Design and Fabrication of Thin Film a-Si/Al_2O_3 Infrared Filter

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ABSTRACT

Long-wavelength infrared filter operated at various temperature are critical for imaging applications. In this paper anew type of infrared filter is investigated, this infrared filter uses a crystalline silicon substrate coated with multi layers of aluminum oxide (AL_2O_3) and amorphous silicon (a-Si) to produce the multi layers thin film infrared filter a-Si/AL2O3 operating in the range (8-14)um. Amorphous silicon is used in this paper due to its high refractive index, while AL_2O_3 due to its low refractive index material. The a-Si/ AL_2O_3 thin film structure were designed using the Thin Film Design software (TF Calc 3.5.6 version). The simulated results obtained shows that the transmittance of the a-Si/ AL_2O_3 infrared filter with 19 layers is about 90% for (8-12.5) µm wavelength, while it is about 95% for 47 layers for (8.25-13.25) µm wavelength. The investigated filter was fabricated using vacuum evaporation process and the results obtained were comparable with the simulated one. The fabricated a-Si/ AL_2O_3 filter is compared with the Ge/ZnS infrared filter and it is found that the results is comparable but the cost of the fabricated filter is small compared to the Ge/ZnS filter.

Keyword: Infrared Filter, Silicon, Aluminum Oxide.

تصميم وتصنيع مرشح الأشعة تحت الحمراء نوع a-Si/Al_2O_3

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الخلاصة

يعتبر مرشح الموجة تحت الحمراء والذي يعمل بدرجات حرارة مختلفة من العناصر المهمة في التطبيقات الصورية. تم في هذا البحث اقتراح نوع جديد من مرشح الموجة تحت الحمراء مكون من طبقة أساسية من مادة السيلكون المتبلور ومرسب عليها طبقات عديدة من مادة أوكسيد الألمنيوم ومادة السيلكون العشوائي التركيب (a-Si) وذلك لتكوين مرشح الموجة تحت الحمراء ضمن الحزمة µm (8-14). تم استخدام مادة السيلكون العشوائي في البحث بسبب معامل انكساره العالي بينما تمتاز مادة أوكسيد الألمنيوم بمعامل انكسار واطئ ، وتمت عملية التصميم باستخدام البرنامج (TF calc 3.5.6 version) حيث تم الحصول على مرشح مكون من 19 طبقة وذات نفاذية مقدارها 82% للطول الموجي µm (8-12.5) ، بينما كانت النفاذية بحدود 90% باستخدام 47 طبقة للطول الموجي µm (8-13.75). تم تصنيع المرشح المقترح باستخدام جهاز التبخير الفراغي وكانت النتائج قريبة جداً من نماذج التمثيل بالحاسوب. كذلك تمت مقارنة النتائج مع المرشح المكون من مادة الجرمانيوم ومادة كبريتيد الخارصين وكانت النتائج متقاربة ولكن مع كلفة قليلة للمرشح المقترح مقارنة مع المرشح المصنع من مادة الجرمانيوم ومادة كبريتيد الخارصين (Ga/ZnS).

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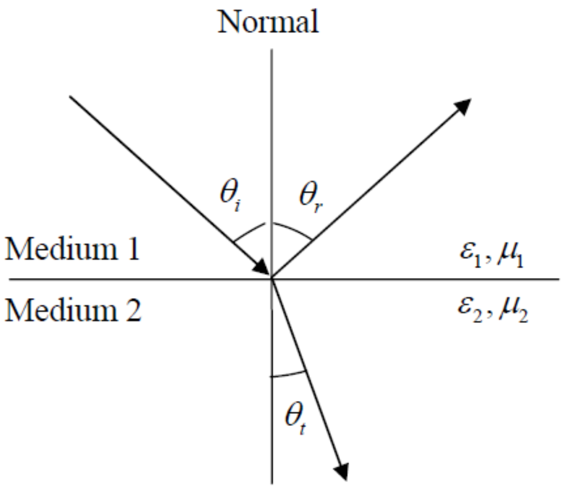
1. Introduction:

Infrared detection is important in a variety of fields, such as military targeting and tracking, law enforcement, environmental monitoring, and space science. Infrared pass band filter have been widely investigated during the past twenty years for operation in the mid-wavelength (3-5) µm and long-wavelength (8-14) µm infrared range. Most of these filters usually uses Zinc oxide (ZnO), Germanium (Ge) and rarely silicon materials, because of the large transmittance of ZnO and Ge compared to Si material. Infrared filters could have a variety of applications and depending on the applications the reflectance and transmittance ranges of these filters need to be highly accurate [1].

