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Analyzing Temperature and Quantum Effects on the Performance of CdTe and CIGS Thin-Film Solar Cells

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Abstract:

Thin-film solar cells based on Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS) are increasingly recognized for their low cost, flexibility and scalability compared to traditional silicon-based photovoltaics. However, their performance is strongly influenced by thermal fluctuations and quantum effects, which are often interdependent. This study combines Density Functional Theory (DFT) simulations, Finite Element Analysis (FEA) and experimental characterization to investigate the impact of these factors on high-efficiency CdTe and CIGS thin-film solar cells. The results demonstrate that increasing temperature (25–75°C) significantly reduces the bandgap, open-circuit voltage (Voc) and overall efficiency in both CdTe and CIGS devices. CdTe cells showed a 5% Voc reduction, while CIGS exhibited a smaller 3% drop. Interestingly, quantum tunnelling improved CdTe performance by ~1.2% at moderate temperatures (45–55°C), partially offsetting thermal losses. Spectroscopic analysis through Photoluminescence (PL) and Electroluminescence (EL) confirmed theoretical predictions, showing reduced recombination rates under optimal conditions. ANOVA analysis indicated statistically significant effects of both material type ($F=12.63$, $p=0.002$) and temperature ($F=8.54$, $p=0.008$), with strong interaction effects ($F=10.12$, $p=0.004$). These findings highlight the necessity of integrating both thermal management strategies and quantum-level design optimizations in advancing CdTe and CIGS thin-film solar cell performance, providing pathways for the next generation of cost-effective, high-efficiency photovoltaics.

Keywords: CdTe; CIGS; Thin-film solar cells; Quantum tunnelling; Density Functional Theory (DFT); Photoluminescence (PL); Temperature effects; Photovoltaic efficiency.

1) Introduction:

Solar energy has gotten a lot of attention as a way to replace fossil fuels in a healthy way. In this case, thin-film solar cells like CdTe and CIGS are better than their solid silicon cousins because they are cheaper and more flexible. But these materials can also be affected by complicated relationships between temperature and quantum effects, which can change how well they work generally. Thin-film technologies need to be improved by making the most of these interactions [2]. Photovoltaic research and development has moved faster because people want to find ways to use green energy. Thin-film solar cells, especially those made from Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS), have gotten a lot of attention because they are cheap, flexible and easy to make in large quantities. But making these solar cells work as well as possible is still hard, especially since temperature effects and quantum effects have many different effects [3].

While there has been a lot of research on solid silicon solar cells, there hasn't been a lot of research on how temperature and quantum effects affect the efficiency of thin-film solar cells. This lack of knowledge makes it hard to improve these potential solar technologies in a focused way [4]. This study tries to fill a gap in research by giving a thorough analysis of how temperature and quantum effects affect the electrical qualities and general performance of high-efficiency CdTe and CIGS thin-film solar cells. Along with physical methods like Photoluminescence (PL) and Electroluminescence (EL) spectroscopy, computational methods like Density Functional Theory (DFT) and Finite Element Analysis (FEA) will be used [5].

2) Review of Literature:

Crystalline silicon-based solar cells have recently been overtaken in popularity by their less expensive and more bendable counterpart, thin-film solar cells. Cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) are two of the most noteworthy materials that have been researched for use in thin-film cells (Dobson, 2018). Other materials have also been investigated. According to Makita and Yamaguchi (2019), CdTe and CIGS both have high absorption coefficients and bandgaps that can be tuned, making them excellent for use in thin-film applications. CdTe has been praised for having a straightforward binary composition, but CIGS offers more flexibility in terms of how its electrical characteristics may be adjusted (Jones et al., 2017). Crystalline solar cells have been subjected to a considerable amount of research about thermal effects, but thin-film solar cells have not received nearly as much attention. According to the findings of a recent study (Smith et al., 2019), researchers found that fluctuations in temperature had a substantial impact on the open-circuit voltage (Voc) and the fill factor, both of which were associated with inefficiencies.

Quantum dot solar cells have been the primary focus of the vast majority of the investigation into the quantum effects of photovoltaics, with just a few restricted research focusing on thin films. Quantum tunnelling and quantized energy levels are two examples of techniques that have been hypothesised as having the potential to either increase or decrease the efficiency (Williams, 2020). Very few research have made an effort to investigate how the thermal effects and quantum effects in solar cells interact with one another. A early investigation into the topic was carried out by Chen and Lee (2021), who found that some quantum effects might, under certain circumstances, mitigate the unfavourable impacts of thermal effects. However, these inquiries are still in the infant phases and there is a need for further research in this area. Although there has been a significant amount of study conducted on the thermal and quantum effects that occur independently in photovoltaic systems, there has not been nearly as much work done to investigate how these two types of effects interact with one another, especially in regards to high-efficiency thin-film solar cells. This void provides a chance for a comprehensive inquiry, which is something that this research intends to fulfil.

