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Energy Dependent Laser Annealing of Au Thin Films on Si for Application of Photodiode

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Abstract

Achieving high ohmic contact efficiency of metal contacts on photodiode is quite challenging due to the low electrical contact resistance characteristics. In the context of photodiodes, ohmic contacts are crucial for efficient extraction of photocurrent generated by the device. Hence, laser annealing was chosen as it is an effective method for improving the properties of thin films and enhance the overall performance of photodiode. In this study, Au thin film was deposited on a p-type silicon using DC sputtering technique followed by thickness measurement of the samples by ellipsometry. Then, the sample underwent laser annealing treatment by using Nd:YAG laser at different energies. The samples were characterized based on the morphological, topological, electrical, and optical properties by using Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), Four-Point Probe and UV-Visible Spectroscopy respectively. The result analysis of AFM shows that the highest laser energy, which is 55 mJ, has the highest grain size and surface roughness compared to the as-deposited sample. Next, the topological analysis of SEM shows that the annealed sample with energy of 55 mJ appeared to have more defects than the 35 mJ and as deposited samples. The electrical characterization analysis shows that the resistivity of the Au thin films dropped as the laser energy increases. The analysis of optical properties shows the sample annealed at 55 mJ has the highest absorbance and lowest reflectance value at wavelength of 600 nm. The results indicate that the laser annealing could significantly improve the efficiency of Au thin films which can be potentially applied in photodiode devices.

1. Introduction

The most widely used methods for annealing are indirect annealing methods. such as rapid thermal annealing and conventional furnace heating. However, in recent decades there are remarkable capabilities of more “direct” annealing techniques, such as laser annealing. Laser annealing has become increasingly apparent to improve optoelectronic properties [1]. Laser annealing is a process used to modify the properties of materials, particularly in the context of semiconductor and thin-film technologies that involves using a laser beam to heat and then cool a material in a controlled manner. This process also induces recrystallization and improves the crystallinity of materials leading to enhanced properties of materials such as optical, electrical and structural properties. Thin films on photodiodes play an important role in improving their performance and functionality

[2]. These films can be from variety of materials, such as metals, oxides, semiconductors, or organic compounds, relying on the preferred properties and application of the photodiode.

In a photodiode, an ohmic contact is essential for efficient charge transport between the semiconductor material and the metal electrode. However, it is a challenge to achieve very high ohmic contact efficiency particularly on metal contacts based on Si. Thus, Au is chosen to improve the thin films' properties.

The addition of an Au (gold) thin film coating on a silicon (Si) photodiode serves as an ohmic contact on the photodiode surface, allowing low-resistance electrical connections. An ohmic contact is characterized by low resistance and good electrical conductivity. The presence of the Au thin film can contribute to achieving ohmic contact properties, facilitating efficient charge carrier transport between the metal and semiconductor [3]. Moreover, the deposition of Au and laser annealing will improve the lattice structure of Au thin films [4].

In this study, Au thin films were deposited onto the p-type Si substrates followed by laser annealing treatment at different laser energy. The samples were analyzed with respect to their morphological, topological, electrical, and optical characteristics.

2. Materials and Methods

Au thin films were deposited using DC sputtering system model Q150RS. Using a constant deposition time which is 10 minutes, Au was sputtered onto Si substrates. The film thickness was set to 10 nm. The sputtering current was 80 mA, and the chamber pumped the base pressure between 5×10^3 mbar to 3×10^3 mbar. Before deposition, the Si substrates underwent a cleaning process using an ultrasonic cleaner with acetone solution, isopropyl alcohol, distilled water, and a dry pump. Afterward, the samples underwent a 15-minute exposure to high-level RF waves in a plasma cleaner. The cleaning process was to make sure the Si substrates were completely free from any contaminants such as dust from the environment, oil from hand and air.

After deposition, the thickness of Au thin films was measured with incidence angle of 70°. Then, Nd:YAG laser was used to anneal the sample at 25 mJ, 35 mJ, 45 mJ, and 55 mJ with 1 cm^2 of the laser spot size. The sample was exposed to a single shot of Nd:YAG laser annealing after the shutter was opened, covering the entire sample.