Optical filters can be defined as thickness dependent refractive index systems which modify the properties of a surface to produce the desired optical characteristics. Since the filter is intended for use in an integrated system, it is important that the materials used are IC-compatible.

Infrared filters, used to help define the wavelength response of infrared instruments, should have sharply defined spectral shapes with high in-band transmission (or blocking, in the case of band blocking devices) and excellent rejection outside the bands of interest [2]. The (a-Si) is a semiconductor material, with optical properties, dopability, mechanical reliability, good adhesion to various substrates and low-cost technology which made it attractive for application in light processing systems. At present, the advantages of a-Si films are mainly used in large-area optoelectronic devices, such as solar cells, image sensors, flat panel displays, etc [3].

The reflected and refracted wave intensities are also related to the properties of the incident wave, such as the wave polarization, angle of incidence, and the frequency of the propagating wave [4]. A sample ray diagram of a plane wave incident on an interface between two dielectrics is illustrated in Figure (1).



Figure(1) A sample of reflected and refracted waves.

The angle of the reflected wave is equal to the angle of incidence by Snell's law of reflection

$$\theta_i = \theta_r$$

This is referred to as secular reflection. The index of refraction of a medium is the ratio of the phase velocity in free space to the phase velocity in the medium. By Snell's law of refraction

$$\mathbf{n_1} \sin\theta_i = n_2 \sin\theta_t$$

Where (n_1 and n_2), are the indices of refraction of media 1 and 2, respectively. The index of refraction is related to the dielectric constant, $n = \sqrt{\varepsilon_r}$. When $n_1 < n_2$, it follows that $\sin\theta_i > \sin\theta_t$ and also that $\theta_i > \theta_t$. Thus, it can be said that the ray entering a higher index medium bends toward the normal.

The reverse is also true, that is, the ray entering a lower index medium bends away from the normal [4], [5].

The basic type of interference filter consists of a stack of alternate high and low index materials, each one-quarter wavelength thick. This quarter wave stack will have high reflectance for a range of wavelengths for which it is designed and the reflectance falls off sharply outside this range. The reflectance of the stack can be made very high just by increasing the number of layers and so it forms a basic building block of many kinds of filters. Optimization approaches towards filter design and the development of highly powerful design software have led to the development of the so-called "Needle" filters, where a profile of refractive indices and thickness would look like a line of needles [1].

2. The choice of materials:

The development of infrared filters for wavelengths in the (3 to 40) µm range is important for many astronomical and atmospheric instruments. Currently available filters are based on interference in multilayer stacks (so-called multilayer interference filters). Multilayer interference filters have been shown to have strong drawbacks in the far IR spectral ranges (10-50µm) for several reasons. The first reason is that there are only a few materials sufficiently transparent beyond 15µm [6]. The material layer is required mainly for multilayer system have high transmittance in the infrared region and high reflection in the visible region [7]. Taking into account that thin films in multilayer interference coatings must be dense and have low absorption in the wavelength range defined for the intended application [8].

The arrangement of material on two faces of substrate must be according to the value of refractive index. First material have higher refractive index than second material as consequently the light will be suffer many of refraction as Snell's law to obtain the desired wavelength as shown in figure (2) and (3).

