



A light-detecting Ru(II)/Si heterojunction system involving a binuclear Ru (II) complex with pyridine-2,6-diimine (pydim) ligand

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ABSTRACT

A meticulously detailed chemical procedure was employed to synthesize the Ru (II)-containing pyridine-2,6-diimine (pydim) organometallic complex. The resulting complex was then applied to Al-coated Si wafers using the spin-coating technique, leading to the production of Al/Ru(II) organometallic complex/n-Si/Al photodiodes. The light responsiveness of these photodiodes was demonstrated through the acquisition of I-V and I-t characteristics. Subsequently, essential parameters such as ideality factor, photosensitivity, barrier height, and photore-sponse values were evaluated based on the obtained I-V and I-t plots. The calculations yielded ideality factors and barrier heights, resulting in average values of 6.41 and 0.552 eV, respectively. Furthermore, an in-depth analysis of the electrical properties of the diodes was conducted using G-V and C-V assessments, revealing a strong dependence on AC signal frequency. This investigation underscored that the observed frequency-related electrical behaviour is rooted in series resistance and interface states.

1 Introduction

Light plays a crucial role in sustaining all living things. Even if certain forms of light are imperceptible to the human eye, we can still interact with various light forms that extend beyond our visible range. Detecting and monitoring such diverse forms of light is both

possible and required for a variety of applications. Advancements in technology occur on a daily basis, empowering us to develop sophisticated devices for light detection. In this context, thin films stand out as fundamental building blocks. These films find application in a myriad of technological devices, including but not limited to diodes, displays, microprocessors,

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photodetectors, solar cells, photodiodes, transistors, and more [1–7]. As technology progresses, the utilization of thin films becomes increasingly vital, contributing to the enhancement of various technological applications. Their versatility makes them integral components in the ever-evolving landscape of electronic and optoelectronic devices. [1–7]. Photodetectors and photodiodes play a pivotal role in the precise tracking and detection of light. Beyond their fundamental function, they serve as integral components in an array of devices, ranging from motion detectors, video imaging devices, and optical communication receivers to security cameras, biomedical imaging devices, and advanced missile technologies [8–10]. Their versatility underscores their significance in diverse technological applications.

Choosing the right material is essential to obtain the desired product, and this principle holds true for photodiodes and photodetectors. Hence, various types of materials are employed in photodiodes and photodetector technologies. [11]. Each material has its own set of advantages and disadvantages. To meet specific criteria and achieve high-performance products, both organic and inorganic films are used in semiconductor, photodiode, and photodetector technologies. Organic molecules typically consist of carbon and hydrogen-based compounds, making them excellent candidates for flexible electronic applications [12, 13]. Organic molecules are frequently regarded as abundant and cost-effective materials; therefore, they are considered advantageous compared to precious materials. However, they may have certain physical drawbacks such as low heat and humidity resistance, low scratch resistance, and low conductance. These drawbacks can potentially impact the electrical and optoelectronic properties of the materials. However, inorganic films comprise metals and metal oxides, which are known for their high stability under challenging conditions and at high temperatures, exhibiting outstanding electrical performance [14–18]. There is an increasing interest in the optoelectronic application of metal complexes owing to their superior optical and chemical properties. [19].

Organometallic thin films, distinguished by their unique blend of organic and inorganic materials, offer a range of advantages. The term "organometallic" denotes a complex organic molecule incorporating metals into its structure, effectively merging organic components with metals or metal oxides. Consequently, these films can embody essential

characteristics from both metals and organic molecules. For instance, they may deliver exhibit electrical performance compared to purely organic materials and boast greater durability than films solely reliant on organic elements. Moreover, their potential for flexibility surpasses that of metal/metal oxide structures, facilitating enhanced operational efficiency. As a result of these advantageous properties, organometallic structures have found applications in diverse fields such as photodiodes, solar harvesting devices, and storage systems. They are particularly favoured for organic electronic applications, and a variety of organometallic-based molecules have been documented in the literature for optoelectronic purposes. Diverse structural proposals were presented by researchers opting to co-deposit/dope organic materials with metals to expand the spectrum of potential applications.[7, 20–22]. On the other hand, some other researchers may choose to synthesize metal containing special organometallic molecules [23–27]

In this context, ruthenium-based organometallic complexes hold particular allure [28, 29]. Specifically, ruthenium complexes in the presence of polypyridine-type ligands find applications in numerous areas, including catalysis, sensing, and optoelectronic devices [30–38]. Ruthenium complexes with polypyridene ligands, especially their use in optoelectronic devices, have been much investigated in recent years because they have high light absorption and light emission efficiency. The steric and electronic parameters of the ruthenium metal centre can be easily adjusted through appropriate ligand modification, allowing for the preparation of complexes with desired properties. Hence, since the optical properties of these complexes are often switchable and tunable, it is possible to provide light emission in different colors. These properties enable their use in optoelectronic devices such as OLED displays, LED lamps, solar cells, and lasers. Furthermore, these ruthenium complexes generally offer long-lasting and reliable performance as they have thermal and chemical stability. In our prior studies, Ru(II) complexes of polypyridine-based ligands were synthesized and optically characterized [35, 39, 40] The most motivating features of these complexes lies in their potential use as high optical responsivity photodiodes. There is an ongoing desire to synthesize complexes with tailored and improved properties (low response time, ability to operate in a wide spectral range, increased detection sensitivity).