The characterization of Au thin film starts with Atomic Force Microscopy (AFM) to study the morphological properties of Au thin film. Next, the topological properties of Au thin film were studied by Scanning Electron Microscopy (SEM). Moreover, the electrical properties of Au thin films were analyzed by using Four-Point Probe. The optical properties were investigated by using UV-Visible Spectrometry to determine the absorbance and the reflectance. The wavelength range used in the characterization were 400-800 nm.

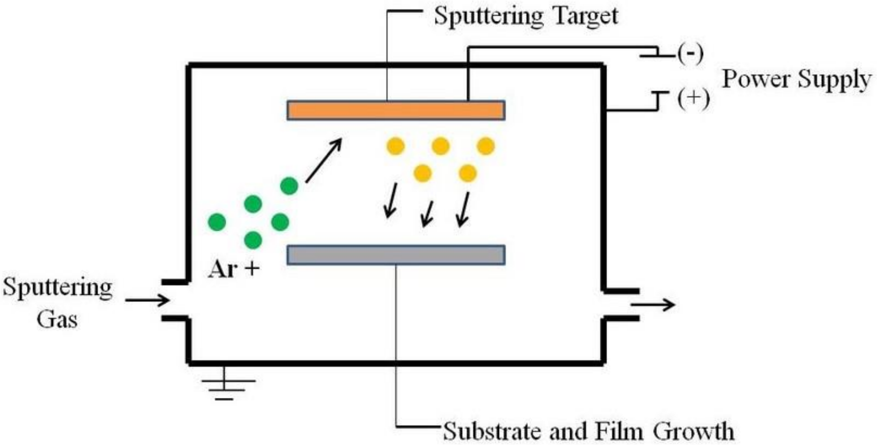


Fig. 1 *Schematic diagram of DC Sputtering [5].*

3. Results and Discussion

3.1 Thickness measurement of Au Thin Films

The ellipsometry method was used after the Au thin films were deposited and get the thickness 25 nm with incidence angle of 70°. Based on Fig. 2, the value of Ψ provides information about the interaction of polarized light with the Au thin films surface. In ellipsometry graph, the experimental Ψ values are typically plotted against the wavelength of incident light or other relevant parameters [6]. The resulting graph often shows oscillations or variations in Ψ as a function incidence angle or wavelength. These oscillations are related to interference effects and can provide information about film thickness and refractive index [7]. Fig. 3 provides valuable information about the optical properties of the sample which show the changes in the Δ value can be correlated with variations in thickness. The 25nm thickness is critical for achieving the desired energy transfer and heat distribution during laser annealing to ensure that the heat is distributed optimally across the entire thickness of the film. This uniform heat distribution is vital for achieving consistent and improved crystallinity.