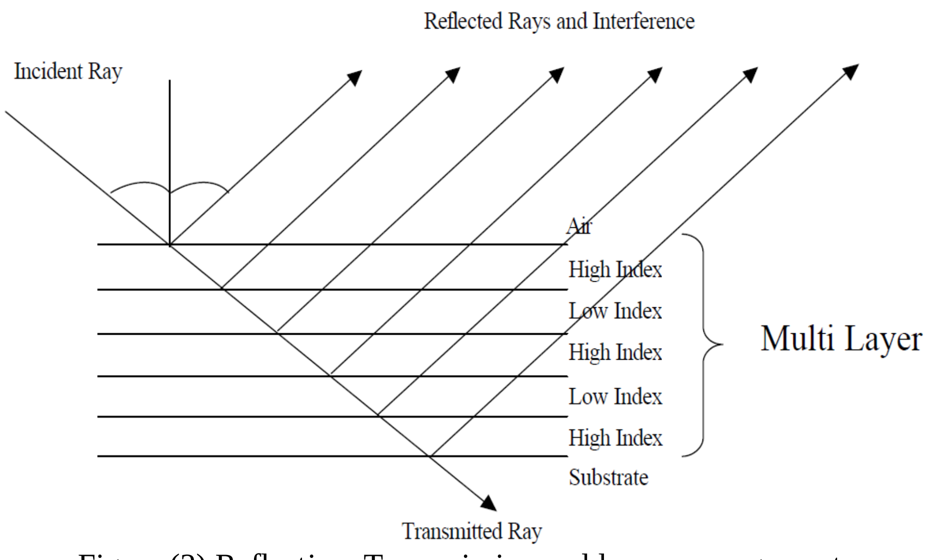


Figure (2) Reflection, Transmission and layers arrangement

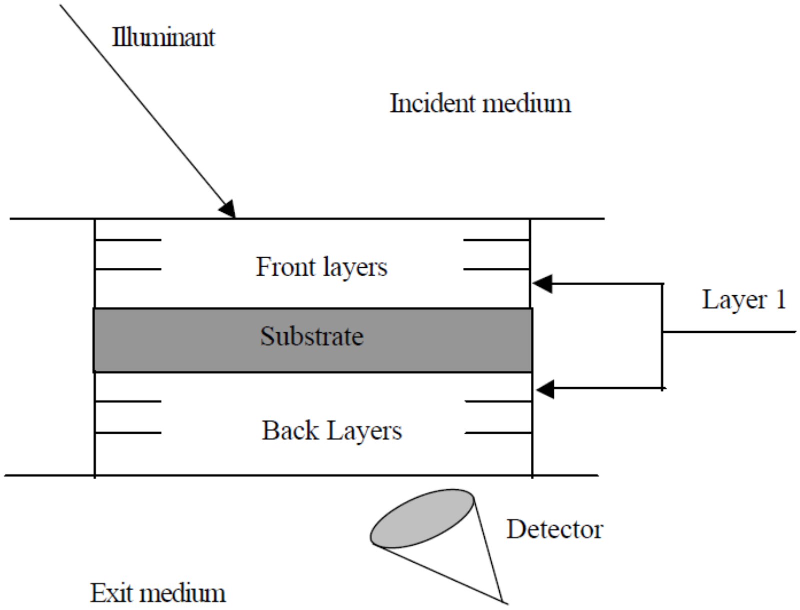


Figure (3) Arrangement of material on two faces of substrate

When the difference in optical path length between the rays transmitted at successive reflections is such that the emerging waves are in the same phase, constructive interference will occur and filter will show the maximum transmittance value.

If this condition does not hold, the interference between successive emerging rays will be destructive and the transmission will be relatively low [9].

3. Simulation and Results:

The aim of this work is the design of multilayer optical filter in the far infrared (IR) region (8-14) µm. The first AL_2O_3 layer will be deposited on the amorphous silicon (a-Si) substrate layer (300µm), the deposited AL_2O_3 layer were used with constrain of layer thickness at least 10nm, a-Si material were used as the second layer with the change of constrain layer at least 5nm. The third layer is the same as the first one but with different layer thickness in order to improve the response of the filter. The same thing is done for the amorphous silicon forth layer and so on.

Case1: Different layers thickness of AL_2O_3 and amorphous silicon were deposited on the silicon substrate wafer (300 µm) in order to design the multilayer optical filter with the requirement.

