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Characterization of Au Thin Film at Different Thicknesses

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Abstract

The demand for high-performance LEDs has fueled extensive research into ideal metal-semiconductor contacts. However, challenges persist in achieving an optimal design and composition, particularly in selecting suitable metals, understanding the impact of thin films, and applying various deposition techniques. This study investigates the properties of sputter-deposited gold (Au) contacts on silicon (Si) semiconductors, contributing to the advancement of LED technology. The research involves depositing gold (Au) thin films on n-type silicon (Si) and glass substrates using DC sputtering. A systematic variation in film thickness, ranging from 10 to 50 minutes, is implemented. The thickness of the deposited material on the samples is determined using ellipsometry. The samples undergo comprehensive characterization based on the topology, morphology, electrical, and optical properties of the treated Au thin film, examined through Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), Four-Point Probe (4PP), and Ultraviolet-Visible Spectroscopy (UV-VIS), respectively. AFM results reveal an increase in grain size and thickness, with the 81.8 nm sample exhibiting the highest surface roughness, thereby impacting the conductivity enhancement of the Au thin film. Higher weight percentages at 81.8 nm result in a rougher surface regarding morphological properties. Four-point probe measurements demonstrate an inverse relationship between resistivity and thickness. Finally, UV-Vis spectrometer analysis reveals increasing trends in absorbance graphs with rising thickness. In conclusion, the Au thin film with a thickness of 81.8 nm is determined to exhibit the best overall properties.

1. Introduction

In the exploration of fundamental principles, electrical characteristics, and applications of metal-semiconductor contacts and Light-Emitting Diodes (LEDs) [1], our focus is on optimizing metal contacts in LEDs, considering factors such as energy efficiency [2], simplified fabrication processes [3], and cost reduction [4]. Crucial for semiconductor device performance [5], metal-semiconductor contacts require careful metal selection, with distinct advantages found in metals like nickel (Ni) [6], aluminum (Al) [7], platinum (Pt) [8], chromium (Cr) [9], gold (Au) [10], and titanium (Ti) [11].

Thin films, particularly those composed of gold (Au), play a central role in electronics and optics due to their distinctive characteristics [12]. Understanding the behavior of thin films, especially the dynamics of thickness [13], is critical for optimizing their applications as it significantly influences structural, electrical, and optical properties. With the increasing demand for high-performance LEDs, our dedicated focus is refining the design and composition of metal contacts to enhance luminous efficiency and electrical properties.

Gold (Au) is interesting due to its widespread use as a transparent current-spreading electrode in GaN light-emitting diodes and liquid-crystal displays. Moreover, Au exhibits resilience to high processing temperatures commonly encountered in semiconductor processes. Overcoming challenges associated with establishing good Ohmic contact, especially when working with novel materials like Ga_2O_3, is essential. In this context, ITO emerges as a potential solution. Previous work by Carey and Oshima demonstrated the feasibility of developing an Ohmic contact using ITO. Importantly, this approach achieves performance comparable to Ti/Au without requiring extensive surface preparation [3].

At the core of this exploration is investigating metal contacts on silicon (Si) semiconductors deposited via the sputtering technique. Advanced tools like Atomic Force Microscope (AFM), Scanning Electron Microscopy (SEM), Four-Point Probe, and Ultraviolet-Visible Spectroscopy (UV-Vis) are utilized to discern topographical, morphological, electrical, and optical characteristics. The overarching objective is to propose optimal electrical characteristics.

2. Materials and Methods

2.1 Material Specification

Precise 1 cm × 1 cm silicon (Si) samples using a diamond scriber pen and marked glass slides, ensuring accuracy. Si and glass underwent thorough chemical cleaning, including heating in Acetone and Isopropyl alcohol for Si and Decon-90 for glass. The sample was heated at 60°C for 15 minutes using an ultrasonic cleaner to eliminate the contamination on the sample surface. After cleaning, the samples were inserted inside plasma cleaner and subjected to the Nitrogen gaseous for 15 minutes to remove impurities including water molecules.

