

Characterization of Au Thin Films on n-type Si for Photovoltaic Applications

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Abstract

The efficiency and performance of photovoltaic devices is challenges to achieve due to the low electrical contact resistance and poor light absorption characteristic in the devices. In this report, Au thin films was deposited on n-type silicon using DC sputtering technique followed by laser treatment by using Nd:YAG laser at different energy. The sample were characterized based on morphological, topological, electrical, and optical properties by using Atomic Force Microscope (AFM), Scanning Electron Microscope (SEM), Four-Point Probe and UV-Vis Spectrophotometer. The AFM analysis shows the sample with 60 mJ energy has the highest grain size and surface roughness as compared to as-deposited sample. Moreover, the SEM analysis shows the annealed sample with 80 mJ has many defects that appeared on the surface compared to annealed sample with 60 mJ. The annealing treatment decreased the resistivity from 4.34×10^{-5} to 3.06×10^{-5} Ω/cm . The optical characterize have the highest absorption of light with average 8.6 at a wavelength of 600 nm. The results indicate that the laser annealing could improve the efficiency of Au thin film, which can be potentially applied in photovoltaic devices.

1. Introduction

Photovoltaic technologies (PV), sometimes known as solar panels, that generate power by absorbing sunlight energy and converting it into electrical energy via semiconducting materials such as silicon. Thus, silicon is a semiconductor that have been focus of much recent interest as a potential material for photovoltaic [1]. Recently, high performance of photovoltaic applications has attracted enormous research interest, because photovoltaics is an excellent option for meeting the rapidly increasing global energy demand [2]. Metal thin films find applications in diverse fields such as electronic, optics, solar cells, sensors, [3]and coating which have their own purposes. The type of metal thin film to use is determined by the final application. Ag, Pt, Cu and Au are the most used thin metal films due to the low resistivity. Gold (Au) and platinum (Pt) is considered as precious metals in the context of thin film applications, which play key role, and their unique properties are used efficiently in industry [4]. The process of creating thin metal films involves deposition techniques such as physical vapour deposition (PVD) or chemical vapor deposition (CVD), sol-gel process, spin coating, dip coating, doctor blade, electroplating [5]. Each technique has its advantages and is chosen based on the requirements of the application. These methods allow for precise control over the thickness and composition of the deposited films.

Gold thin films are choice for the application in photovoltaic because of high electrical conductivity and chemical stability. Au thin films have many advantages and wide application prospects [7]. It has been studied extensively by previous researcher to explore its advantages in specific configurations to improve the performance of photovoltaic devices even though Au is high in cost. Some of previous researcher stated that the Au have been shown to increase the absorption in the active material and the cell performances [8].

Over the past few decades, there has been a substantial growth in the advancement of photovoltaic technology, resulting in larger, thinner, and lighter devices. However, this progress has led to an undesired increase in electrical resistivity. Thin film materials' physical properties are generally influenced by various factors, including substrate type, deposition technique, deposition conditions, and annealing treatment [6]. In industrial contexts, magnetron sputtering is a widely used deposition technique due to its simplicity and maturity [9]. There are two common sputtering processes, employing either direct current (DC) or radio frequency (RF) methods. This research places a greater emphasis on DC magnetron sputtering, as it proves to be a highly effective method for physically depositing thin film layers onto conductive substrates.

The purpose of this study is to characterize the Au thin films with different laser energy for photovoltaic applications. In this study the methods used are DC magnetron sputtering and laser annealing. The morphological, topological, electrical, and optical properties of the Au thin films structure was examined as functions of different laser energy.

2. Experimental details

2.1 Sample preparations

The Si substrate was cut into pieces of $1.0 \times 1.0 \text{ cm}^2$ and cleaned to suit the specifications of characterization equipment. Utilizing ultrasonic cleaning, the Si substrates were treated with acetone, isopropyl alcohol, and distilled water. Subsequently, nitrogen gas was employed to dry the Si samples, followed by a 15-minute treatment in a plasma cleaner to eliminate water molecules, hydrocarbons, and other particles or impurities prior to applying the thin film coating. The purpose of this cleaning procedure was to ensure the optimal performance of the Si substrate and to completely rid it of contaminants such as environmental dust, hand oils, and airborne particles.