In this study, we fabricated organometallic photodetectors using a Ru(II) complex containing pyridine-2,6-diimine (pydim) and investigated their optoelectronic properties. The synthesized Ru(II)-based organometallic complex was applied to Si wafers using the sol-gel method. Photodiode characteristics of the Ru(II)-based photodetectors were examined under daylight illumination. Besides, the electrical properties of the Al/Ru(II) organometallic complex/n-Si/Al diodes were exhibited under varying frequency to check electrical behaviours.

2 Materials and method

The organometallic complex mentioned in the title, containing Ru(II) with pydim ligand (see Fig. 1), was synthesized following the procedure outlined in our prior work, as reported in the literature [30]. The confirmation of complex formation was achieved through the utilization of ^1H -NMR spectroscopy, with the corresponding spectrum provided in the supplementary information section (Figure S1). Before the preparation, the n-type Si wafers underwent cleaning and etching procedures to ensure a surface free from dirt and contamination [41]. The Si wafer used in the device production is a monocrystalline silicon wafer with 9–15 $\Omega\text{-cm}$ resistivity and a thickness of 600 μm . Initially, the Si substrate was washed and followed by sonication in acetone cleaning. Acetone cleaning was employed for 5 min and then rinsed with water. Subsequently, Si wafers were sonicated with alcohol for 5 min, and rinsed again. The Si wafers were then etched in $\text{HF}:\text{H}_2\text{O}$ (1:10 ml) solution: Etching was employed for 30 s, followed by rinsing and sonication in deionized water for 5 min [41]. An Al contact was employed on the backside of the n-Si substrates by thermal evaporation, where a Nano Vak. evaporation system was used. Coating is resulted a thin film with a thickness of 100 nm. The Al/n-Si structures

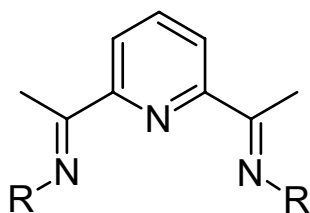


Fig. 1 Pydim ligand structures

were kept at 570 $^{\circ}\text{C}$ for 5 min. 5 min of sonication in deionized water was applied to Al/n-Si wafers. The solution of the Ru (II) organometallic complex was dissolved in DMF (dimethylformamide). The mixture was then drop-cast on the Al/n-Si structures and spin coated. The Ru(II) organometallic complex was then dried at 50 $^{\circ}\text{C}$ for 10 min and cooled to room temperature. Al metal was applied as the top contact, which was coated by a sputtering system. Consequently, a diode in the configuration Al/Ru(II) organometallic complex/n-Si/Al was obtained (see Fig. 2). The electric and photoresponsive properties of the Al/Ru(II) organometallic complex/n-Si/Al structures were performed using a FYTRONIX 9000 AAA class Solar Simulator IV characterization system (Fig. 2c) using software (Fig. 2d). FYTRONIX 9000 solar simulator provides a white light in different intensities between 10 mW/cm^2 to 100 mW/cm^2 which mimics sun light from 380 to 1100 nm (Fig. 2e). Active area of the photodiode is about 5 mm^2 . FYTRONIX 9000 I-V characterization system is equipped with C-V analyser (Fig. 2f).

3 Results and discussion

3.1 Photodiode characterization

To assess the photodiode's capability, we examined the photocharacteristics of the Al/Ru(II) organometallic complex/n-Si/Al photodiodes. To validate the diode mechanism, we analysed the I-V characteristics within a voltage range of -3 V to $+3\text{ V}$. These characteristics were acquired under daylight at various illumination intensities. I-V plots are illustrated in Fig. 3. I-V plots indicate that the Al/Ru(II) organometallic complex/n-Si/Al photodiodes display rectifying behaviour in the negative bias region, confirming their diode characteristics.

Different illumination intensities of external light were used to investigate the photodiode characteristics. Substantial variances were noted in the I-V plots obtained under light compared to those in the absence of light (dark conditions). Especially in the reverse bias region, a noteworthy higher measured current is achieved, when the diodes are exposed to light. This observation highlights how the presence of light generates a photocurrent in the diodes, thereby confirming their photocurrent behaviour.

The I-t (current-time) plots of the photodiodes were evaluated at various illumination values ranging from

Fig. 2 Molecular structure of Ru (II) containing pydim organometallic complex (a) and structure of Al/Ru(II) organometallic complex/n-Si/Al photodiode (b) Fytronix 9000 AAA class solar IV characterization system (c) software of Fytronix 9000 solar simulator (d) spectrum of solar simulator (e) and software of Fytronix 9000 C-V analyser (f) are illustrated