Si substrates underwent DC sputtering, depositing gold (Au) atoms with Argon gas using the Q300T DC sputtering system. The machine, loaded with Au target material, ensured precise deposition. The sample holder, covered in aluminum foil, controlled the process. The base pressure during the sputtering process was 1×10^{-2} mbar and 1×10^{3} mbar with rotation of the sample holder of ~50 rpm. **Fig. 1 (a) and (b)** present a simplified.

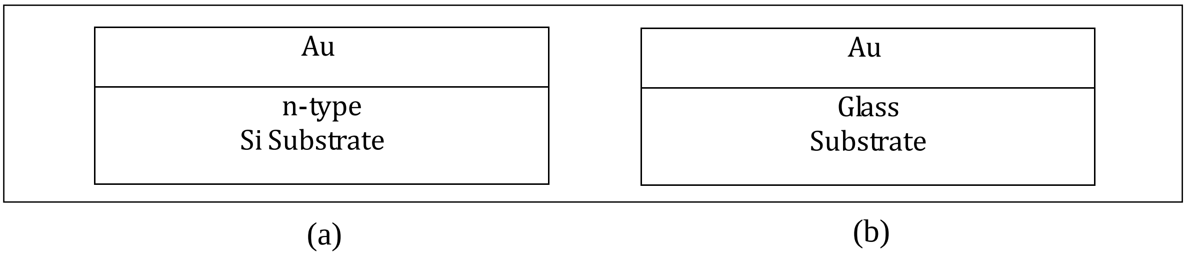


Fig. 1 *A simple diagram of the Au layer deposited on (a) Si and (b) glass substrate was presented.*

The deposition process involved repeating the application of Au five times, with each session lasting for varying durations: 10, 20, 30, 40, and 50 minutes. After each deposition, SE-2000 Spectroscopic Ellipsometer was used to determine the thickness of the deposited material on the samples.

Post-deposition, the characterized metal contacts were analyzed, focusing on the Bruker Dimension Edge Atomic Force Microscopy (AFM) to determine the grain size and the roughness of Au thin film, the COXEM Scanning Electron Microscope with Energy-Dispersive X-ray Spectroscopy (SEM-EDX) for examining structural properties, the Pro-4 Probing Station Model LUCAS LABS for evaluating electrical properties, and the UV-3600i Plus UV-Vis-NIR spectrophotometer to determine the optical properties. The wavelength range used was 300 nm - 1500 nm.