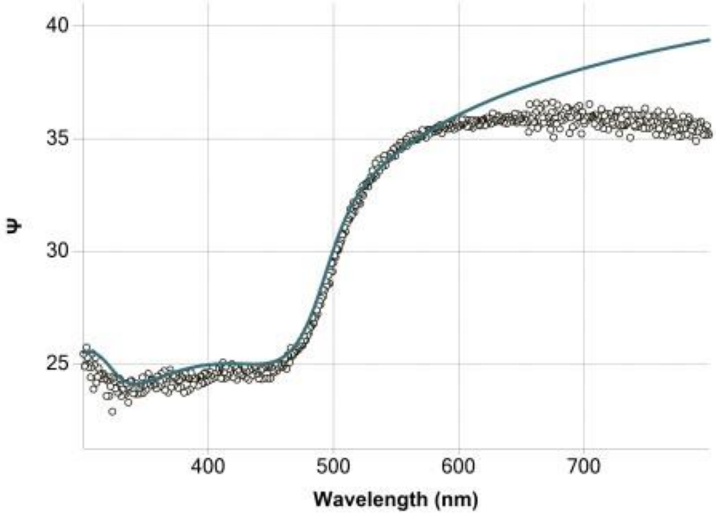


Fig. 2 *Ellipsometry graph obtained in Ψ.*

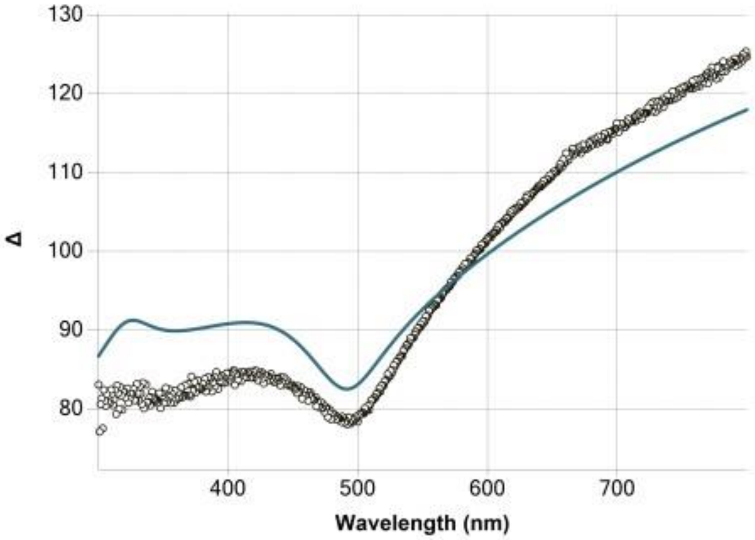
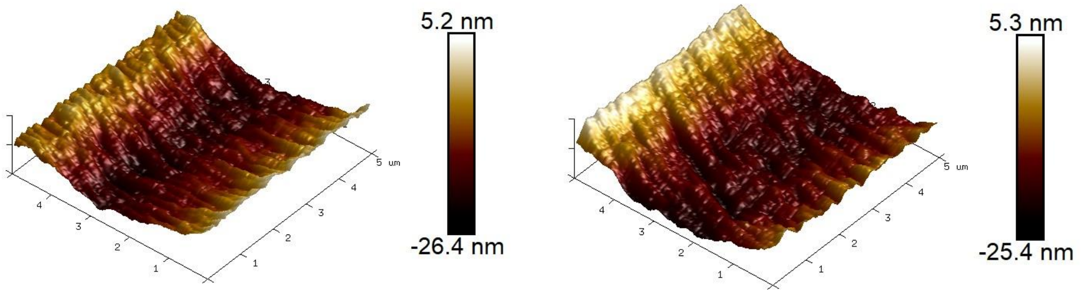


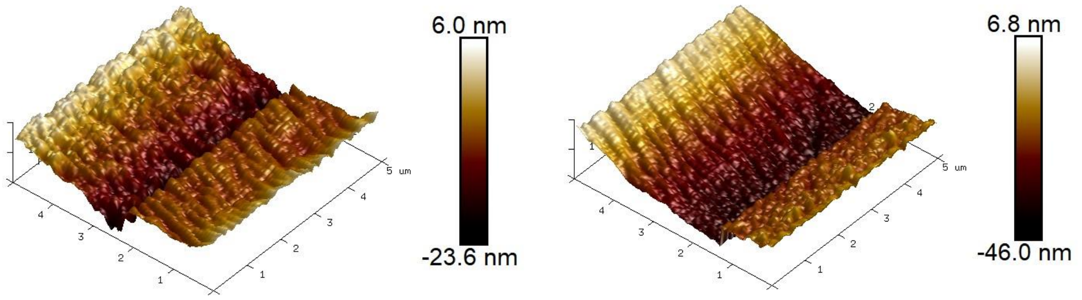
Fig. 3 *Ellipsometry graph obtained in Δ.*

3.2 Morphological Properties of Au Thin Films

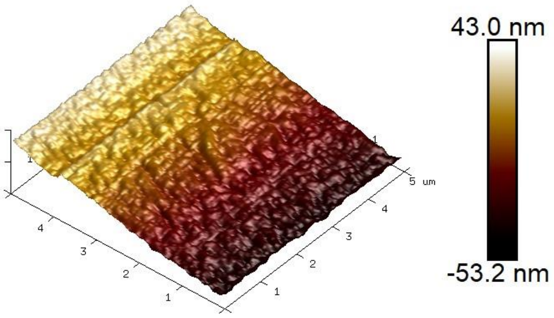
Morphological characteristics of Au thin film was conducted by AFM to identify properties of materials such as grain size and RMS roughness. The different morphology for as deposited and annealed sample were obtained by scanning over area of 5.0 × 5.0 µm. Fig. 4 shows the AFM 3D images of Au thin films of different laser energies. Due to laser heat absorption, when the applied laser energy increases, the grain size and roughness of the treated samples gets bigger and rougher [8], from as deposited to 55 mJ. Rough texture can enhance light absorption and trapping within the thin films, thus increasing the efficiency of photodiode. The result in size and distribution of the grain changes due to the different laser annealing energy of Au thin films.