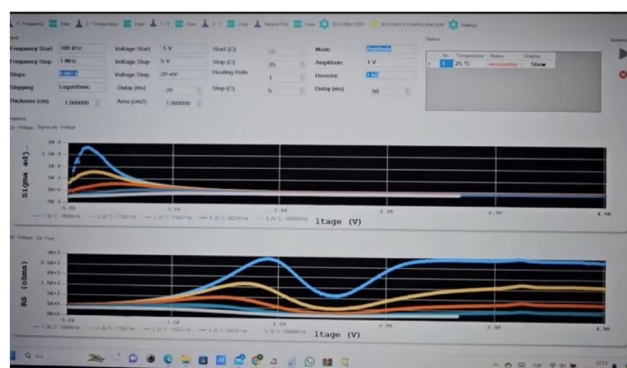
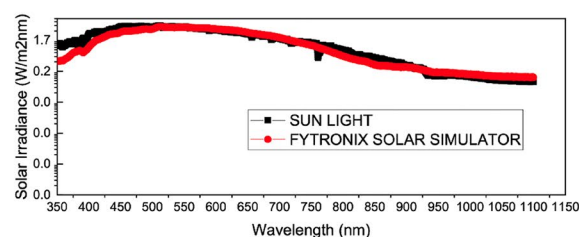
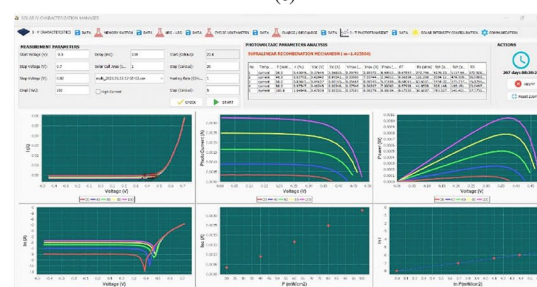
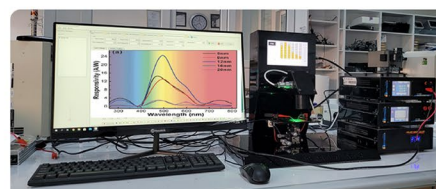
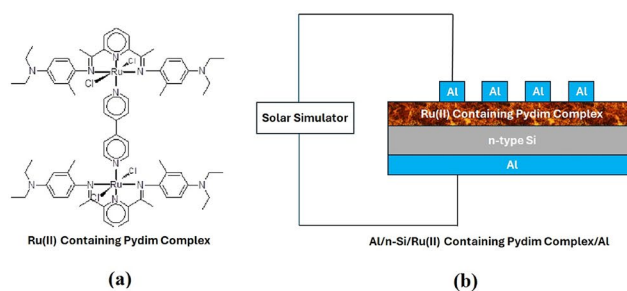
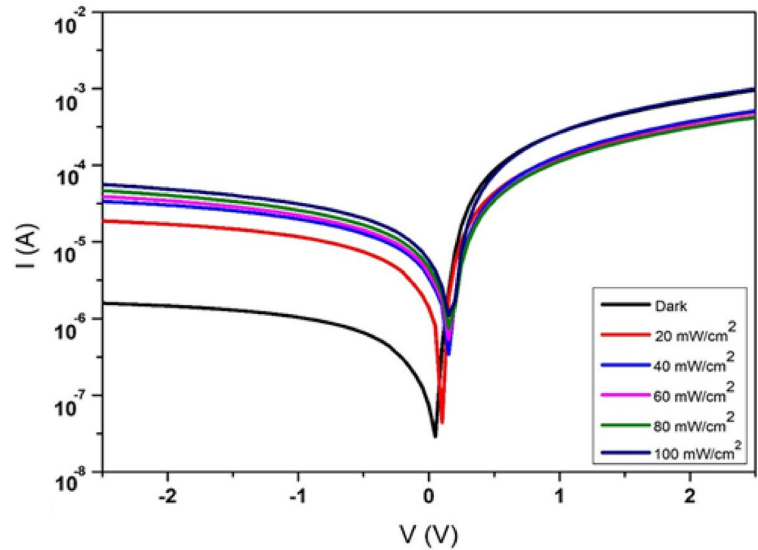


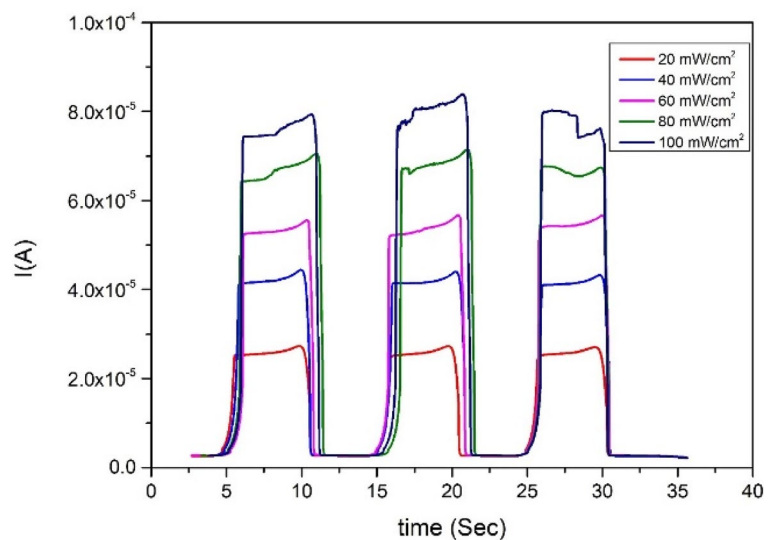
Fig. 3 I–V characteristics of Al/Ru(II) organometallic complex/n-Si/Al photodiodes



20 mW/cm² to 100 mW/cm² to verify their photore sponsive behaviours, as shown in Fig. 4. During the experiment, light was alternately turned on and off in 5 s intervals on the photodiodes. When the light was off, no photocurrent was detected. However, when illuminated, distinct photocurrent peaks were observed, varying based on the intensity of the light. The highest photocurrent was recorded at an illumination intensity of 100 mW/cm², while the lowest photocurrent was observed at 20 mW/cm². An increase in light illumination intensity resulted in an enhanced photocurrent. The peak photocurrent measured approximately 8×10^{-5} A under 100 mW/cm² illumination. For comparison, Tataroglu et al. reported a

maximum of 1.5×10^{-4} A under 100 mW/cm² for single crystal ruthenium photodiodes [35]. Other studies of the same group on ruthenium(II) complex-based photodiodes yielded a result: 1.3×10^{-4} A [42]. Other studies on ruthenium(II) complex-based photodiodes yielded varying results: 2.5×10^{-4} A [43], 2.7×10^{-4} A [44] under the same illumination conditions. Furthermore, investigations on silicon-based photodetectors with Ru(II) complex organic interlayers reported a photocurrent of 9×10^{-5} A [45]. Additional research on ruthenium electro-optic devices obtained 1×10^{-4} A under the same illumination conditions [46]. In a separate study by Ilhan et al., maximum photocurrent values under both 100 mW/cm² daylight and IR

