

## **CONTROLLABLE OPTICAL TRANSMISSION IN BIFACIAL SILICON SOLAR CELLS**

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### **ABSTRACT**

Crystalline Si-based, pollution free photovoltaic electricity generation technology is expected to play a dominant role in meeting rising energy demands. However, the cost of PV electricity generation is still higher than fossil fuels. Since wafer represents almost 50% of the PV conversion cost, a highly effective approach cost reduction has been solar cell fabrication on thinner wafers. Current, wafer thickness have been reduced to 150-180[ $\mu\text{m}$ ] range; further thickness reduction will lead to reduce yields and efficiencies respectively due to reduced mechanical strength and optical absorption. Therefore, there is an urgent need to develop alternative inexpensive solar cells configurations based on thinner Si wafers. Bifacial solar cells with symmetric front and back surface contacts offer an attractive solution with potential for enhanced output, through sunlight absorption from both surfaces and a diffuse reflector located behind the bifacial panel can guide light back to the rear surface to generate additional e-h pairs. In this paper, optical transmission through Si is investigated as a function of wafer thickness. Starting with 200[ $\mu\text{m}$ ] thick (100) crystalline Si wafer thickness is symmetrically reduced by through wet-chemical etching methods. Optical transmission in 800-1200[nm] spectral range is measured with a custom-designed IR transmission system.

*Keywords: Optical transmission; thin Si wafers; wet-chemical etching;*

### **INTRODUCTION**

As development of human population requires free access to energy[1]. Energy is required for human fundamental such as transport, food, industrial, medicine and communications. At present, almost 1.6 billion population is without access to electricity. Therefore, there is an urgent need to find alternative energy resources to fulfill the global energy requirements. Renewable energy technologies offer the most desirable solutions for sustainable environmental friendly, carbon-free, clean and affordable future. In this matrix of renewable energy resources (hydro, wind, solar thermal) silicon stands out due to its abundance (~28% of the Earth's crust) and advanced stage of development. Silicon dominates the photovoltaic technology[2].

Generally, the cost of Si accounts for almost 50% of a photovoltaic panel[3]. Historically, a pathway to reduced cost has been realized by economic use of Si in the form of thinner substrates; current Si wafer thickness is in 150-200[ $\mu\text{m}$ ] in range[4]. Si PV technology is almost exclusive based on mono-facial solar cells in which light is incident from the front surface with the back surface completely metallized. The bifacial solar cell is an emerging solar cell configuration in which electrical grid patterns are identical on both front and back surfaces. This device configuration has the potential to generate more power than the mono-facial solar cell by capturing scattered light from the rear surface. The challenging problems in bifacial solar cell is to ensure that photo-generated e-h pairs absorbed near the back surface are collected by the front surface emitter prior to recombination. This work can be done by using appropriate surface texturing methods, light trapping can be enhanced and absorption in the rear-infrared (NIR) [5]. The optical properties of a broad range of different bifacial configurations with varying surface morphologies and rear side reflectors have been extensively investigated in the literature.

Although, wafer thickness reduction translates into smaller recombination losses and large open circuit voltages, absorption is reduced as well[6,7]. These considerations have led to extensive research on performance limiting factors in amorphous[8], multi-crystalline[9], and single crystalline solar cells[10]. The highest efficiency achieved by crystalline solar cells is approximately~25% by University of New South Wales[11]. Due to its indirect band gap, crystalline silicon has weak optical absorption particularly in the range ~900-1100[nm][12]. Therefore, in solar cell studies aimed to increase the efficiency and the primary goal is to enhance of light absorption while minimizing recombination losses. Surface texturing aimed at enhanced absorption in silicon has been extensively investigated by geometrical optic[13]. Geometrical textures reduce reflection of light into the semiconductor. Despite their effectiveness and industrial applications, geometrical texturing schemes suffer from several disadvantages that limit their effectiveness. Some of those are listed below[14].

- 1) Wet-chemical alkaline anisotropic etching used to form random pyramids in  $\langle 100 \rangle$  oriented crystal is not effective in texturing of low cost multi-crystalline(mc-Si) wafers.
- 2) Anti-reflection films have a resonant structure which limits their effectiveness to a narrow range of angles and wavelength.
- 3) With geometrical optics based texturing, sufficient IR absorption in thin film(<10 $\mu\text{m}$ ) silicon solar cells is not possible.