A. Transmittance value < 5% for wavelengths (1-7.8) µm.
B. Transmittance value > 99% for wavelengths (8-14) µm
C. Transmittance value < 5% for wavelengths (14.1-20) µm

At the beginning, the coating materials were started with a single thin layer, the needle method was used in (TF Calc) software with constrain thickness of layers at least 10nm, than the thickness of the layer will be chosen by the program in order to get the optimum results. Figure(4) shows the transmittance of 19 layers infrared filter, it is clear that the filter has an average transmittance of about 80% for a bandwidth of (8-12.5) µm. The transmittance is less than 40% for a bandwidth less than 8 µm and more than 14 µm.

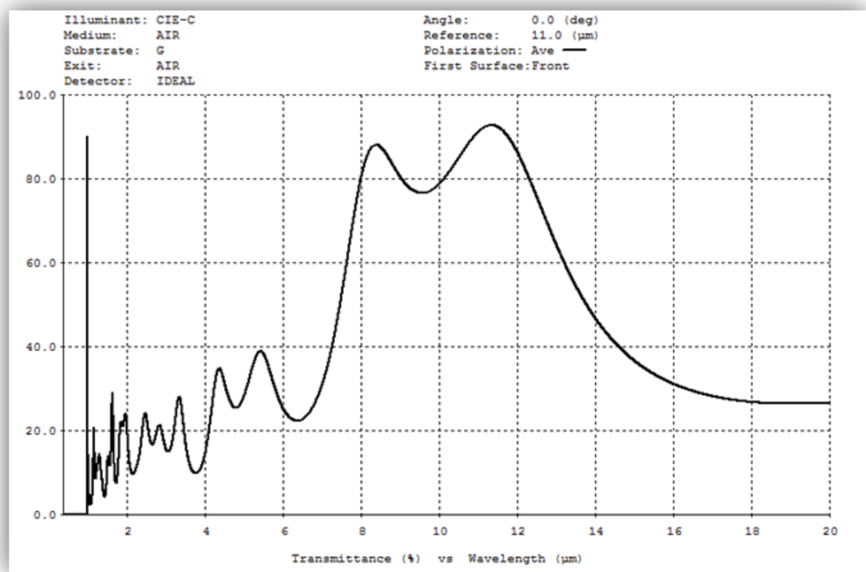


Figure (4) Far region infrared filter (a-Si/ AL_2O_3) 19 layer

Case2: This coating is the same as case 1, with constrain of layers thickness at least 5nm, then needle method was used in (TF Calc) software to create a 25 layer to obtain the optimum result as shown in figure(5). It is obvious that increasing the layers will leads to increasing the transmittance of the filter, the average transmittance is about 85%.

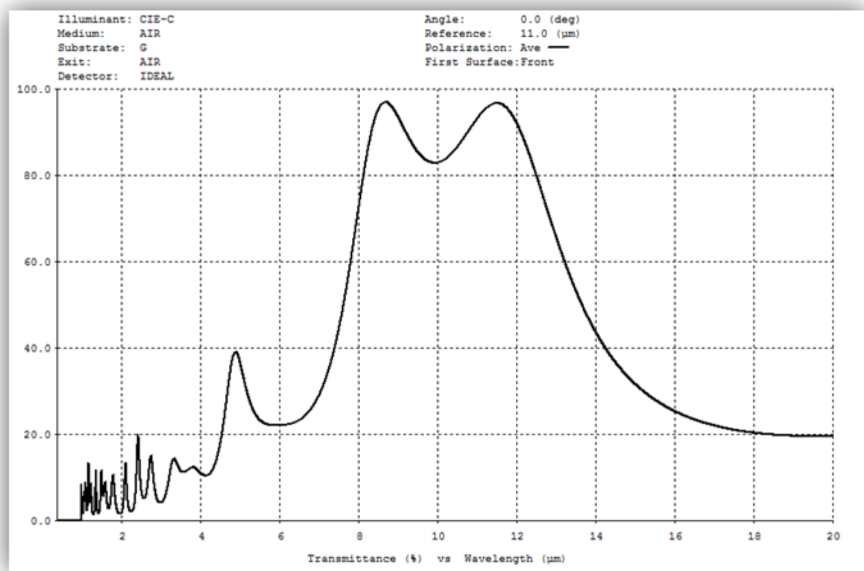


Figure (5) Far region infrared filter (a-Si/ AL_2O_3) 25 layer

Case3: This coating is the same as case 1, with constrain of layers thickness at least 10nm with increasing the number of layers, then needle method was used in TF Calc software to create a 36 layer to obtain the optimum result as shown in figure(6). The overall transmittance is about 90% and the bandwidth of the design filter is increased compared to case 1 and case 2.

