution then cool it at room temperature then wash it with DI water & clean it with wipe. Start UV-VIS Spectrometer instrument and check % transmittance after chemical treatment & compare value with blank.

D. *Environmental* testing: As per IEC 61646 following environment test carried out successfully-

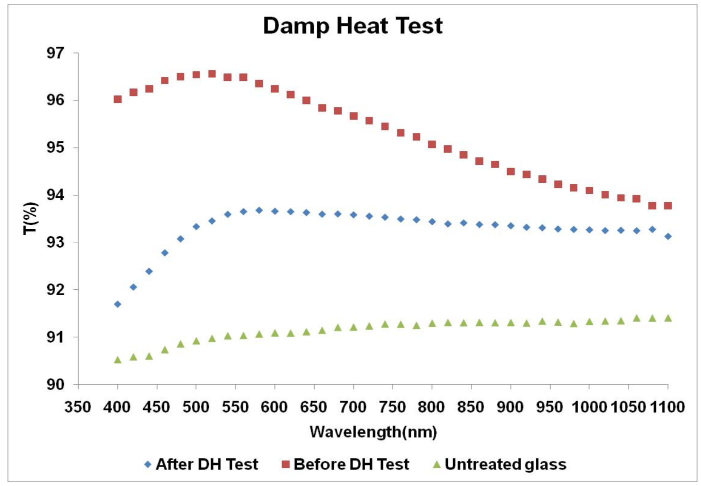
\# **Annealing test for treated glass-** After chemical treatment of toughen glass we kept glass in oven at 90'C for 24Hrs, 48 Hrs, 72 Hrs & 96 Hrs. After annealing test of glass The treated substrates transmission was measured before annealing and after annealing. The results are described below due to UV-VIS spectra.



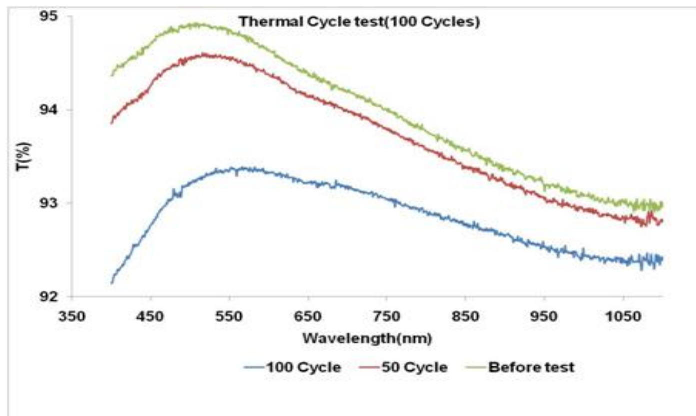
Humidity Freeze test- 85 C to - 40C @ 85%RH 10Cycle each cycle=24Hrs



#□**Damp heat test - 85/85 for 1000Hrs**



•# **Thermal Cycle test - 40C to 85C each cycle of 6 Hrs, increment of 50, 100 & 150 cycles**



VII. RESULTS & DISCUSSION

We have concentrated on measuring the transmission of the treated glass with respect to the untreated glass. We have measured the transmittance before the experiment and take transmittance of the same treated substrate after all type of environmental test . The overall result for both Soda-Lime and BK-7 glasses can be summarized below:

2) *Low iron glass:* Fig 8 shows the effect of λ_{min} change with treatment time as well as the effect of annealing of the treated glass.

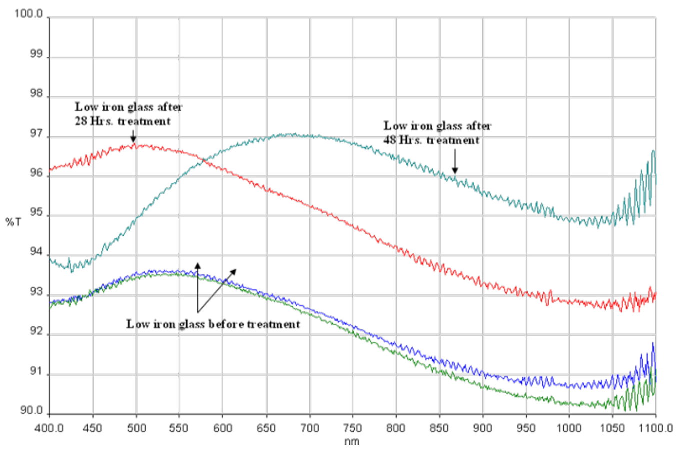


Fig 8

The transmittance peaks at 97% which is less than that of BK-7 glass. Thus, depending upon glass composition the change in transmittance will vary. Similar to BK-7 glass, the peak has shifted when we had varied treatment time from 28Hrs to 48Hrs.

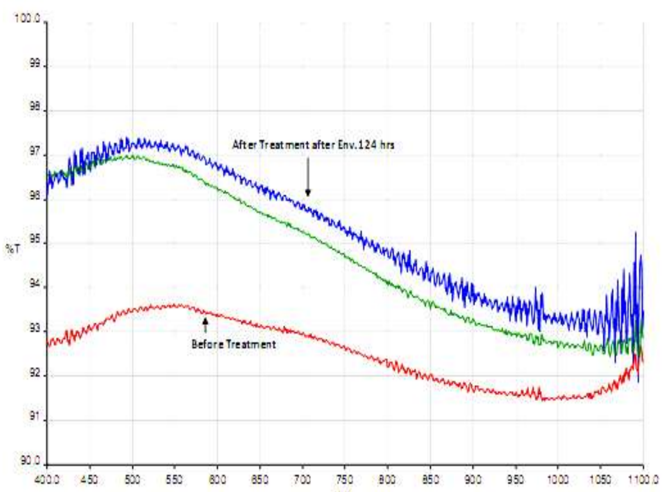


Fig 9

Fig 9 shows the effect of dry heat in this case; there is actually a slight increase in transmission which we feel may be due to presence of moisture in air (the heating of samples was done in a oven without any control in humidity). What this shows is that change in transmittance due to dry heat may vary from glass to glass with some type of glass showing larger change as compared to other.

VIII. CRYSTALLINE SILICON PHOTOVOLTAIC MODULES WITH ANTI-REFLECTED COATED GLASS

Sets of experiment done to determine what efficiency gain can be achieved by using AR coated glass. The most direct way to determine the effect of energy is to measure modules both with and without AR coated glass in the same system and evaluated expected performance under standard test conditions (1000 W/m2. AM1.5 spectrum, 25 deg C). Module made using same procedure as per small module production line without any visual evidence of degradation of the coatings

CONCLUSION

From the above observations, we can conclude the following

a) The chemical process described changes the microstructure of the surface of glass and increases the transitivity.
b) The increase in transmittance depends on type of glass upto a certain extent.
c) The increase in transmittance is all across the visible wavelength and peaks at a certain wavelength.
d) Varying the process condition can shift the peak wavelength of transmittance.
e) Annealing the treated surface results in change in transmittance value and this change depends on nature of glass; in all cases however, transmittance settles down to a constant value after e period of anneal time and remains constant thereafter.

The above observations point to the fact that treated glass will be a good candidate for making solar photovoltaic modules. The requirements typically are; good transitivity, good heat stability, easy and cheap to produce. All these criterion are satisfied by the treated glass that we have experimented with and it remains to be seen how the process works on large form factor glass. We are currently working on the same.

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