Fig. 4 I–t characteristics of Al/Ru(II) organometallic complex/n-Si/Al photodiodes



illuminations were reported: 4×10^{-5} A and 3.81×10^{-4} A, respectively, for Al/p-Si/Cu₂NiSnS₄/Al and Al/p-Si/Cu₂CoSnS₄/Al setups [47, 48]. Under IR illumination, the values were 3.1×10^{-5} A and 2.7×10^{-5} A for the same setups [49, 50].

The capacitance related characteristics (C-t) of the Al/Ru(II) organometallic complex/n-Si/Al photodiodes were evaluated to underscore their photoresponsive attributes. C-t graph was presented in Fig. 5. A light was applied to the Al/Ru(II) organometallic complex/n-Si/Al photodiodes, with the light toggling on and off in 5 s intervals for 100 mW/cm² illumination. In the case of the absence of light, no measurable photocapacitance was detected. In contrast, exposure of light revealed a discernible increase in measured capacitance, reaching its peak at 5.25×10^{-11} F. Capacitance-time plots further substantiated the photoresponsive nature of the Al/Ru(II) organometallic complex/n-Si/Al photodiodes. Similar trends were noted in other ruthenium-based investigations. Tataroglu et al. achieved a maximum photocapacitance value of 3.4×10^{-10} F at 100 mW/cm² for single crystal ruthenium photodiodes [35]. The same research group explored ruthenium(II) complex-based photodiodes, yielding a photocurrent of 8.4×10^{-10} F under 100 mW/cm² illumination [42]. Imer et al. investigated ruthenium(ii) complex based photodiodes and obtained a photocurrent as 9.4×10^{-10} F [43], while Karabulut et al. evaluated Si based Ru (II) complex organic interlayer photodetector and obtained a photocapacitance as 3×10^{-11} F under the same illumination conditions [45]. In a separate study run by Imer

et al. who assessed ruthenium electro-optic device and obtained a photocapacitance as 1.95×10^{-10} F for 100 mW/cm² illumination [46].

Using I-V and I-t graphs, *n* (ideality factor), *I*₀ (saturation current), *R* (photosensitivity) and ϕ_b (barrier height) of Al/Ru(II) organometallic complex/n-Si/Al photodiodes were assessed.

For the assessment of barrier height and ideality factors Thermionic emission theory (TET) was used [51].

$$I = I_0 \left[\exp \left(\frac{q(V - IR_s)}{nkT} \right) - 1 \right] \quad (1)$$

In the formula *n* represents ideality factor, *T* is absolute temperature, *q* is the charge of electron. In addition, *I*₀ is saturation current, and *R*_s is serial resistance, *V* is applied voltage, *k* is Boltzman constant and backward bias saturation current. *I*₀ is evaluated using Eq. (4).

$$I_0 = AA^*T^2 \exp \left(-\frac{q\phi_b}{kT} \right) \quad (2)$$

where *A* is the area of the diode and *A*^{*} is the Richardson constant. The slope and the intercept of the forward bias $\ln(I)$ vs. voltage (*V*) plot yield values for *n* and ϕ_b , respectively.

The findings for the Al/Ru(II) organometallic complex/n-Si/Al photodiodes are outlined in Table 1, encompassing calculations across various illumination intensities. Although the ideality factors of a ideal diodes were anticipated to be 1, real-world

Fig. 5 C-t plot of Al/Ru(II) organometallic complex/n-Si/Al photodiodes obtained under 100 mW/cm² illumination

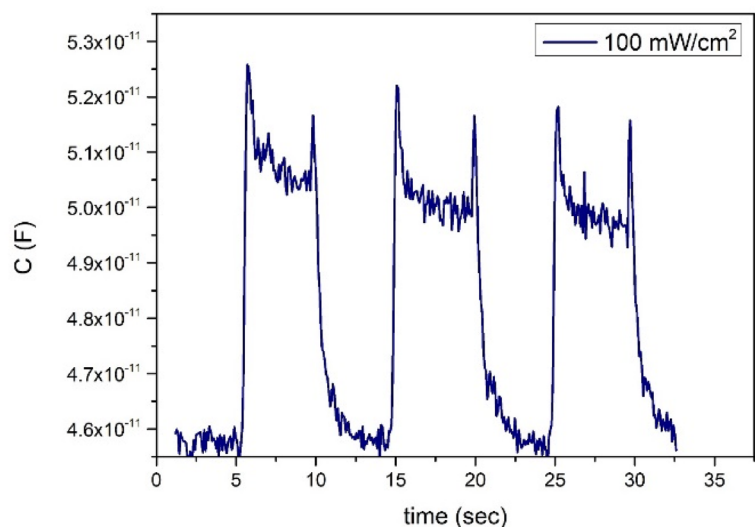


Table 1 Calculated n (ideality factor), ϕ_b (barrier height) of Al/Ru(II) organometallic complex/n-Si/Al photodiodes obtained under daylight and infrared illumination