Light trapping schemes based on geometrical optics considerations have been developed for enhancing oblique coupling beyond narrow angle range of ( $\sim 16^\circ$ ) defined as  $\sin^{-1}(1/n)$ . Where n is the refractive index of silicon[15]. In general, the required feature dimensions for geometrical optical path length enhancement are  $\gg$  optical wavelength, therefore their applicability to thinner wafers is impractical. Periodically textured surfaces based on diffractive[16] and waveguide optics[17] have been shown to significantly enhance optical absorption. For a weakly absorptive medium, statistical

analysis by Yablonovitch[18] and optical analysis of scattering from a lambertian surface by Sheng[19] predicted absorption enhancement in textured surfaces by  $(\sim 4n^2)$  over a planar surface, where  $n$  is the refractive index of the material. In literature application of diffractive and physical optics structures aimed enhancement of optical absorption in thin Si films and solar cells have been reported with good results[20-29].

Lambertian schemes and related geometrical optics-based ray tracing approached were applied to both amorphous silicon[30] and crystalline silicon solar cells[31] with successfully results. A lambertian surface capable of filling all the available k-space with light beams of equal intensity is difficult to achieve in practice. A close approximation is a randomly textured surface supporting subwavelength features. Therefore, the random surface can be described by Fourier summation over a large number of periods. Although the resulting diffractive scattering ensures almost complete filling of the k-space. Light incident normally on such surfaces is diffractively scattered over a broad angular range determined by

$$\theta_{m,i} = \sin^{-1} (m_i \lambda / n d_i) \quad (1)$$

Where  $n$ ,  $d_i$  represents the  $m^{\text{th}}$  diffraction order corresponding to the spatial period  $d_i$  and  $n$  is Si refractive index. Optical path length in geometrical optics is simply the sum of number of passes through a thin film of thickness  $t$ . For a single grating the total optical path length enhancement is given by summing over the lengths of all transmitted diffraction orders

$$d_{\text{opt}}^{\text{grating}} = \sum_i \gamma_i d_i \quad (2)$$

Where  $\gamma_i$  is fraction of incident energy coupled into diffractive  $d_i$ . For a normally propagating zero order,  $d_0$  is identical to  $t$ ; for the diffraction orders the optical path is  $t/\cos \theta_{ij}$  where  $\theta_i$  the angle of propagation of the  $i^{\text{th}}$  diffraction order. For a random sub-wavelength diffractive surface the total optical path length is summed over all grating( $i$ ); each of which generates diffraction orders( $j$ ) as defined as

$$d_{\text{opt}}^{\text{random}} = \sum_{i,j} \gamma_{i,j} d_{i,j} \quad (3)$$

Comparison of the three cases (planar, single period and random surface) illustrate that an appropriately designed random surface is highly effective in filling the k-space and therefore in reaching the  $4n^2$  enhancement limit.

### Optical Absorption

For a good solar cell it is critically important that all of the incident energy be scattered into obliquely propagating transmitted orders in order to enhance optical path length and hence increase absorption. This can be achieved for feature dimensions either substantially larger refer to Figure 1 or comparable or substantially smaller than optical wavelength refer to Figure 2. The first configuration refers to geometrical optics,

second to diffractive optics, and the third to physical optics. In the physical optics approach deeply etched subwavelength structures are created in three dimensions, on the surface and through the substrate. Rigorous coupled wave analysis [32] has been used to calculate optical absorption in these 3D grating structures. Physical optics also described in terms of subwavelength surfaces (sws) essentially acting as multi-layer anti-reflection films [33]. Structures play no role in optical path length enhancement . Absorption in such structure is opposed to conventional horizontal, thin-film waveguide structures such as those proposed by Sheng[19].