3. Results and Discussion

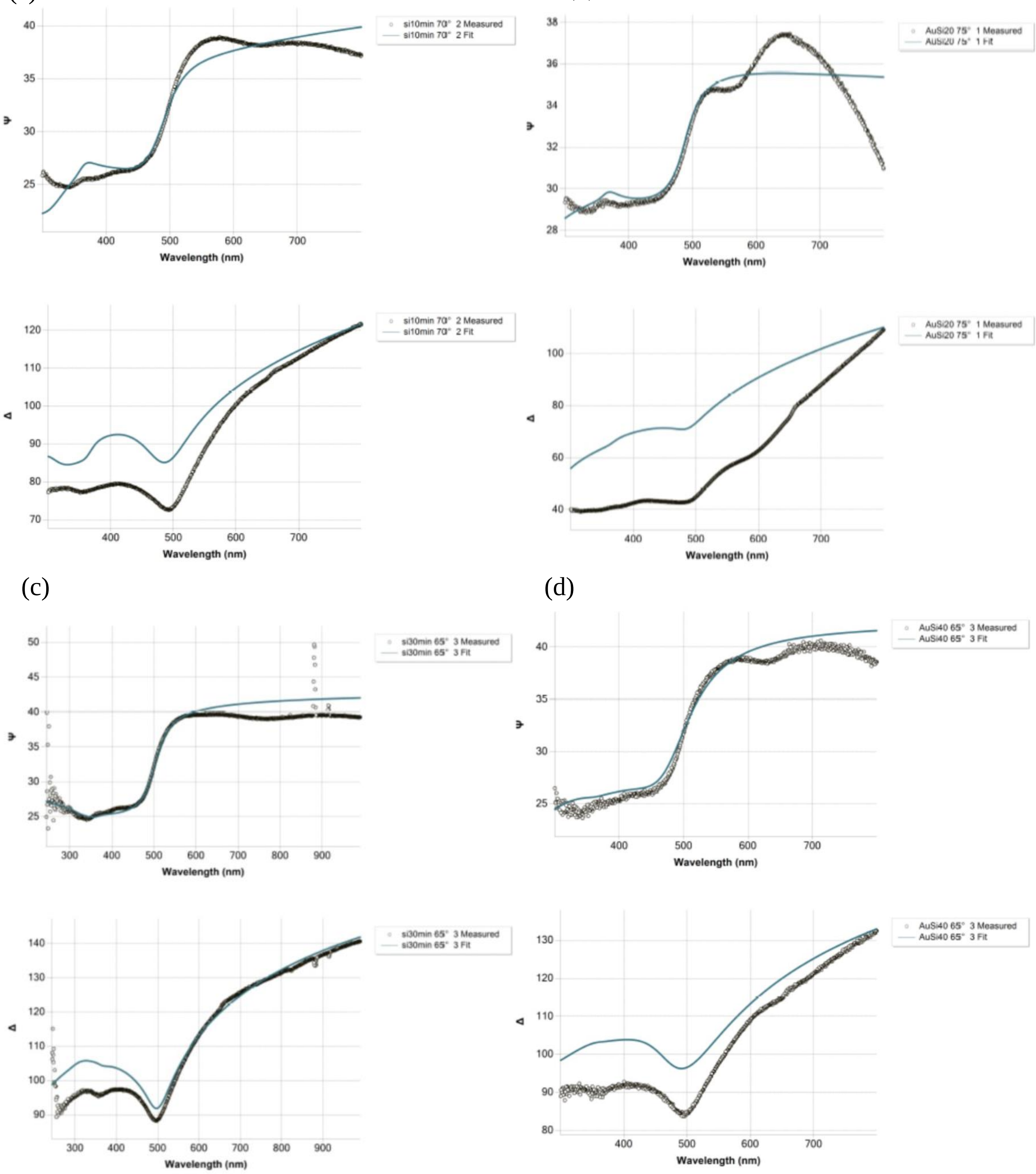
The collected data were systematically processed to explore the correlation between the thickness of Au thin films deposited on n-type Si and glass substrates. Comprehensive characterization was conducted using an ellipsometer, atomic force microscopy (AFM), scanning electron microscopy (SEM), and ultraviolet-visible spectroscopy (UV-Vis). The Si/Au substrates provided insights into topological properties, morphological structure, and electrical characteristics, while data on optical properties, specifically light transmittance, were gathered for glass/Au substrates.

3.1 Ellipsometry analysis

The ellipsometer measured the thickness of Au thin films deposited on Si and glass substrates. Ellipsometric studies of the Si/SiO_2 interface revealed the existence of an intermediate layer (SiO_x) between an atomically abrupt Si and SiO2 interface. The impact of this intermediate layer is minimal for modeling thicker films compared to SiO_x, with a few nanometers of thickness. The ellipsometric data include a tabulated database for a SiO layer, and the models of Si/SiO_2 and $Si/SiO/SiO_2$ can be chosen for the best fitting of the data [13].

Fig. 2 displays the thicknesses of Au thin films measured at different sputtering times. The first deposition yielded a fitting that accurately estimated the film thickness, measuring 29.6 nm for the 10-minute sputter time of Au. Similarly, the 20-minute deposition showed an accurate estimation, with a thickness of 35.8 nm. The 30-minute deposition resulted in a film thickness of 49.7 nm, and the 40-minute deposition yielded a thickness of 64.6 nm. Finally, the 50-minute deposition offered an accurate estimation of film thickness, measuring 81.8 nm.