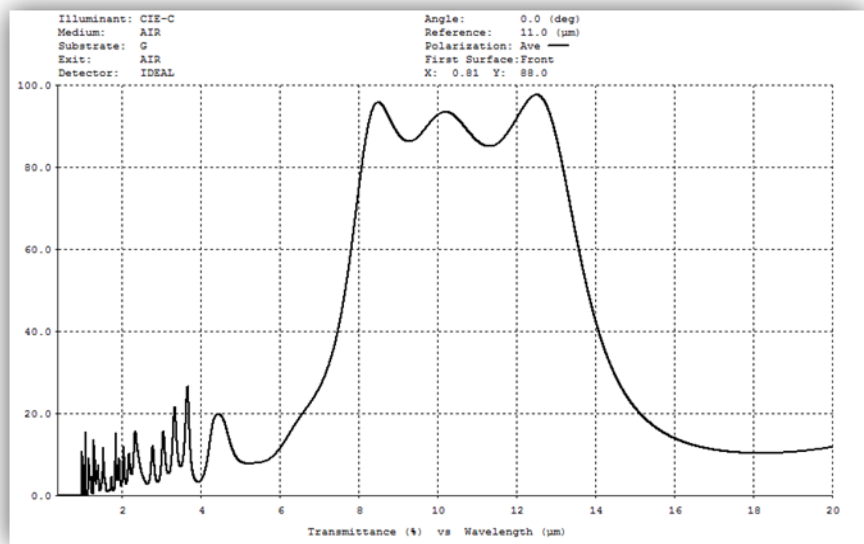


Figure (6) Far region infrared filter (a-Si/ AL_2O_3) 36 layer

Case4: This coating is the same as case1, but without any constrain of layers thickness, then needle method was used in TF Calc software to create a 47 layer to obtain the optimum result as shown in figure(7). The optimum results is obtained by 47 layers and without any constrain of filter thickness, which has to be decided by the program, the overall transmittance value is about 90% and more, which seems to be the best obtained results compared with the last three cases.

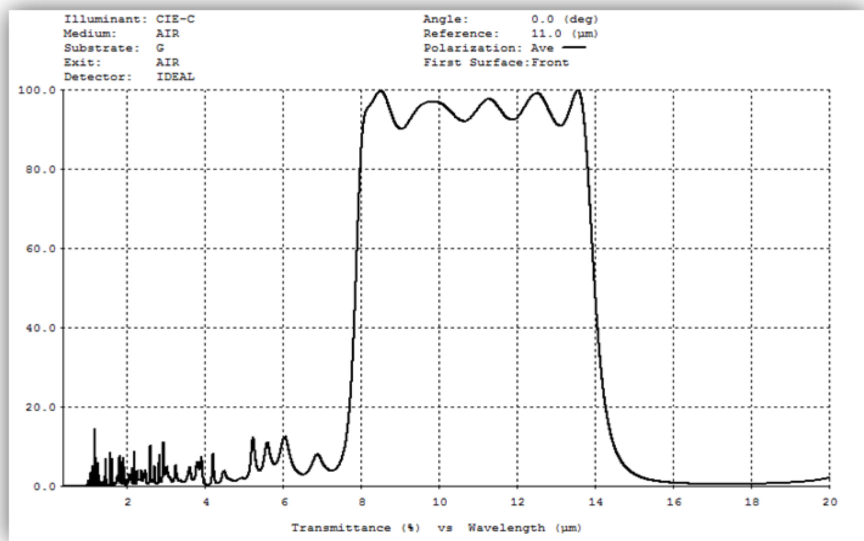


Figure (7) Far region infrared filter (a-Si/ AL_2O_3) 47 layer

Several germanium thin films and Zinc Sulfide (Ge/Zns) were used in one simulated result at different thickness in order to be compared with the response of a-Si/ AL_2O_3 as shown in Figure (8). It is clear that the results obtained from the investigated filter is comparable to the results obtained from Ge/ZnS filter, while the Ge/ZnS filter is a very expensive IR filter because of the high costs of Ge and ZnS material compared to the a-Si and Al_2O_3 material.