P (mW/cm ²)	Ideality factor (n)	Barrier height (ϕ_b) eV
Dark	3.89	0.571
20	3.30	0.569
40	6.91	0.545
60	8.08	0.542
80	8.09	0.543
100	7.49	0.545

results often deviate from this theoretical expectation. In our study, ideality factors were determined as 3.89 for dark measurements, while those for illuminated measurements varied between 3.30 and 8.09. Consequently, the average ideality factor was computed at 6.41. The barrier height was initially established at 0.571 eV for dark measurements, but it fluctuated between 0.596 eV and 0.542 eV for different illumination values. The overall average barrier height was computed at 0.552 eV. Notably, no direct correlations were discerned between illumination intensity, barrier height and ideality factor. Our results were found to be consistent with those previously documented in the literature, revealing parallel outcomes. For instance, Tataroglu et al. investigated the ideality factor and barrier height for single crystal ruthenium photodiodes, obtaining values of 3.20 and 0.85 eV, respectively [35]. The same research group investigated ruthenium(II) complex-based photodiodes, determining an ideality factor of

3.51 for dark measurements and 3.22 for illuminated measurements, with barrier heights of 0.88 eV and 0.91 eV, respectively [42]. Imer et al. assessed the ideality factor and barrier height for ruthenium(II) complex-based photodiodes, yielding values of 4.018 and 0.847 eV, respectively [43]. Elgazzar et al. explored heteroleptic neutral Ru(II) complex-based photodiodes, extracting an ideality factor of 2.78 and a barrier height of 0.76 eV [39]. Farooq et al. investigated ruthenium(II) complex-based photodiodes, the group assessed an ideality factor as 4.4 while the barrier height was found as 0.83 eV [44]. Karabulut et al. scrutinized silicon-based photodetectors with Ru(II) complexes organic interlayers, determining an ideality factor of 9.42 and a barrier height of 0.59 eV [45]. Imer et al. delved into ruthenium electro-optic devices, resulting in an ideality factor of 1.32 and a barrier height of 0.805 eV [46]. A comparative table, presented as Table 2, highlights the alignment of our results with those in the existing literature. This analysis underscores the consistency of our findings with the broader body of research.

I-t and C-t data was used to assess the photosensitivity and photoresponsivity of the Al/Ru(II) organometallic complex/n-Si/Al photodiodes.

$$I_{ph} = AP^m \quad (3)$$

where m is a constant, P is the illumination intensity, and I_{ph} is the photocurrent. In the evaluation, the equation below was used:

Table 2 Comparison of calculated n (ideality factor), ϕ_b (barrier height), max photocurrent (A) and max photocapacitance (F) of Al/Ru(II) organometallic complex/n-Si/Al photodiodes with different photodiodes reported in the literature

Diode Type / (Illumination Type)	n	ϕ_b (eV)	Max Photo-current (A)	Max Photocapacitance (F)	Reference
[(pydim) ₂ Ru ₂ (Cl) ₄ -(4,4'-bpy)]	6.41	0.552	8×10^{-5}	5.25×10^{-11}	TW
[(pydim)RuCl(NN ¹)]Cl	3.20	0.85	1.5×10^{-4}	3.4×10^{-10}	[35]
[(pydim)RuCl(NN ²)]Cl	3.51–3.22	0.88–0.91	1.3×10^{-4}	8.4×10^{-10}	[42]
Ru@NNN ¹ composite	9.42	0.59	9×10^{-5}	3×10^{-11}	[45]
[(NNN ¹)RuCl(NO ¹)] and [(NNN ¹)RuCl(NO ²)]	2.78	0.76	NA	NA	[39]
[(NNN ²)Ru(Cl) ₂ (CH ₃ CN)]	4.018	0.847	2.5×10^{-4}	9.4×10^{-10}	[43]
[(NNN ¹)RuCl(NN ³)]Cl	4.4	0.83	2.7×10^{-4}	NA	[44]
[(pydim)Ru ₂ (Cl) ₄ (pyzn)]	1.32	0.805	1×10^{-4}	1.95×10^{-10}	[46]
Cu ₂ NiSnS ₄	5.23	0.469	4×10^{-5}	NA	[48]
Cu ₂ CoSnS ₄	5.31	0.461	3.4×10^{-5}	NA	[47]

TW this work; NA Not Available; NN¹ 4,4'-dimethyl-2,2'-bipyridine; NN² N-[(1E)-pyridin-2-yl-methylene]benzenesulfonamide; NN³ 4-chloro-N-[(1E)-pyridin-2-ylmethylene]benzenesulfonamide; NNN¹ 2,6-bis(2-benzimidazolyl)pyridine; NNN² 2,6-di(1H-pyrazol-3-yl) pyridine; pyzn pyrazine; NO¹ pyridine-2-carboxylate; NO² quinoline-2-carboxylate

$$R = \frac{I_p - I_d}{PA} \quad (4)$$

where R is the photosensitivity, I_p is photocurrent, P is power, I_d is the dark power, and A is the surface area of the films. In the photoresponsivity assessments, the formula mentioned below was used

$$RR = \frac{I_p - I_d}{I_d} \quad (5)$$

where RR is the photoresponsivity, I_p is photocurrent, I_d is the dark power. Figures 6 showcase graphs illustrating the relationships between light intensity and photocurrent (I_{ph} - P), photosensitivity (R - P), and photoresponse (RR - P). Table 3 indicate results pertaining photoresponsive characteristics. The graphs distinctly reveal a positive correlation between escalating illumination intensity and heightened photodiode properties. Specifically, the measured photocurrent

demonstrates an upward trend with increasing illumination intensity. Furthermore, elevated illumination intensity corresponds to an enhanced photoresponsivity. In contrast, photosensitivity experiences a decline as illumination intensity increases.