2.2 Deposition of Au thin films

Au thin films were deposited onto an n-type silicon (111) substrate for comprehensive examination of their topological, morphological, electrical, and optical properties. The deposition process employed DC magnetron sputtering, specifically utilizing a Quorum Q150R S system at a pressure of 1×10^{-3} mbar. The magnetron sputter apparatus featured a single high-purity target (approximately 99.99%) designed for sputtering gold onto the silicon substrate. During sputtering, a sputter current of 40 mA was utilized, and the sputtering time was set to 600 seconds. To ensure a uniform surface for the deposited thin films, the sample plate underwent continuous rotation at approximately 50 rpm. The thickness of the gold films was precisely controlled at 10 nm, monitored by two Quartz Crystal Microbalance integrated within the chamber. Fig.1 shows the DC magnetron sputtering technique used in this study.

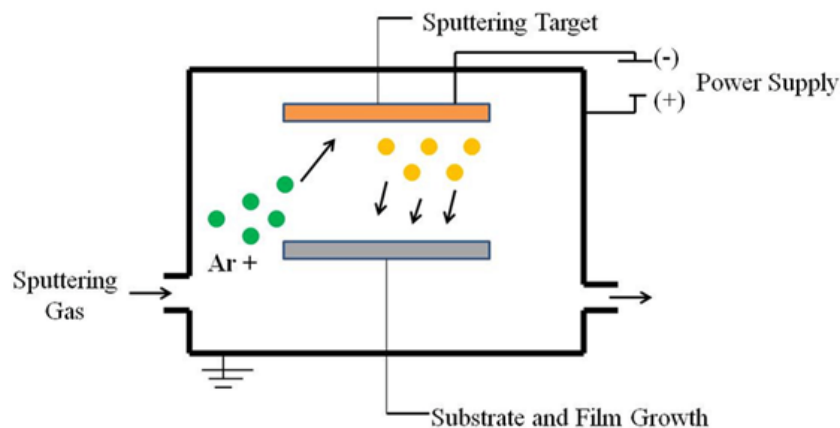


Fig. 1 The schematic diagram of DC magnetron sputtering technique [10].

The gold Au thin films deposited on a silicon substrate through sputtering were analysed for their morphological, topological, electrical, and optical characteristics. Fig. 2 illustrates a simplified representation of the structure of the Au thin films deposited on the silicon substrate.

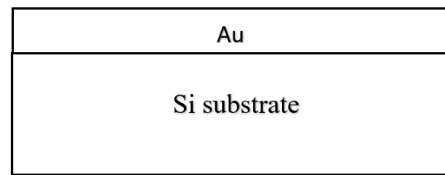


Fig. 2 The simple diagram of Au thin film deposited on Si substrate.

2.3 Thickness measurement by Ellipsometry

The ellipsometry is the method that serve as non-destructive optical technique used widely in characterization of thin films and surfaces. Through the analysis of changes in the polarization state of light during interaction with samples, ellipsometry provides a comprehensive understanding of optical characteristics, thickness, reflective index, and extinction coefficient of material. This method plays a role for many scientific and industrial applications, ranging from semiconductor technology to the development of solar cells and coatings. Ellipsometry is a very powerful tool to optimize the material properties and to monitor the process of deposition, especially in the electronic industry where to measure the thickness of deposited films [11]. Ellipsometry observes the change in polarization state of a light beam caused by surface reflection from a surface [12]. The angle of incidence ellipsometry has varies angle 60°, 70°, 75°. Ellipsometry equipped with an analyser which can measure the two crucial ellipsometry parameters which is Ψ (psi), representing the amplitude ratio, and Δ (delta), indicating the phase difference. Thus, for data analysis, the software is used to fit the experimental data to the model parameters to minimize the difference between measured and calculated values. The ellipsometry method was used after the deposition of Au thin films and get the thickness 25 nm with angle of 70°.