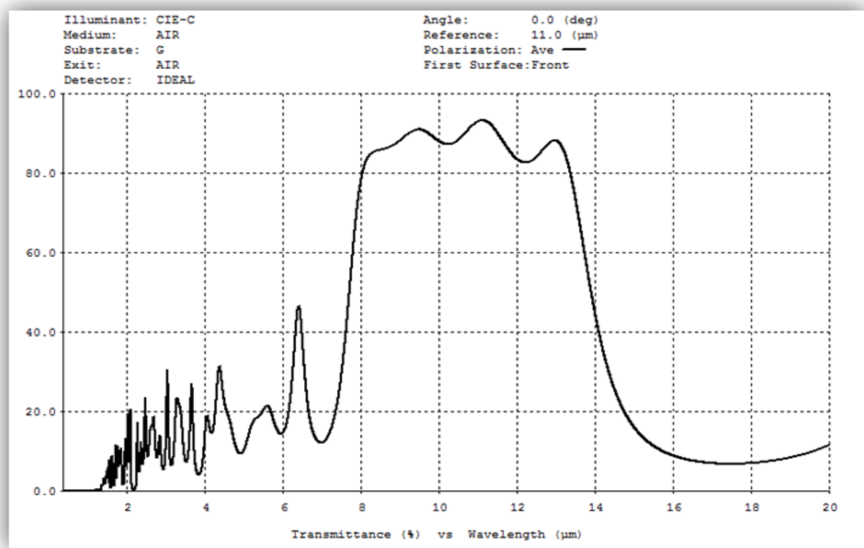


Figure (8) Far region infrared filter (Ge/ Zns) 25 layer

4. Experimental Work:

The fabricated a-Si/AL_2O_3 filter samples were prepared by vacuum evaporation technique using Balzer unit as a coating system. Mon crystalline n-Si wafers with thickness of 300 µm and resistivity of about 4.5 Ω.cm, oriented in (100) plane, were used as substrate material. However, n-type silicon or p-type silicon can be used. The silicon substrate wafers were cut into relatively small segments to be used as base substrate material for the fabricated IR filter. The samples were cleaned with ethyl alcohol to remove organic residues and then etched in buffered hydrofluoric acid for 2 minute to remove oxide films, then they were stored and protected from atmospheric contamination in vacuum desiccators.

A thin film (10 nm) of AL_2O_3 were deposited on the back and front surface of the silicon substrate wafers, then a Si thin film (as the simulated thickness layers) were also deposited on the back of the front surface of the first AL_2O_3 deposited layers. The above process were repeated 47 times using two evaporation source in order to deposit the a-Si and AL_2O_3 material consequently and without breaking the vacuum inside the chamber. Figure 9 shows the structure of the a-Si/AL_2O_3 filter.