(a) (b)



(e)

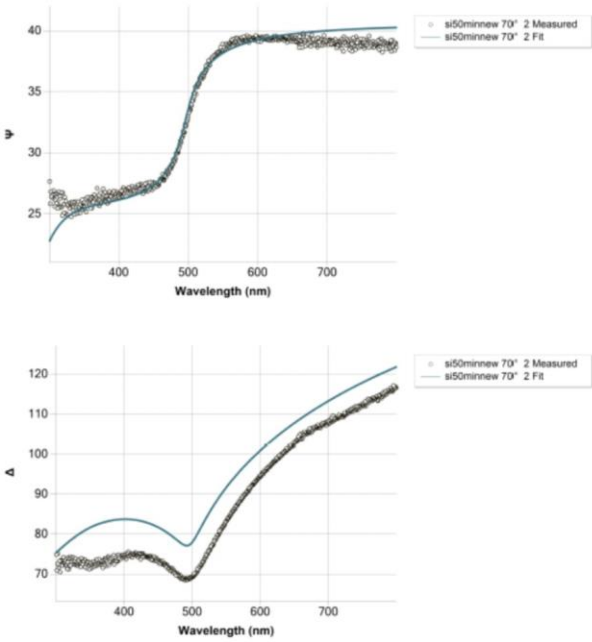


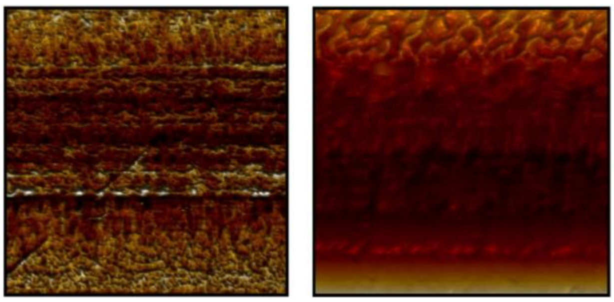
Fig. 2 *Comparison of measured and fitted curves for Au thin film at (a) 29.6nm, (b) 35.8nm, (c) 49.7nm, (d) 64.6nm and (e) 81.8nm.*

In evaluating the ellipsometry dataset, the most accurate thickness for characterization is determined by considering the Coefficient of Determination (R^2) and Root Mean Square Error (RMSE). In ellipsometry, the R^2 serves as a measure of how well the ellipsometric model fits the experimental data Conversely, lower RMSE values signify a more accurate prediction by the model. The thickness of 81.8 nm stands out as the most accurate for characterization, featuring the highest R^2 (0.97916) and the lowest RMSE (1.72511). Therefore, 81.8 nm is the ideal thickness for reliable material characterization in this context.

3.2 Surface Topography

Atomic Force Microscopy was used to investigate the surface morphology of Au thin films. The AFM techniques allowed us to determine material properties such as grain size. Fig. 3 displays 2D AFM images of Au thin films of various thicknesses. When the thickness of an Au thin film increases, the film exhibits tiny grain growth of a few grains. Small grains combine to form larger grains when thin film thickness increases from 29.6 nm to 81.8 nm.

a) b)



c) d) e)

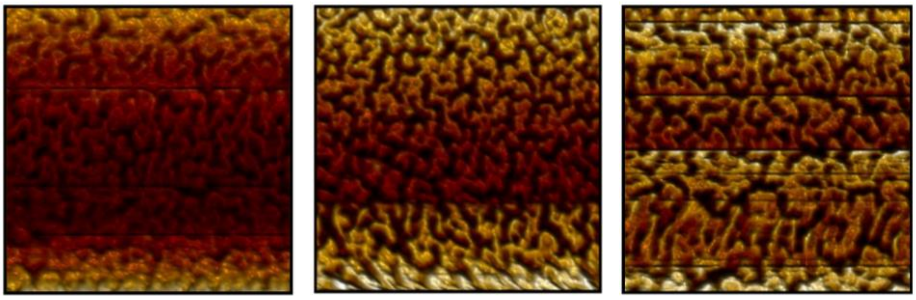


Fig. 3 *The 2D AFM image of Au thin films of various thicknesses a) 29.6 nm, b) 35.8 nm, c) 49.7 nm, d) 64.6 nm, e) 81.8 nm*