2.4 Laser treatment by Nd:YAG laser

There have been many distinct types of lasers developed, each possessing unique characteristics. The Neodymium-doped Yttrium Aluminum Garnet (Nd: YAG) laser stands out as a solid-state laser employing Nd:YAG as its laser medium. After deposition, the Au thin film was treated using a Nd:YAG pulsed laser featuring a wavelength of 1064 nm and a repetition rate of 1 Hz. The sample was annealed using Nd:YAG laser energy at varying levels: 50 mJ, 60 mJ, 70 mJ, and 80 mJ, all with a laser spot size of 1 cm². The laser radiated the material surface without changing its bulk. The differences in laser energy were used to differentiate the morphological, topological, electrical, and optical properties of the sample. A converging lens was positioned between the laser and the sample, and the samples were situated beyond the focal plane of the lens, resulting in low intensity and a large spot size. The sample was placed about 20 cm from lens and about 40 cm from the laser beam. The sample was bombarded with the Nd:YAG laser annealing for 2 shot. The laser annealing helped to improve the thin films performance.

2.5 Sample characterizations

Sample characterizations involved assessing the morphological properties using an Atomic Force Microscope (AFM), which excels in surface characterization by producing detailed three-dimensional structures at the nanoscale. The AFM employed a cantilever with a tip for imaging and measuring various forces, such as adhesion strength and mechanical properties. Topological properties were examined using a Scanning Electron Microscope (SEM), which is particularly effective in providing the high-resolution images, allowing us to closely examine the surface structure of our films especially in topographical information, such as surface roughness and texture, which are crucial for this study. The Four-Point Probe technique was utilized to measure the electrical properties, offering a non-destructive means to determine the resistivity of thin materials. This method can accurately determine the electrical resistance of Au thin films and understand how efficiently they can carry an electric current. Finally, UV-Visible Spectrophotometry assessed the optical properties of Au thin films, analysing absorption, transmission, and bandgap characteristics in the UV and visible regions. This tool helps in understanding how Au thin films interact with light by shining different colours of light onto the films and measuring how much is absorbed or reflected. These characterizations provided a comprehensive understanding of the Au thin film based on morphological, topological, electrical, and optical features for potential photovoltaic applications.

3. Results and discussion

3.1 Thickness measurement of Au Thin Film

The ellipsometry method was used after deposited the Au thin films and get the thickness 25 nm with angle of 70°. The value of Ψ provides information about the interaction of polarized light with the Au thin films surface as shown in Fig.3. In ellipsometry graph, the experimental Ψ values are typically plotted against the wavelength of incident light or other relevant parameters. The resulting graph often shows oscillations or variations in Ψ as a function of wavelength or angle of incidence. These oscillations are related to interference effects and can provide information about film thickness and refractive index.

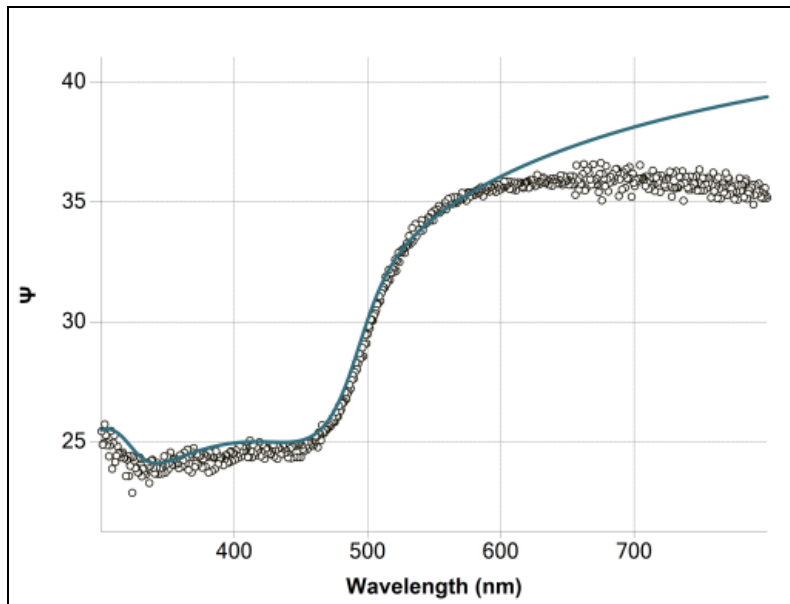


Fig.3 The result of ellipsometry graph in Ψ .