a) 0 mJ b) 25 mJ



c) 35 mJ d) 45 mJ

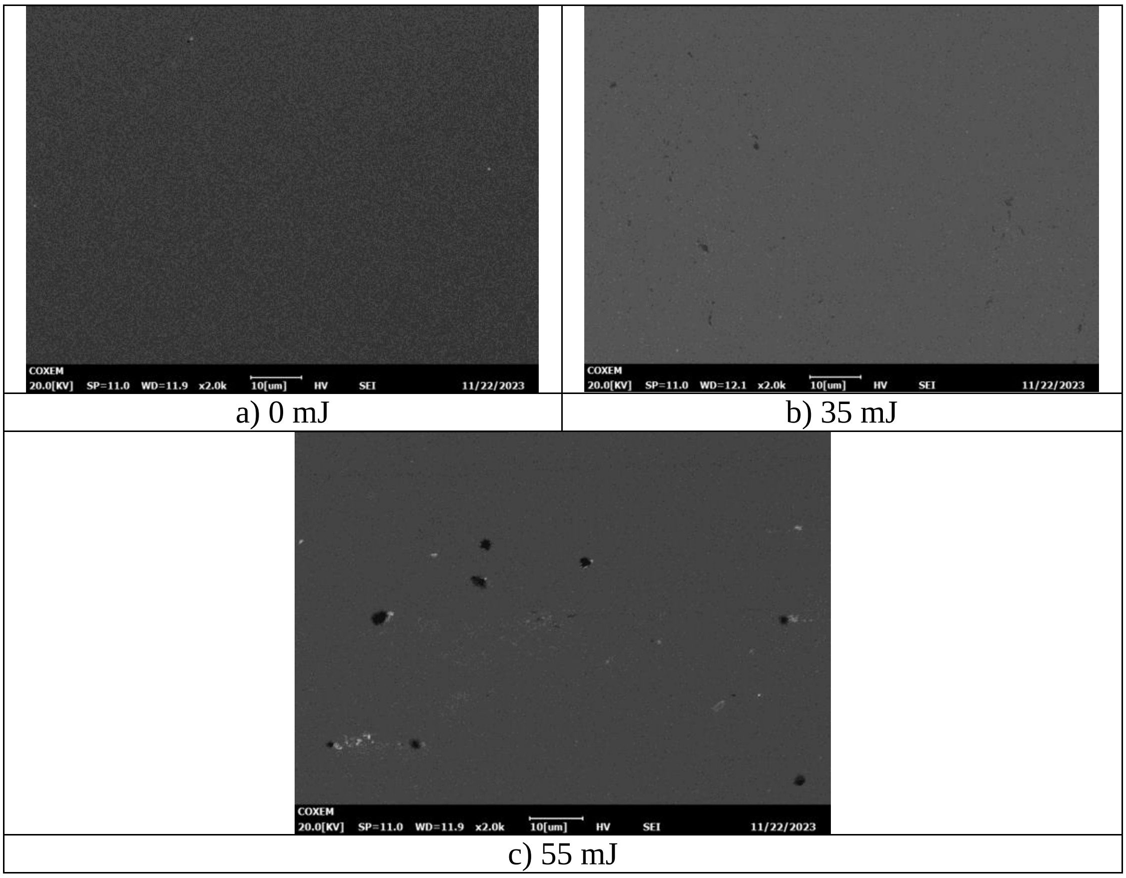


e) 55 mJ

Fig. 4 *3D images of Au thin films of different laser energies.*

3.3 Topological Properties of Au Thin Films

SEM technique was conducted to determine the topological characteristics of Au thin films. Different laser energies of Au thin films were used which are 0 mJ, 35 mJ and 55 mJ. Fig. 5 shows the 2D image of Au thin films of different laser energies. As can be seen in the results, as the laser energies increases, the defect spots increase. The as deposited samples were rather flat and there were no holes or other defects on the surface. The samples annealed at 35 mJ showed fine grains on the surface of film. This occurred because of laser annealing that was shot on sample before characterization. Meanwhile, Au thin film with energy of 55 mJ is rougher and have many grains appeared on the surface due to highest laser energy applied.