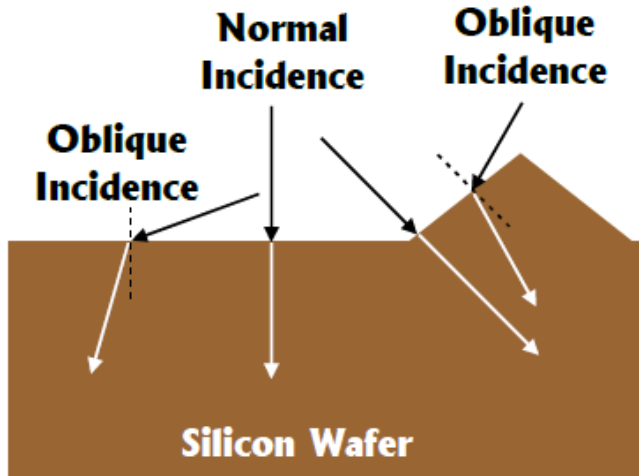


Figure 1: Schematic description of light, interaction with surface features >> optical wavelength ; for convenience reflected beams are not shown

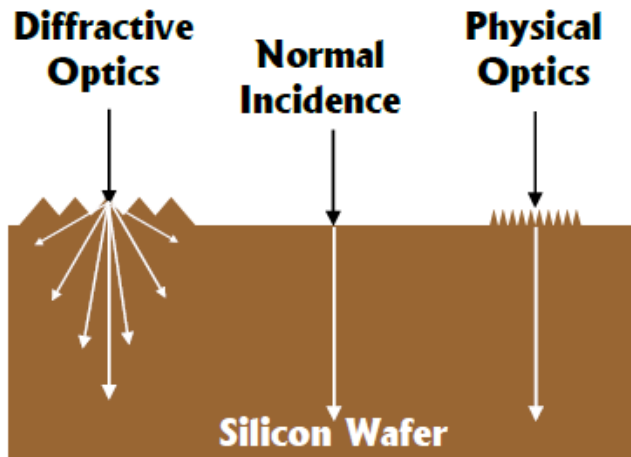


Figure 2: Schematic description of light interaction with surface features either ~ or << optical wavelength; for convenience reflected and diffracted beams are not shown

In this paper, near IR transmission in ~800-1700[nm] spectral range for planar and randomly textured Si wafers have been investigated for Si wafers with thickness of ~ 200[ $\mu\text{m}$ ]. The wafers used are typical of solar substrates used in manufacturing with (1000 crystal orientation).

### IR Transmission Measurements

A simple experimental setup based on optical configuration described in Figure 3 has been developed for characterization of near IR transmission as a function of wavelength. This system is designed to measure optical transmission system in near and far infrared (IR) range specifically for the wavelength. A computer controlled IR monochromator is used to vary wavelength in the desired range. Spectrally variable light from the monochromator is incident normally on the sample under measurement (SUM). The transmitted light from the sum is collected with focusing lens onto an InGaAs photodetector. The output from photodetector is connected to a lock-in amplifier, which is connected with a computer. Intensity variation as a function of wavelength is measured with a LABVIEW based computer programme.