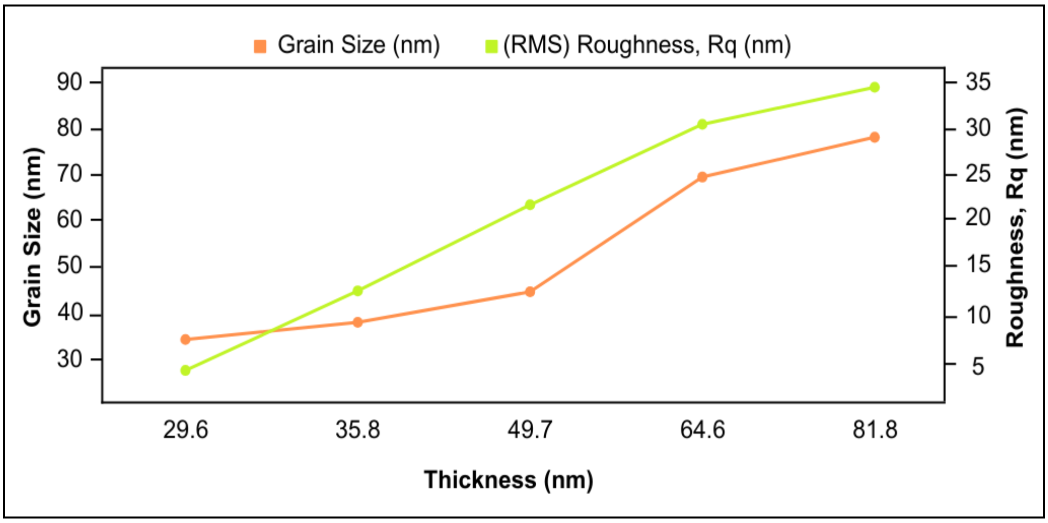


Fig. 4 *The graph of Au thin films at different thicknesses.*

Fig. 4 illustrates the relationship between RMS roughness and grain size in gold (Au) films. Roughness increases exponentially with thickness, reflecting a rise in mean grain size. Thicker films result in a more uniform structure, with noticeable roughness fluctuations (29.6 nm, 35.8 nm, 49.7 nm, 64.6 nm, 81.8 nm). Grain size mirrors this pattern, indicating a correlation [14]. Grain growth, influenced by atom transfer at boundaries, depends on thickness [15]. The best roughness is observed at 29.6 nm, showing the lowest Ra of 3.00 nm and RMS of 3.81 nm, indicating a smoother surface. However, it is essential to note that a smoother surface is often associated with improved electrical conductivity, while variations in grain size and roughness can influence resistivity and other electrical parameters [15]. To strike a balance between surface morphology and electrical conductivity, a thickness of 81.8 nm might be a reasonable compromise, showcasing the lowest Ra of 27.60 nm and RMS of 34.40 nm.

3.3 Surface morphology

SEM analysis was conducted with a constant accelerating voltage of 10 kV and 30,000× magnification on Au thin films of three different thicknesses. The SEM images reveal an uneven surface at 29.6 nm, a uniform surface at 49.7 nm, and a rougher, uneven morphology at 81.8 nm (**Fig. 5**). The observed variations in thickness influence the weight percentage Leading to diverse surface features in Si/Au thin films [16]. Weight percentages (81.8 nm: 99.29%, 49.7 nm: 97.35%, 29.6 nm: 86.35%) play a crucial role and correlate with surface features. Higher weight percentages at 81.8 nm result in a rougher surface, while lower percentages at 49.7 nm and 29.6 nm contribute to smoother morphologies. The intricate interplay between deposition time and weight percentage is a significant factor influencing the characteristics of Si/Au thin films, particularly their surface morphology.