Graph Δ provides valuable information about the optical properties of the sample. Fig.4 show the changes in the Δ value that can be correlated with variations in the thickness.

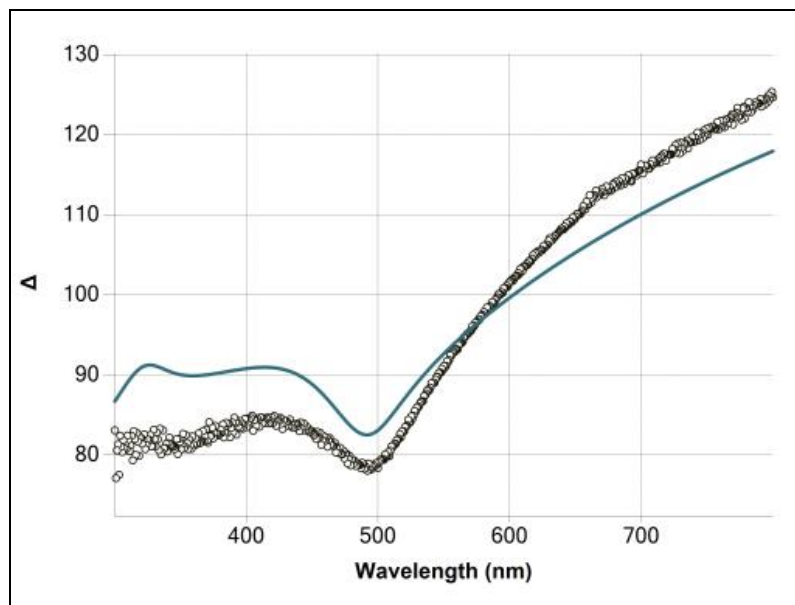


Fig.4 The result of ellipsometry graph in Δ .

3.2 Surface Morphological Properties

The atomic force microscope (AFM) analysis was done to observe the morphological properties of Au thin films. The AFM was produced 3D images of Au thin films on Si substrate. The different morphology for as a deposited and annealed sample were obtained by scanning over area of $5.0 \times 5.0 \mu\text{m}$. The different laser energy can influence the growth and morphology structure of the film, by affecting the surface roughness, grain size, and other morphological features. From as deposited to 80 mJ, when the applied laser energy increases, the roughness of treated samples get bigger and rougher due to the laser heat absorption. The result in size distribution changes due to the different laser annealing energy of Au thin films. Fig.5 displays the surface morphological in 3D images of Au thin film for the as deposited and annealed sample.