a) 0 mJ

b) 35 mJ

c) 55 mJ

Fig. 5 *2D images of Au thin films of different laser energies using SEM technique.*

3.4 Electrical Properties of Au Thin Films

The electrical properties of Au thin film were obtained by using four-point probe measurement. In this method, different laser energies of thin films of Au will be used to measure the electrical resistivity of Au. Table 1 shows the resistivity $\rho \times 10-5$ (Ω/cm) obtained for different laser energy of Au thin films (mJ). From Fig. 6, it is observed that the resistivity decreased as the laser energy increased which is from 3.52×10^{-5} Ω/cm to 3.15×10^{-5} Ω/cm. The increase in laser energy may induce local heating in the Au thin film [9]. This heating could lead to annealing effects, such as grain growth or reduction of defects, which can enhance the crystallinity of the film. Improved crystallinity often results in lower resistivity [10], which are essential for the photodiode's performance.

Table 1 *Resistivity* $\rho \times 10-5$ *(Ω/cm) obtained for different laser energy of Au thin films (mJ).*

Laser Energy (mJ)	Resistivity ρ (10^{-5} Ω /cm)
0	3.52
25	3.49
35	3.33
45	3.27
55	3.15

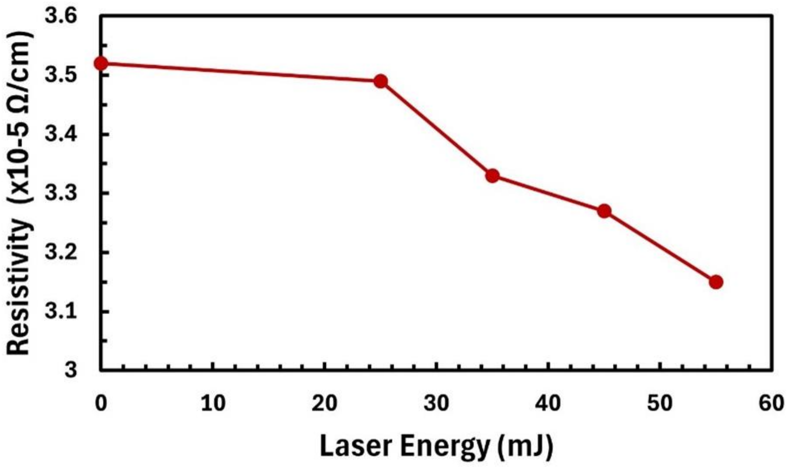


Fig. 6 *Resistivity ρ × 10−5 (Ω/cm) vs laser energy (mJ) graph.*

3.5 Optical Properties of Au Thin Films

The absorbance of Au thin films, an aspect of their optical properties, was determined within the wavelength range of 400 nm to 800 nm for UV-Visible Spectroscopy. Fig. 7 shows the as deposited sample showing the lowest absorption of light with average of 0.4 Au at a wavelength of 400 nm, while the annealed sample was showing the increase in the absorption of light due to increasing of the laser energy. The sample that annealed with 55 mJ have the highest absorption of light with average 8.4 Au at a wavelength of 600 nm. This is due to the rough texture of the sample. This result can be related to morphology of a thin film, where a rough texture can enhance its optical properties and light absorption capabilities. Figure 8 shows that the sample with 55 mJ has the lowest reflectance value which is 0.2 % at 600 nm which is is desirable because it allows more incident light to reach the photodiode's active area, increasing its sensitivity to light. The UV-Vis proved that the annealing have significant effect on the Au thin films. In the context of photodiode devices, it is 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 [11].