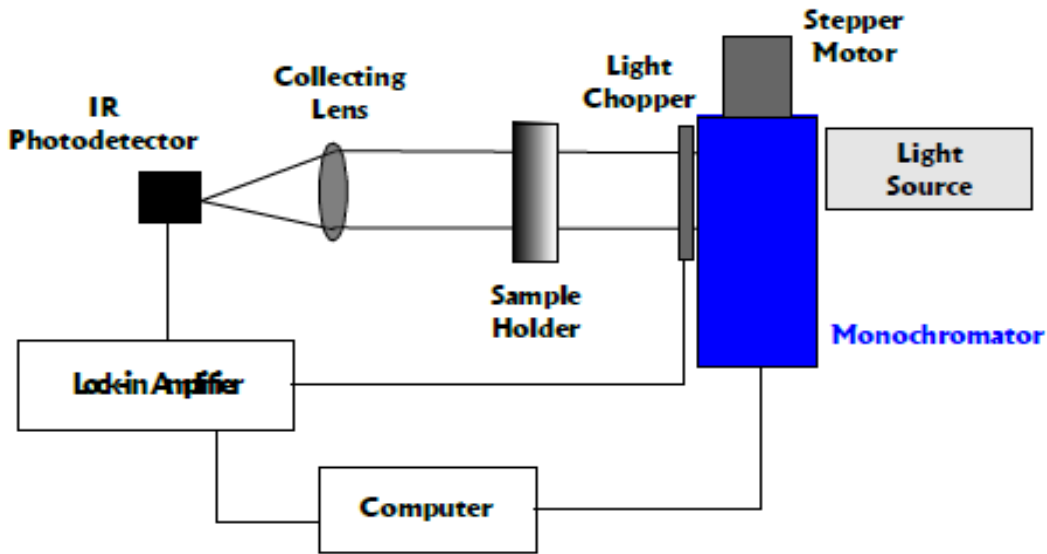


Figure 3: Schematic diagram for IR transmission measurement system

## EXPERIMENTAL

Single crystalline silicon (c-Si) wafer with thickness is about 200[ $\mu\text{m}$ ] is used. P-type Si wafers with resistivity ranging between 0.5-3.0[ $\Omega\cdot\text{cm}$ ] with doping density between  $10^{15}$  and  $10^{16}$  were used. The Si wafer was initially cleaned by dipping into solution of hydrofluoric acid (HF) and nitric acid ( $\text{HNO}_3$ ) in a ratio 1:100 for 10 minutes. After rinsing with deionized water then dipped into HF and water in 1:50 ratio for 1 minute. The wafer was immersed in 10% potassium hydroxide (KOH) at a temperature of 70-80[ $^{\circ}\text{C}$ ] for 5 minutes. Subsequently, the wafer was repeatedly cleaned in HF:H<sub>2</sub>O for 1 minute. Then, the wafers were rinsed with deionized wafer for about 2 minutes and then dry it with nitrogen gas. Etching process led to reduce the thickness of Si wafers. Figure 4 show the process flow of etching by using 10%KOH solution. Si wafer with damage removal need to go through the texturing process with ratio of 1:5:125.

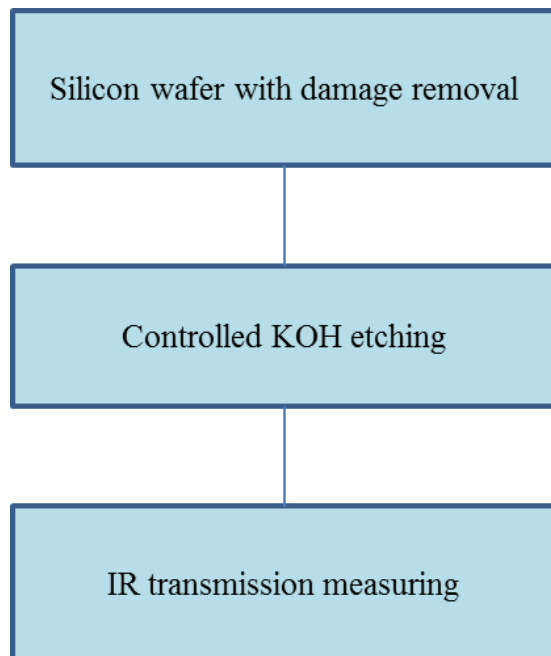


Figure 4: Process flow for KOH etching process on silicon wafer with 200[ $\mu\text{m}$ ] thickness

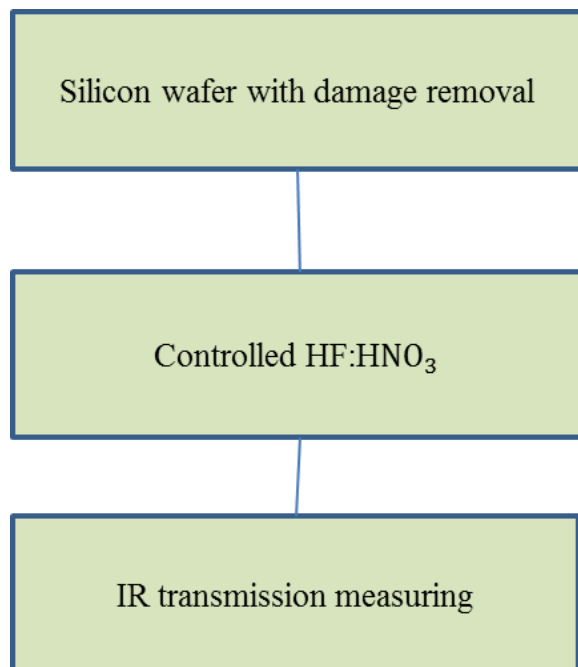


Figure 5: Process flow for HF:HNO<sub>3</sub> etching process on silicon wafer with 200[ $\mu\text{m}$ ] thickness