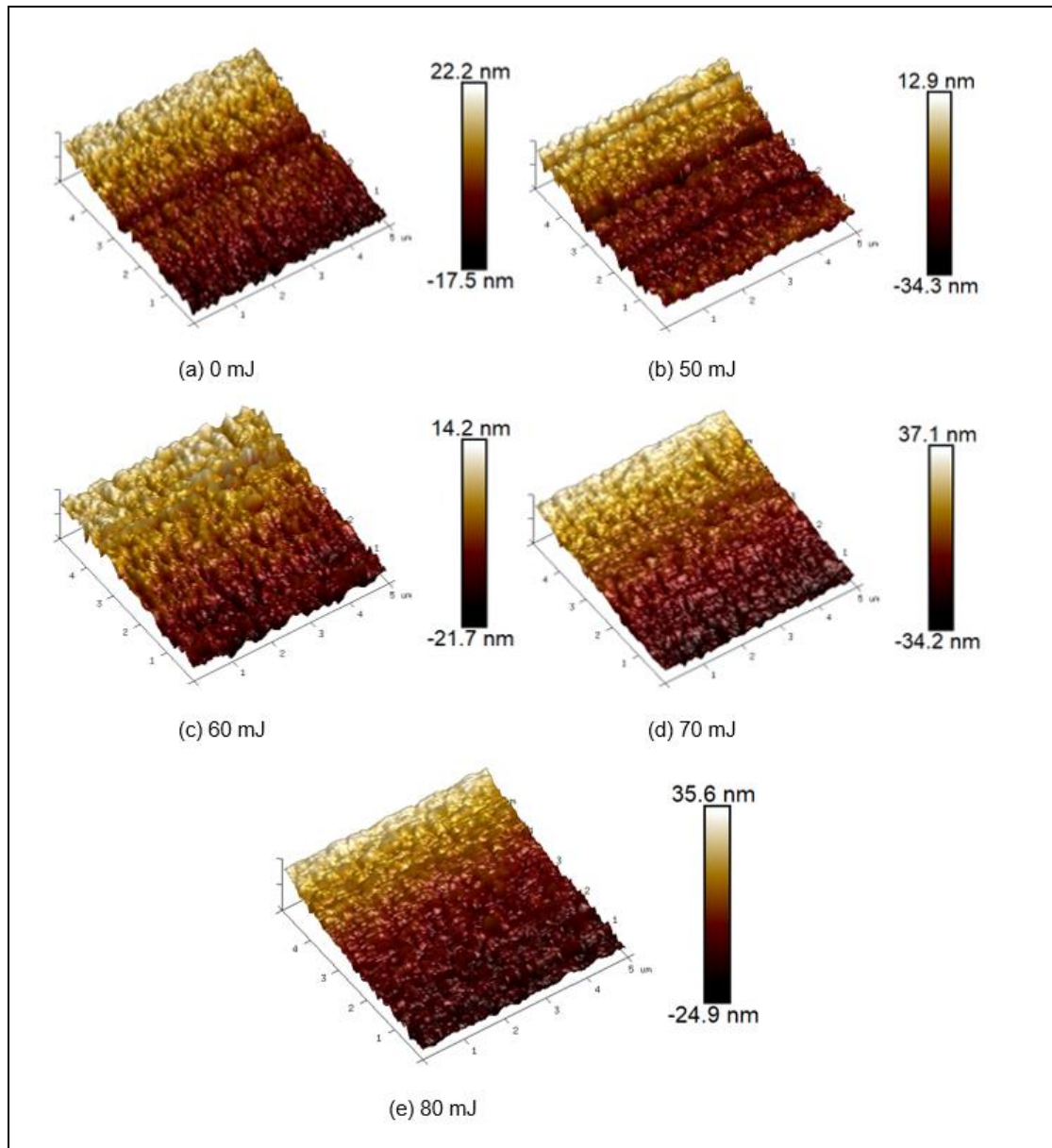


Fig.5 The 3D images of Au thin films morphological by AFM with different laser energy.

The roughness of the surface changes depending on the energy used for laser annealing. The sample with 60 mJ energy has the highest surface roughness as compared to as-deposited sample. From the observations show the laser annealing can influence the surface morphology of Au thin film. The textured surfaces help to reduce reflection of incident light, promote light trapping within the thin film and can increasing the optical path length which leading to higher absorption in thin film. This is crucial for maximizing the efficiency of photovoltaic devices. Table 1 shows the R_a and R_q of Au thin films measured at different energy levels.

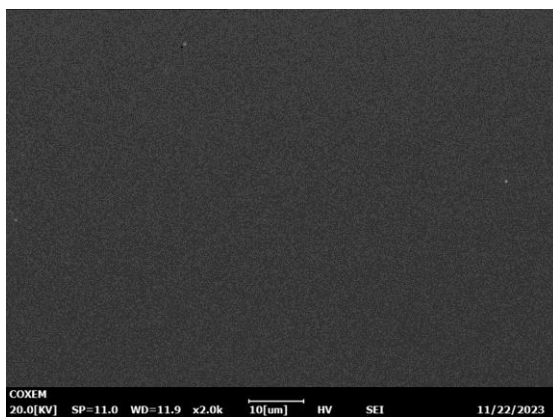
Table 1 The roughness average, R_a and RMS, R_q of Au thin films at different energy levels.