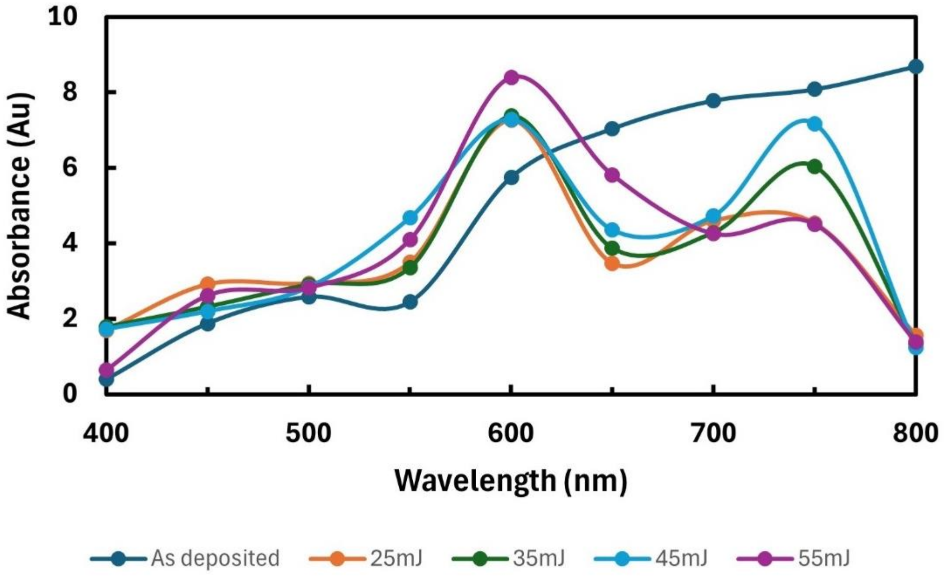


Fig. 7 *Absorbance (Au) with wavelength (nm) graph with different laser energy of Au thin films.*

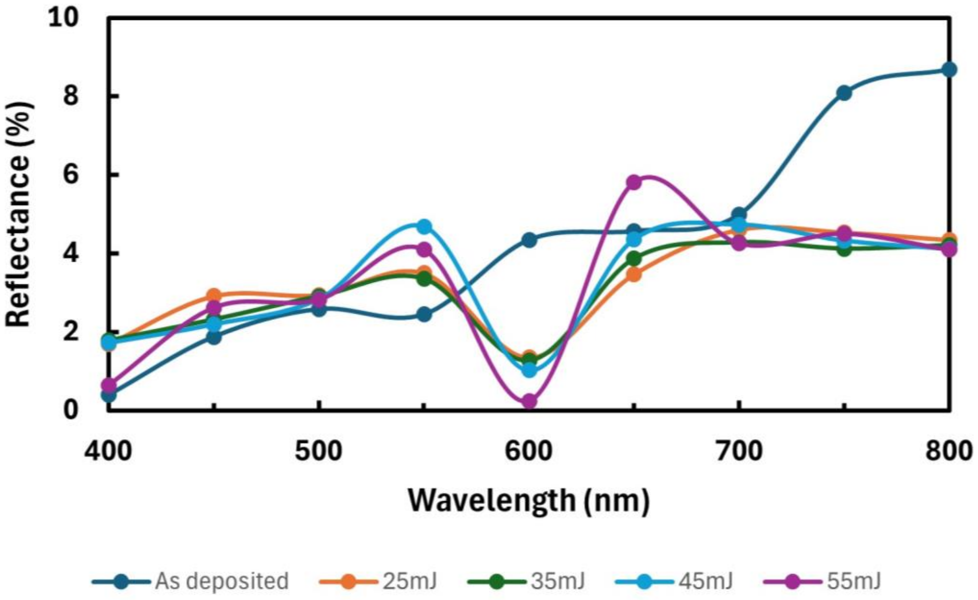


Fig. 8 *Reflectance (%) with wavelength (nm) graph with different laser energy of Au thin films.*

4. Conclusion

In this study, the morphological, topological, electrical, and optical properties of Au films were investigated to study the characterization of Au thin films with laser annealing at different laser energy. For laser energy of 55 mJ, the AFM analysis shows that the film has the highest grain size and surface roughness compared to the deposited sample. Furthermore, the topological characteristics were observed from SEM images. The analysis of SEM shows that the annealed sample with energy of 55mJ appeared to have many grains and is rougher than 35 mJ and as deposited sample. Meanwhile, the value of resistivity obtained by Four-Point Probe for 55 is mJ $3.15 \times 10^{-5}\Omega$/cm. Finally, the optical properties analysis for Au thin films shows the sample annealed at 55mJ has the highest absorbance which is 8.4 Au and the lowest reflectance value which is 0.4 % at wavelength of 600 nm. Therefore, from this analysis, it is found that the optimum laser energy of Au thin film is 55 mJ because it has the most suitable requirements for an effective application of photodiode such as rough surface, low resistivity, and high light absorption.

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Conflict of Interest

Authors declare that 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 Amirah Mahadzor and Ahmad Hadi Ali. All authors reviewed the results and approved the final version of the manuscript.*

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