The texturing process is a combination of 4g of KOH pallets, 20ml of isopropanol and 900ml of deionized water. The Si wafer will be laminated by using the laminator as shown in Figure 8. Then, the laminated wafer will be transferred into a beaker which contained 10%KOH. The estimated time would be 1 hour and 45 minutes at temperature of 70-80[°C] . Next, the IR transmission data will be collected. Figure 5 show the process flow of etching by using HF:HNO<sub>3</sub> with a variation 1:10 ratio. The value of HF is 10ml and 100ml for HNO<sub>3</sub>. Then, Si wafer were dipped into the solution for 1 hour and 45 minutes. The IR transmission data is recorded from 60-1200[nm] wavelength with subwavelength is 25[nm].

## RESULTS AND DISCUSSION

From the surface profiler the thickness of Si wafer will reduced 31[μm] for every 30 minutes. Therefore, the etching rate is approximately 1.04[ $\frac{\mu\text{m}}{\text{min}}$ ]. Figure 1 illustrates scanning electron microscope(SEM) analysis of KOH-etched surfaces. The etching rate of silicon depends on the product of hydroxide ion [OH<sup>-</sup>] and free water concentration [40]. Recently ingot cutting technology has been significantly improved which reduced the importance of having an etching process[34,35]. After the etching process the surface becomes shiny. KOH-etching is one of the mechanisms by texturization is carried out in c-Si. Meanwhile, the thickness of the water can be controlled by the time etching.

Table 1: Result of the thickness for KOH etching vs time from SEM data

Samples [minutes]	Thickness [μm]	Etching rate [μm/min]
30	58.4	1.94
60	41.3	0.63
90	97.3	1.08
180	135.2	0.75

Table 2: Result of the thickness for KOH etching vs time from surface profiler.

Samples [minutes]	Thickness [μm]	Etching rate [μm/min]
30	31.2387	1.04
60	58.0560	0.96
90	91.8626	1.02
180	213.186	1.18