Laser Energy (mJ)	Roughness Average, R_a (nm)	Root Means Square (RMS) Roughness, R_q (nm)
0	0.243	0.405
50	0.362	0.551
60	0.385	0.647
70	0.192	0.452
80	0.302	0.465

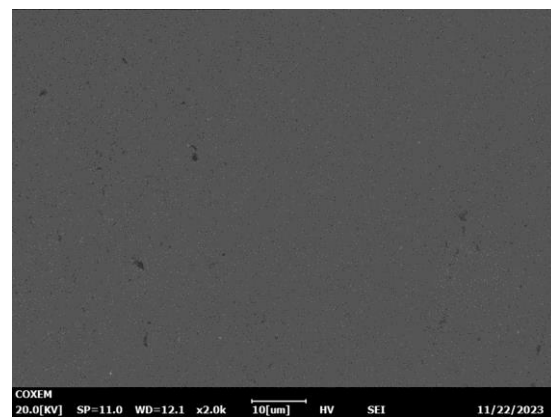
There is an increase in R_a and R_q corresponds to an increase in laser energy. This could be explained by considering the thermal considering the coalescence of small grains induced by thermal annealing. This process leads to substantial grain growth, where atoms transfer at grain boundaries, influencing the final grain size depending on the specific annealing conditions. Despite this, there are instances of minor fluctuations, including points where a reduction in roughness is observed, such as at 70 mJ and 80 mJ, with R_a and R_q values of 0.192 nm and 0.452 nm, 0.302 nm and 0.465 nm, respectively. Likewise, the grain size follows a comparable pattern to the RMS roughness.

3.3 Surface Topological Properties

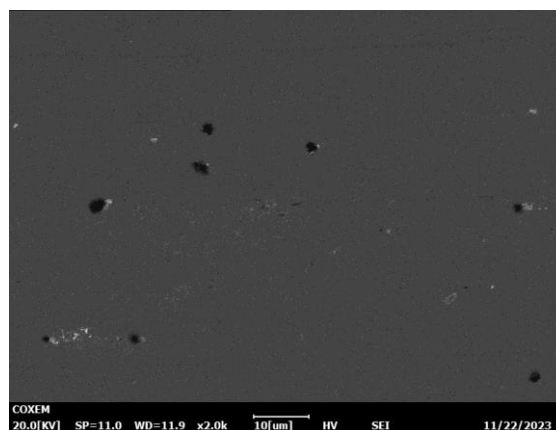
SEM was used to determine the topological properties of Au thin film. The thickness for each film was same which is 25 nm. The Au thin films were observed by 2000 x magnification via SEM. The selection of samples 0 mJ, 60 mJ, 80 mJ for this characterization is to see a more significant difference on the surface topology of the Au thin films. Fig.6 displays the surface topology in 2D images for the deposited and annealed samples of Au thin films.



(a) 0 mJ



(b) 60 mJ



(c) 80 mJ

Fig.6 The 2D surface morphological of Au thin films with different laser energy using SEM at 2000 x magnifications.

SEM images of the as-deposited Au thin films show a relatively uniform and compact surface with discernible grain boundaries. The surface was generally smooth, indicating the initial quality of the deposition process. The as deposited samples were rather flat and there were no holes or other defects on the surface. SEM images of the samples annealed at 60 mJ showed fine grains and a slight increase in surface roughness were observed. The surface of films has a small defect on it, which show the beginning of structural changes induced by the laser before characterization. SEM images after laser annealing at 80 mJ displayed significant changes in the Au thin film. Larger grains and more textured features were observed, many defects that appeared on the surface due to highest laser energy applied. These defects can significantly affect the performance and reliability of photovoltaic devices. From the result of experimental analysis, the black and white regions was identified as Si and Au.