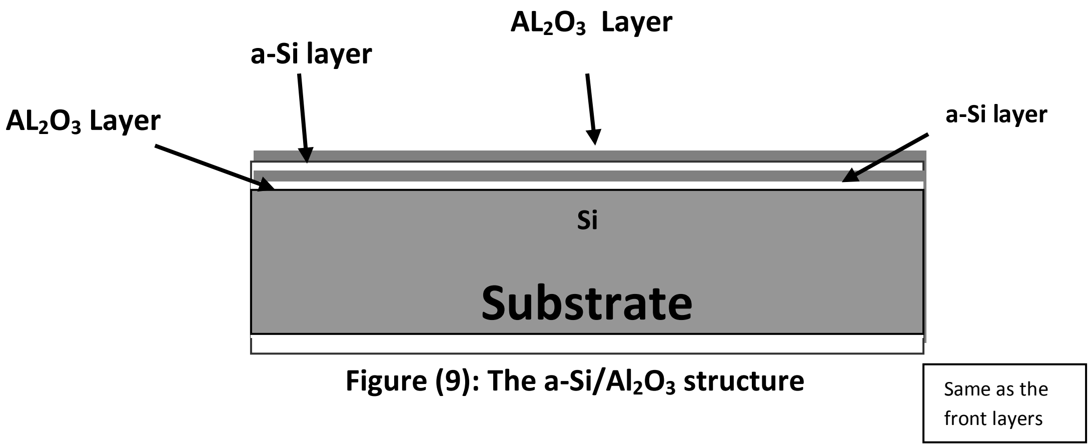


Figure (9): The a-Si/Al_2O_3 structure

The overall process were completed using vacuum pressure of about 10^{-5} mbar at 25 °C ambient temperature.

The fabricated samples were tested using infrared spectrometer in the range (1-20) μm. Figure 10 shows the transmittance spectra of the fabricated a-Si/AL_2O_3 IR filter using 47 layers, deposited on both side of the silicon substrate as shown in figure (10) .

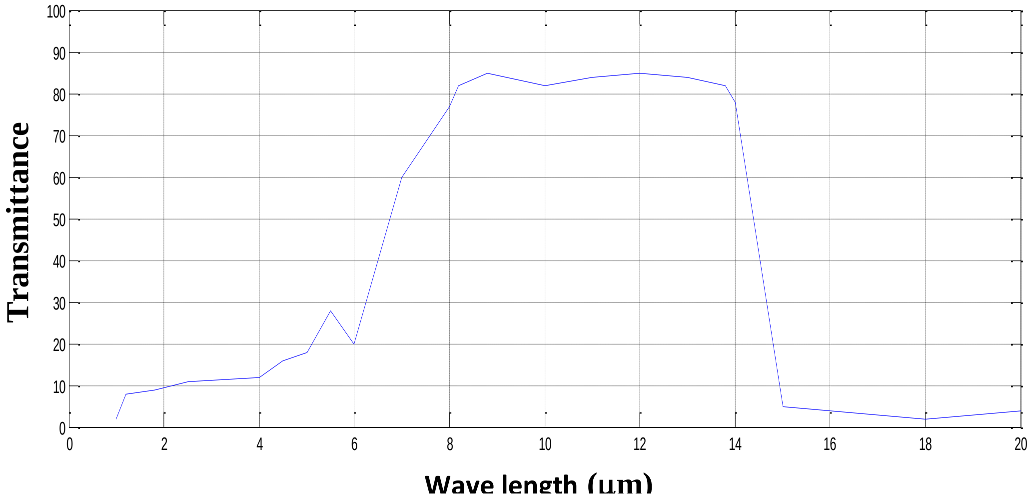


Figure (10) The Fabricated infrared filter (a-Si/ AL_2O_3) with 47 layers

It is clear that the fabricated filter has a good transmittance value of about 85% in the range (8-13.8) μm, while the transmittance value is very small below 8 μm and above 14 μm.

The difference between practical and simulated results can be attributed to the value of the layer thickness, which cannot be as the simulated one because of practical problem in fabricating very thin layers, while this layer thickness was increased or decreased exactly by the program to give the optimum results in simulation.

4. Conclusion:

In conclusion, results were presented for the development of far IR filters for minimum layer based crystalline silicon technology. Both simulation and practical work shows that such filters offer multiple superior properties compared to the common interference filters. The results of amorphous silicon and AL_2O_3 thin films on the crystalline silicon substrate indicate that the practicability of the design of thin film optical filter in the far region by using these materials. The layers thickness constrain, at least 5nm, will be increase the number of layers (25-layer) compared with (10nm), as a minimum thickness (19-layer). The response of 5nm minimum was better than the first case without any constrain of layer thickness, the results show that more sharp filter can be obtained with transmittance of about 90% and more using 47 layers filter.

The fabricated a-Si/Al_2O_3 IR filter with 47 layers shows that the transmittance value (85%) was comparable to the simulated one, the results obtained show that the a-Si/Al_2O_3 IR filter can be used instead of Ge-ZnO IR filter with lower costs and with comparable characteristics.

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