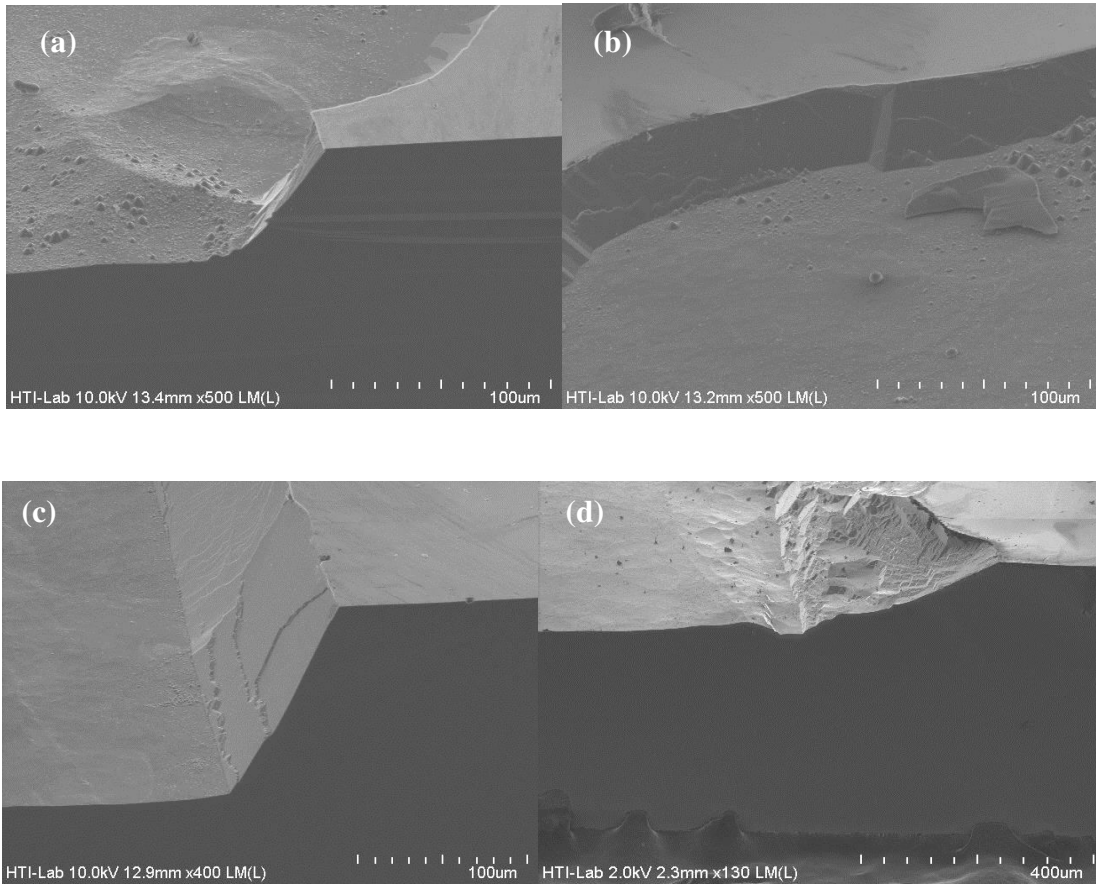


Figure 6: SEM pictures for KOH-etched Si surfaces for etching times of 30 minutes (a), 60 minutes (b), 90 minutes (c) and 180 minutes (d)

Figure 7 Plots as recorded transmission data as a function of wavelength; comparison, transmission response in air without Si wafer has also been plotted. The baseline is for Si planar wafer after damage removal with approximate thickness of 200[µm]. The transmission response has been plotted on a log scale due to several orders of magnitude variation in transmitted signal. Transmission through air is highest value. Transmission through relatively planar, polished sample in (red line) described in Figure 7 is lack of absorption in a non-textured surface. The wafer thickness reaches approximately ~180[µm] after going through the process of damage removal. The transmission through Si wafer with KOH-texture etching process is the lowest in 1000-1200[nm] range. The wafer becomes thinner compare with baseline wafer. The wafer with KOH etching is completely textured with estimated thickness of ~80[µm]. The absorption of incident light is enhanced due to texture-based trapping. Figure 8 Plots optical transmission as a function of etching times with HF:HNO<sub>3</sub> solutions at 1:10 ratio. In this work, as etching time increases, the Si wafer thickness become thinner. However, as etching time is increased, wafer starts to develop substantial texture and thus no

longer planar. Therefore, the transmission through the etching time at 1 hour and 45 minutes is the lowest compared with less etched times due to enhanced light trapping. Figure 9 Plots the comparison of transmission measurements with KOH and HF:HNO<sub>3</sub> method. It is seen that lowest transmission is for the KOH-textured surface due to its superior light trapping properties. Through the different method of etching process the slight dips in transmission of wavelength ~1050[nm] are instrument related. The transmission through relatively planar polished in (green line) described in Figure 9 is highest at 975-1050[nm] range due to the lack of light trapping. The transmission through acid etching process is substantially higher due to planar surface and lack of light trapping although its thickness is larger than KOH-etched wafer. The transmission through Si KOH etching is the lowest due to a combination of low reflection and diffractive scattering. As the result, the thickness of wafer could reach ~80[μm] after go through KOH etching process. The surface of Si wafer becomes more textured so the light will trapped and reduce the light to be transmitted.