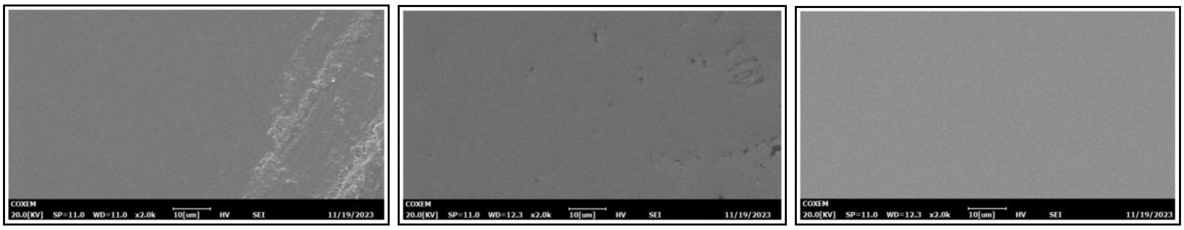


Fig. 5 *Image of Si/Au on Si substrate at (a) 29.6nm, (b) 49.7nm, and (c) 81.8nm.*

3.4 Electrical properties

The electrical properties of Au thin films were assessed using the four-point probe method, measuring electrical resistivity across various thicknesses. As depicted in **Fig. 6**, a decrease in resistivity is observed with an increase in the thickness of Au thin films. This trend suggests that Au thin films are effective contact materials with low resistivity [17], [18]. Additionally, resistivity is found to be correlated with grain size properties (**Fig. 4**). The variation in conductivity is attributed to grain boundary scattering, where charge carriers scatter at the grain boundary. An increase in grain size, coupled with a decrease in grain boundary effects, leads to enhanced conductivity and reduced resistivity. The recommended thickness for accurate material characterization in this electrical assessment is 81.8 nm, with a resistivity of 7.76×10^{-3} Ω-cm.

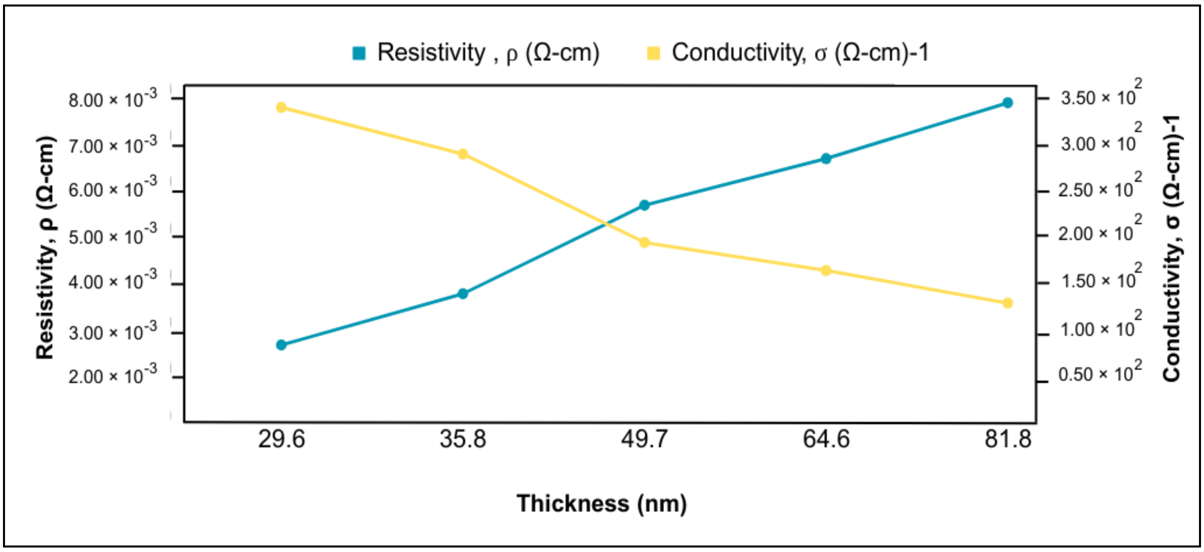


Fig. 6 *Resistivity and conductivity of Au on Si as a function of Au thicknesses.*