3.4 Electrical properties

The electrical properties of Au thin film were obtained by using four-point probe measurements. The findings demonstrate a reduction in resistivity, going from 4.34×10^{-5} to $3.06 \times 10^{-5} \Omega/\text{cm}$, for the as-deposited sample and the sample annealed at 60 mJ. In the pursuit of enhancing the performance of photovoltaic devices, the investigation focused on the impact of annealing energies on resistivity variations within Au thin films structure. The observed trend indicated an increase in resistivity with higher annealing energies. This phenomenon was attributed to the intricate interplay between the metal–semiconductor contact behaviour and the influence of laser annealing on structural defects at the material surface. Based on Table 2 the highest resistivity value recorded was $4.56 \times 10^{-5} \Omega/\text{cm}$, and this was achieved after annealing at 60 mJ. Above 60 mJ, the figure of merit increased with the increase of laser energy.

Table 2 The measured resistivity of Au thin films by four-point probe.

Laser Energy (mJ)	Resistivity ρ ($10^{-5} \Omega/\text{cm}$)
0	4.34
50	3.68
60	3.06
70	4.12
80	4.56

Consequently, the result of these findings led to the identification of an optimal laser energy for the Au thin film structure. The pinnacle of performance was achieved at 60 mJ, as supported by the presented electrical results. The decrease in resistivity at 60 mJ can be attributed to the controlled heating effect of the laser energy. At this energy level, the laser serves as a precise heat source, facilitating localized annealing within the thin film without causing excessive damage. Thus, this study underscores the relationship between annealing energies, resistivity variations, and the overall electrical performance of thin film structures, providing valuable insights for the advancement of photovoltaic devices. Electrical properties of Au thin films were obtained from four-point probe measurements shown in Fig.7.

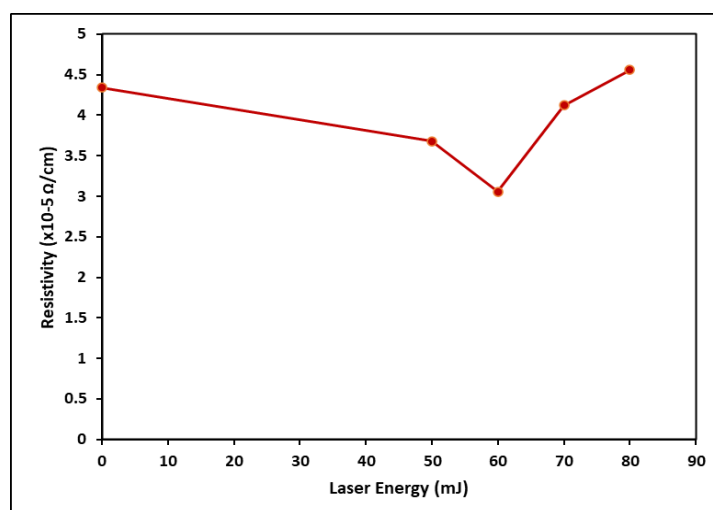


Fig.7 The resistivity measured of Au thin films deposited on silicon as a function of the laser annealing energy.

3.5 Optical properties

The optical properties of Au thin film are the absorbance which is highly dependent on the deposition method. The relationship between sputtering method parameters and Au thin film properties was important to achieve good reproducibility of film characteristic for industrial scale applications especially in photovoltaic application. The absorption of Au thin films is influenced by its, thickness, material properties, and the wavelength of light.

Fig 8 shows the optical absorbance of the as deposited and annealed Au thin films. The optical properties of Au thin films are measured by UV-Vis spectrophotometer. The measurement was taken in the wavelength with range 300-500 nm. The deposited sample was showing the lowest absorption of light with average 1.7 at a wavelength of 450 nm, while the annealed sample was showing the increase in the absorption of light due to increasing the laser energy. The Au thin film that annealed with 60 mJ have the highest absorption of light with average 8.6 at a wavelength of 600 nm. The UV-Vis proved that the annealing have significant effect on the Au thin films. In the context of photovoltaic devices, it's often desirable to have a high absorption of light within the active layer of the device. This is because a higher absorption of photons means more efficient conversion of light energy into electrical energy. Fig.8 shows the absorption of Au thin films for different laser annealing energy.