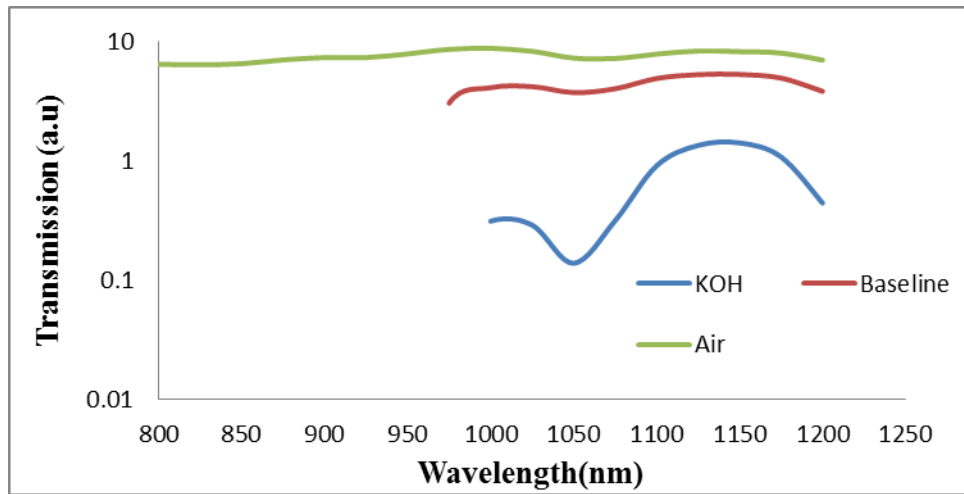


Figure 7: Optical transmission measurement as a function of wavelength for Si by KOH etching process

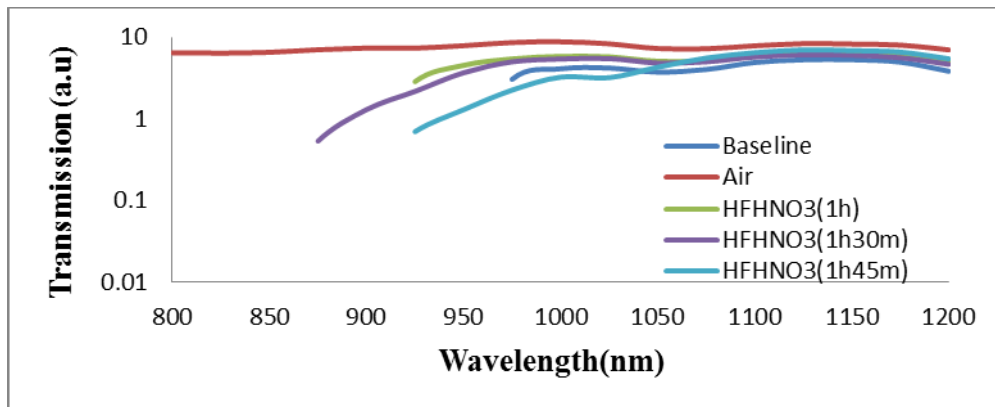


Figure 8: Optical transmission measurement as a function of wavelength for Si thickness

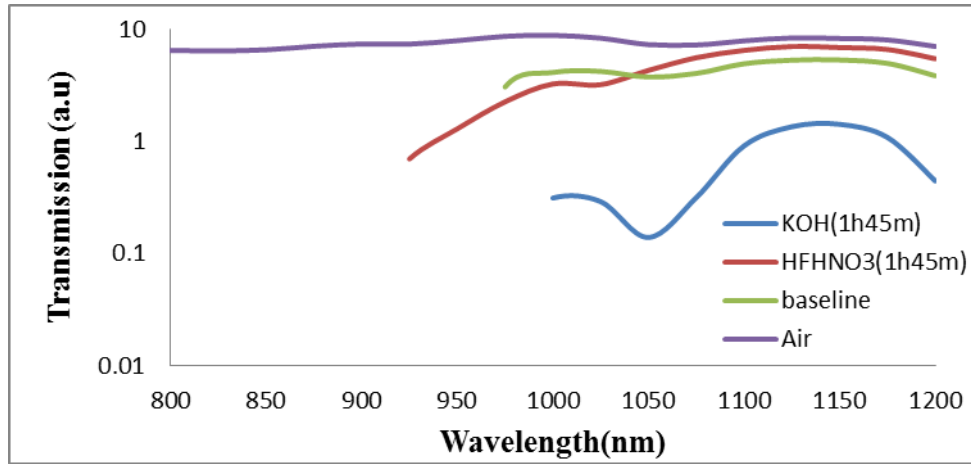


Figure 9: Optical transmission measurement as a function of wavelength for Si by different etching process

## CONCLUSION

A simple IR spectral transmission system based on InGaAs photodetector and monochromator was successfully developed for spectral optical measurement. Based on feature dimensions, incident interaction can be described in terms of geometrical, diffractive and physical optics. The thinner, textured-Si wafer gives the lowest transmission due a combination of low reflection and diffractive scattering.

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