3.5 Optical properties

The optical properties of Au thin films were investigated using UV-visible spectrometry, focusing on absorbance and wavelength. From the resulting UV-vis spectrometer data in **Fig. 7**, a graph of absorbance (A) for Au vs. wavelength (λ) was obtained. With increasing thickness, free carrier absorption increases, leading to a higher carrier concentration in thick films. This causes the absorption of more light, resulting in a slight decrease in average transmittance [19]. The phenomenon can be correlated with the effect of grain size, which increases as thin film thickness rises (refer to **Fig. 4**), contributing to light scattering. As a consequence, the intensity of UV-vis peaks increases with increasing thickness from 29.6 nm to 81.8 nm.

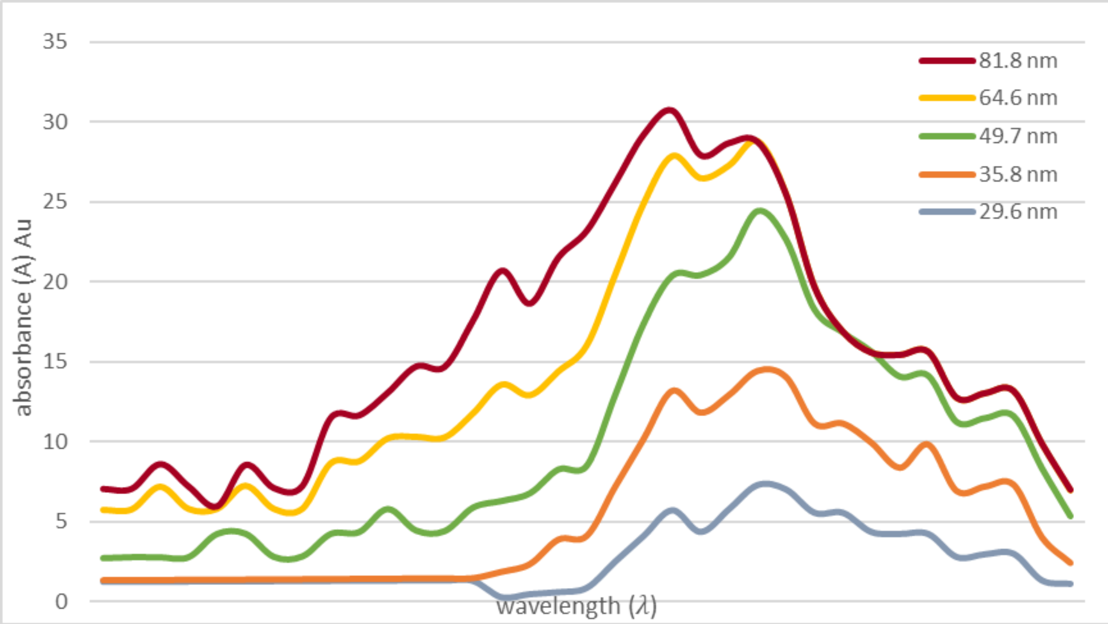


Fig. 7 *The absorbance A (Au) vs. wavelength ⍰ (nm) was plotted for different thicknesses of Au thin films.*

4. Conclusion

In this study, the topological, morphological, electrical, and optical properties of Au films were investigated as a function of film thickness. The RMS roughness and mean grain size of the Au thin film at 81.8 nm were measured at 27.60 nm and 34.40 nm, respectively. Meanwhile, the resistivity value obtained from the four-point probe for 81.8 nm was 7.76×10^{-3} Ω-cm. Higher weight percentages at 81.8 nm resulted in a rougher surface for morphological properties. Regarding optical characterization, a film thickness of 81.8 nm exhibited superior performance. Therefore, based on these analyses, it is concluded that the best thickness for Au films is 81.8 nm.

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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:*** *Nur Syafiqah Selamat and Ahmad Hadi Ali. All authors reviewed the results and approved the final version of the manuscript.*

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