3.2 Electrical characterization

Figures 7a and b present capacitance–voltage (C–V) and conductance–voltage (G–V) graphs, respectively. The electrical characteristics of the diodes were examined across a range of -3 V to $+3$ V under varying AC signal frequencies. Notably, the AC signal exhibited a discernible impact on the G–V and C–V features of the diodes. Within the negatively biased range, the capacitance values demonstrated significant sensitivity to AC signal frequencies. Specifically, higher frequencies corresponded to lower capacitance values, resulting in a decreased capacitance. A

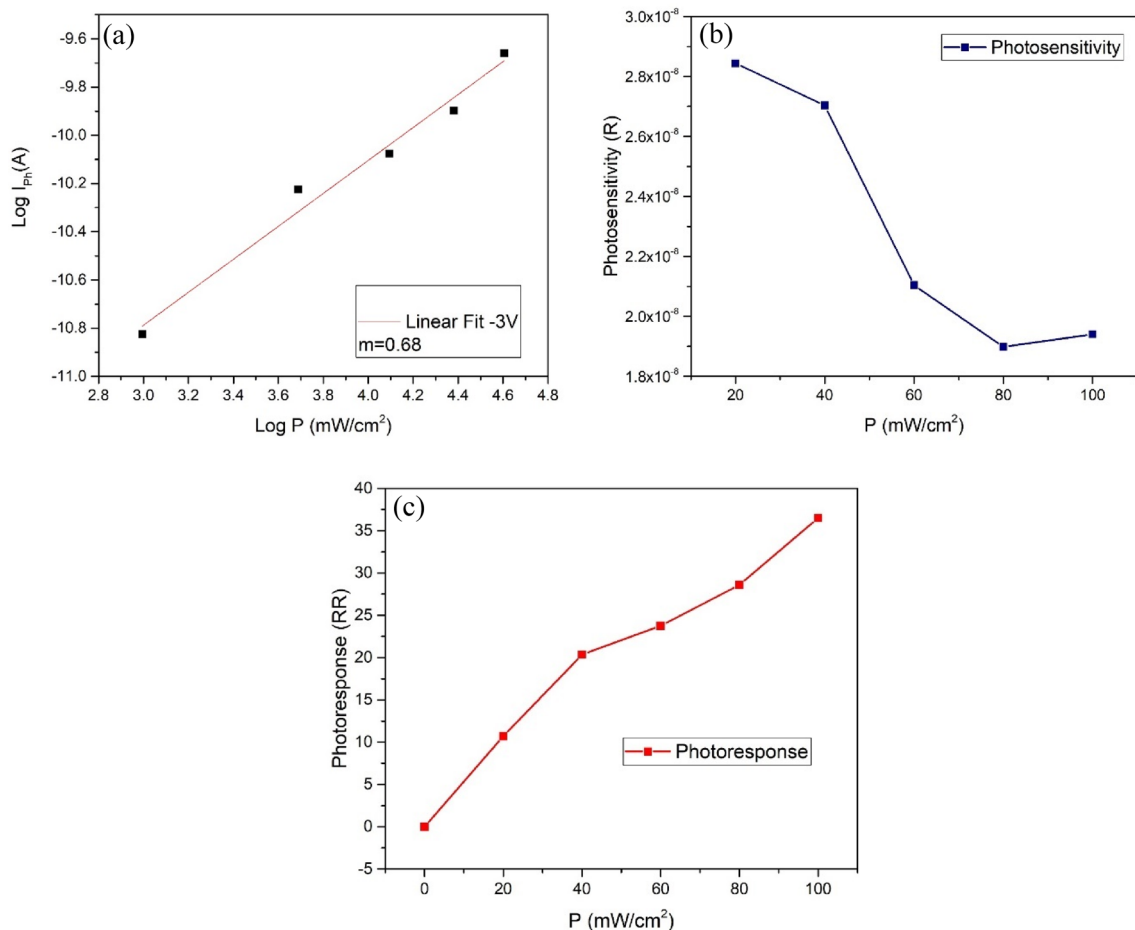
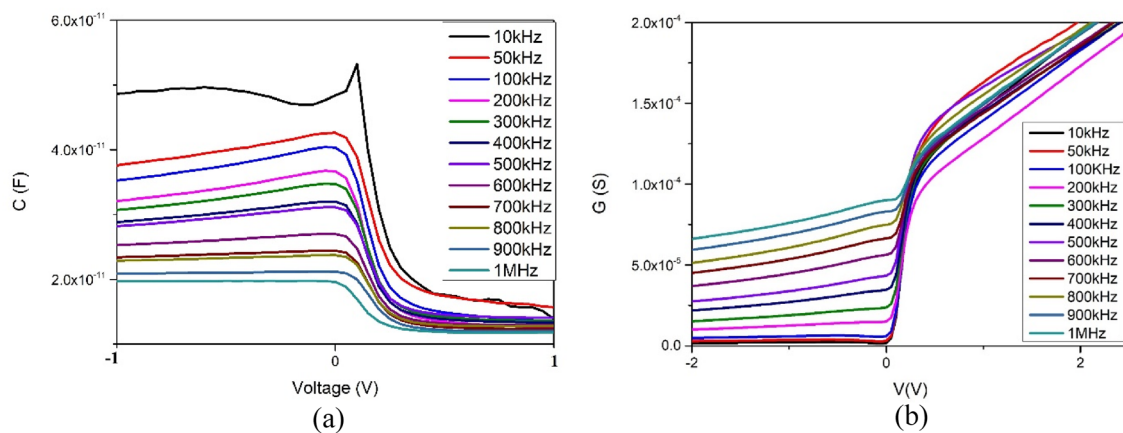