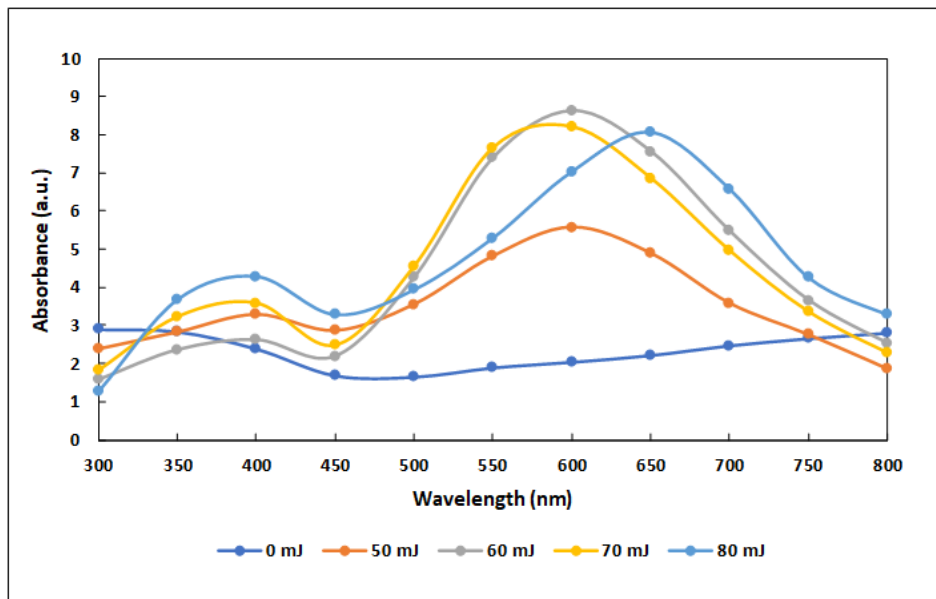


Fig.8 The absorbance measured of Au thin films by UV-Vis Spectrophotometer for different laser annealing energy.

4. Conclusion

In conclusion, Au thin films, initially deposited on silicon substrates through DC magnetron sputtering, were systematically investigated, focusing on their morphological, topological, electrical, and optical properties following laser treatment with varying laser energy. The thickness of the Au thin films was maintained at a constant 25 nm throughout the experiment. The laser treatment, conducted with a Nd:YAG at a 1064 nm wavelength and varying energy levels 50 mJ, 60 mJ, 70 mJ and 80 mJ aimed to assess the impact on thin films for potential application in photovoltaic systems. AFM analysis shows a significant increase in surface roughness after the laser annealing from 50 mJ to 80 mJ. SEM analysis initially showed a smooth and defect free surface for the deposited Au thin films exhibited a smooth and defect-free surface. Au thin film of 60 mJ laser energy induced subtle changes, while 80 mJ laser energy of Au thin film led to significant alterations, including larger grains and surface defects. Additionally, the annealing treatment show a significant improvement in resistivity, which leading to decrease from 4.34×10^{-5} to $3.06 \times 10^{-5} \Omega/\text{cm}$. After the annealing treatment, the optical absorption increases significantly to 8.6 for the 60 mJ of laser energy at a wavelength of 600 nm. These findings highlight the efficacy of laser annealing in enhancing the efficiency properties of the Au thin films, showcasing their potential applicability in photovoltaic applications such as solar panels. The observed improvements in surface roughness, surface topology, resistivity, and optical absorption suggest promising advancements for the integration of these Au thin films in photovoltaic devices, contributing to their performance in solar energy conversion. It also can be applied to many applications, including flat panels, gas sensor, and LEDs.

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Conflict of Interest

There is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design, data collection, methodology, analysis and interpretation of results:** Nurul Athirah Mat Nayan and Ahmad Hadi Ali. All authors reviewed the results and approved the final version of the manuscript.

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