Fig. 6 I_{ph} - P graph (a), photosensitivity (b), photoresponse (c) behaviours of Al/Ru(II) organometallic complex/n-Si/Al photodiodes

Table 3 Photoresponsive characteristics of Al/Ru(II) organometallic complex/n-Si/Al photodiodes

Light Intensity (mW/cm ²)	Photosensitivity	Photoresponse	Max Photocurrent (A)	Raising Time (sec)	Decay Time (sec)
20	2.84×10^{-8}	10.70588	2.73×10^{-5}	1.6385	0.741
40	2.70×10^{-8}	20.35294	4.44×10^{-5}	1.8929	0.684
60	2.10×10^{-8}	23.76471	5.55×10^{-5}	1.8645	0.997
80	1.89×10^{-8}	28.58824	7.05×10^{-5}	2.0906	1.193
100	1.94×10^{-8}	36.52941	8.38×10^{-5}	1.3277	0.8325

**Fig. 7** C–V (a) and G–V (b) behaviours of Al/Ru(II) organometallic complex/n-Si/Al structures acquired under varying AC signal

parallel characteristic was observed in the conductance–voltage behaviours, where increased AC signal frequency correlated with reduced conductance in the reverse-biased zone. The increased capacitance at lower frequencies signifies the accumulation of charges, impeding their free movement. Similarly, the heightened conductance with increased AC signal frequency corroborates this scenario, indicating enhanced charge movement. Various factors, including interface states, serial resistance, and electron hopping mechanisms, could contribute to this frequency-dependent behaviour observed in capacitance and conductance.

To thoroughly examine the frequency-related traits of capacitance and conductance, we scrutinized corrective capacitance–voltage (C_{adj} –V) and corrective conductance–voltage (G_{adj} –V) characteristics. The calculations for corrective conductance and corrective capacitance were performed using the following formulas:

$$C_{adj} = \frac{[G_m^2 + (\omega C_m)^2] C_m}{a^2 + (\omega C_m)^2} \quad (6)$$

And

$$G_{adj} = \frac{[G_m^2 + (\omega C_m)^2] a}{a^2 + (\omega C_m)^2} \quad (7)$$

where ω is angular frequency, G_m and C_m are measured conductance and capacitance, and a is variable parameter [52].

Figures 8a and b depict the corrective capacitance–voltage (C_{adj} –V) and corrective conductance–voltage (G_{adj} –V) behaviours of Al/Ru(II) organometallic complex/n-Si/Al photodiodes. The graphs of G_{adj} and C_{adj} distinctly showcase peaks in both positive and negative bias zones. Notably, the corrective capacitance graph reveals frequency-related

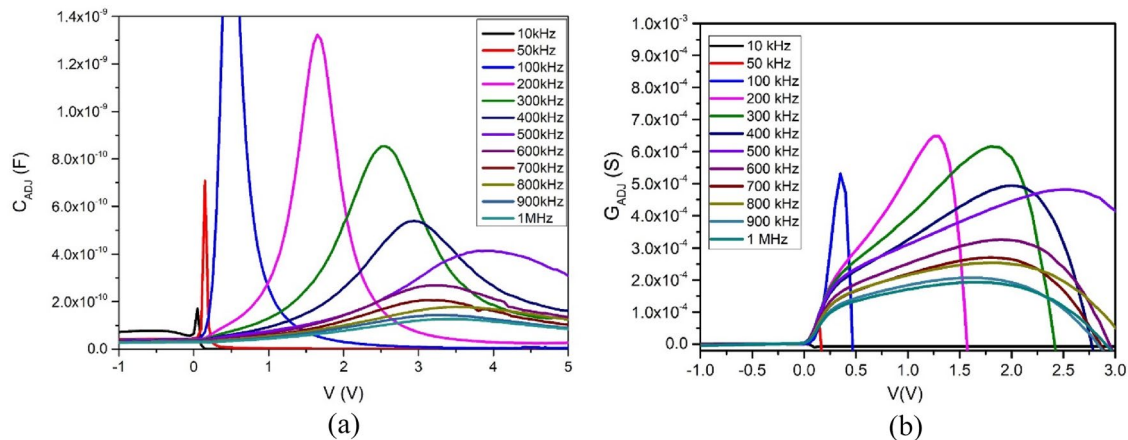


Fig. 8 C_{adj} - V (a) and G_{adj} - V (b) behaviours of Al/Ru(II) organometallic complex/n-Si/Al photodiodes

peaks, and the intensity of these peaks undergoes variations with changing frequencies, exhibiting a slight shift towards the positive bias zone. This observation suggests a significant impact of the applied signal frequency on capacitance. A similar pattern is observed in the G_{adj} plots, where various frequency-related peaks manifest in the forward bias zone. The peaks diminish and shift towards the right as the AC signal frequency increases.

$$R_s = \frac{G_{ma}}{G_{ma}^2 + \omega^2 C_{ma}^2} \quad (8)$$

The electrical behaviours associated with the signal may influence series resistance. Consequently, R_s values were computed, and the series resistance-voltage (R_s - V) graph is illustrated in Fig. 9. This graph evaluates R_s values across various frequencies ranging from -2 V to 2 V. The R_s - V graph reveals a robust relation between R_s values and AC frequencies, particularly in the backward bias zone. Notably, there is a decrease in R_s with increasing frequency. It is plausible that heightened AC signal impacts the intrinsic properties of the material, facilitating electron transfer between points. This outcome aligns coherently with the results observed in the C - V and G - V behaviours. To further scrutinize this scenario, the density of interface states was calculated.

To obtain the density of interface states the mentioned formula was utilized:

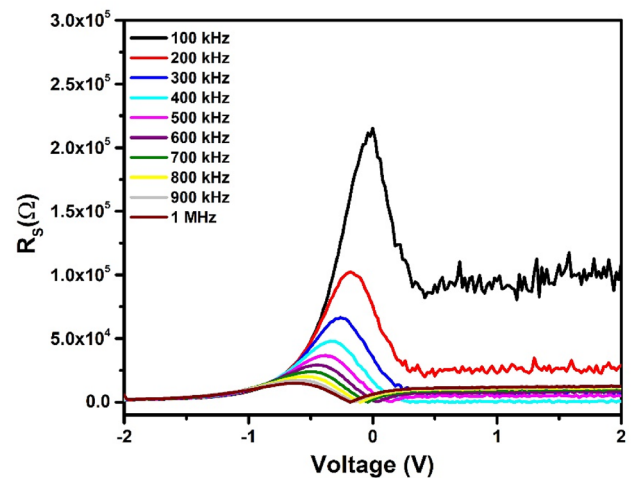
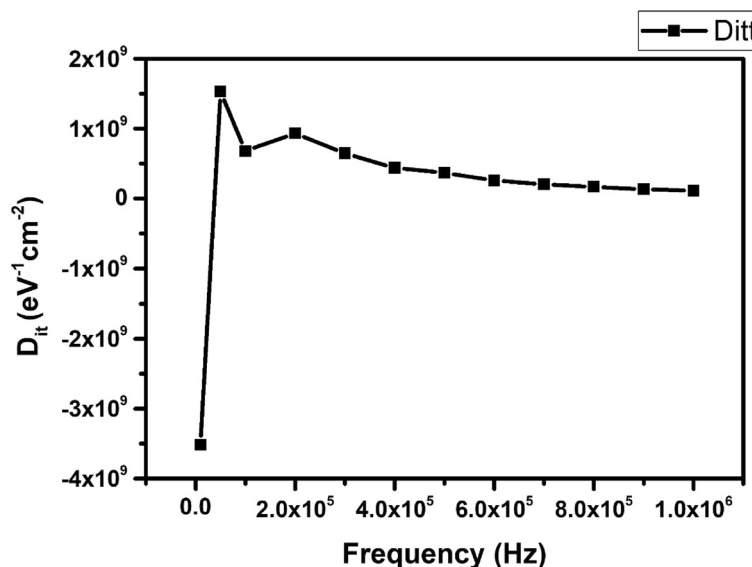


Fig. 9 Series resistance-voltage (R_s - V) characteristics of Al/Ru(II) organometallic complex/n-Si/Al photodiodes at different frequencies

$$D_{it} = \left(\frac{2}{qA} \right) \left[\frac{(G_{adj}/\omega)_{max}}{\left[(G_{max}/\omega C_{ox}) + (1 - C_{max}/C_{ox})^2 \right]} \right] \quad (9)$$

where A is the surface area, D_{it} is density of interface states. G_{max} is the maximum conductance, (G_m/ω) is the measured conductance, q is the charge, C_{ox} is the capacitance of the insulator layer, and ω is angular frequency (in our calculation it is $2\pi f$). The evaluation of the density of interface states was conducted across each recorded signal frequency, resulting in the preparation of a D_{it} - f graph presented in Fig. 10. This plot illustrates a discernible trend wherein the D_{it} with an

Fig. 10 Density of interface state (D_{it})—frequency (Hz) graph of Al/Ru(II) organometallic complex/n-Si/Al photodiodes



increase in signal frequency. The observation of these frequency-related electrical characteristics implies that electrical behaviours may be influenced by inherent factors such as electron transfer mechanisms, interface states, etc.

4 Conclusions

This study focused on the investigation of the photodiode and electrical behaviours exhibited by Al/Ru(II) organometallic complex/n-Si/Al photodiodes. The I–V, I–t, and C–t behaviours of Al/Ru(II) organometallic complex/n-Si/Al photodiodes were analysed, affirming their photoresponsive attributes. The results unequivocally validate the photoresponsive properties of Al/Ru(II) organometallic complex/n-Si/Al photodiodes, with increased illumination intensity correlating to heightened photocurrent. Additionally, an examination of the electrical properties revealed a dependence on AC signal frequency, indicating a frequency-related characteristic attributed to interface states. The coherence of our findings with literature supports the notion that these photodiodes possess potential applications in photodiode and photodetector technologies.

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Author contributions

All authors contributed to the study conception and design. MMK: drafting, conceptualisation, formal analysis, and writing. OD: editing, synthesis of organic compound and writing analysis. AD: production of Ru(II) thin film, I–V measurement, C–V measurement, writing and editing. BÇ: editing, synthesis of organic compound and writing analysis. BC: drafting, conceptualisation, formal analysis, and writing. FY: production of Ru(II) thin film, I–V measurement, C–V measurement, writing and editing. All authors read and approved the final manuscript.

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Data availability

The data used in the manuscript can be provided upon a reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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