3) Objectives:

1. Understand the Thermal Effects in CdTe and CIGS Thin-Film Solar Cells.
2. Investigate Quantum Effects in High-Efficiency Thin-Film Solar Cells.

4) Methods:

To make a model of the quantum mechanical features of thin films of CdTe and CIGS. DFT simulations were done with Quantum Espresso. We looked at the bandgap, the number of states and the rate of electron-hole recombination [6]. In this study, we looked at the effects of temperature and quantum effects on the efficiency of high-performance CdTe and CIGS thin-film solar cells using both computer models and real-world tests. Density Functional Theory (DFT) studies were used to model electrical features like bandgap and carrier concentration, while Finite Element Analysis (FEA) was used to model temperature behaviour and gradients in the materials [7]. Simulations were run on a high-performance computing system, which made sure that the results were reliable and correct.

For the actual part of our study, we used magnetron sputtering and chemical vapour deposition to make thin-film solar cells made of CdTe and CIGS, respectively. After that, spectroscopic methods like Photoluminescence (PL) and Electroluminescence (EL) were used to judge the quality of the materials and figure out what was going on with recombination [8]. Measurements of the current-voltage (I-V) graph were done at temperatures ranging from 25°C to 75°C to find out how temperature affects the performance of solar cells. Our methods were made to be all-encompassing, using both computer and experimental techniques, so that we could learn about the subject from many different angles [9]. This combined method let us not only check our computer models against real-world data, but also come to more detailed conclusions about how temperature and quantum effects interact in high-efficiency thin-film solar cells. [10]

5) Results:

The bandgap was determined to be about 1.48 eV, which is close to the numbers found in the literature. Under certain situations, quantum tunnelling was seen to improve performance by 1.2%. Based on the makeup, the bandgap ranged from 1.12 to 1.53 eV. Unlike CdTe, quantum effects like tunnelling didn't affect the effectiveness very much. Both CdTe and CIGS films had a regular spread of heat, which was important for keeping their electrical properties fixed. When the temperature was raised from 25°C to 75°C, the open-circuit voltage (Voc) of CdTe went down by 5%. Under the same conditions, CIGS cells showed a 3% drop.

Our dual-method approach gave us important information about how CdTe and CIGS thin-film solar cells behave when the temperature and quantum conditions change. Density Functional Theory (DFT) studies showed that as the temperature went up, the bandgap of both CdTe and

CIGS cells dropped by a lot. This was in line with the results of the experiments, which showed that as the temperature went up, the open-circuit voltage (Voc) and total performance went down. Quantum tunnelling effects made CdTe cells work better at moderate temperatures (45–55°C), which helped to make up for some of the efficiency losses caused by heat.

On the practical side, spectroscopic readings of Photoluminescence (PL) and Electroluminescence (EL) proved that the theory models were correct. Under mild temperatures, the PL spectra of CdTe cells showed that the rate of recombination was lower, which suggests that quantum effects were at play. Measurements of the current-voltage (I-V) graph showed that the efficiency of CdTe cells dropped less quickly as the temperature went up than that of CIGS cells. Starting with the type of material, which is either CdTe or CIGS, an F-value of 12.63 and a P-value of 0.002 highly suggest that the type of material used has a big effect on how well the solar cell works. Because the P-value is low (0.05), we can reject the null hypothesis and say that choosing between CdTe and CIGS is a crucial feature. With an F-value of 8.54 and a P-value of 0.008, the temperature setting, which is broken down into 25°C, 50°C and 75°C, also has a big effect on cell efficiency. Again, the low P-value shows that the null hypothesis can be thrown out, which confirms that temperature does have a big impact on efficiency. Most interesting is that the F-value for the interaction term between material type and temperature is 10.12 and the P-value is 0.004. This shows that the link between the type of material and temperature is not separate, but that they work together in a way that has a big effect on how well the solar cells work.

6) Conclusion:

This study provides a comprehensive understanding of how temperature and quantum effects jointly influence the performance of CdTe and CIGS thin-film solar cells**.** The results confirm that: Increasing temperature leads to significant reductions in bandgap, open-circuit voltage (Voc) and efficiency**,** with CdTe more strongly affected than CIGS. Quantum tunnelling can partially mitigate thermal losses, particularly in CdTe cells, improving efficiency by ~1.2% under moderate heating conditions. Spectroscopic (PL, EL) and electrical (I-V) characterizations validated simulation models, confirming the dual importance of thermal and quantum considerations. Statistical analysis revealed strong interaction effects between material type and temperature**,** underscoring the need for material-specific design strategies. Overall, optimizing thermal stability **and** quantum-level charge transport mechanisms is crucial for pushing the efficiency of CdTe and CIGS solar cells closer to their theoretical limits. Future work should focus on nanostructured designs, hybrid materials and advanced encapsulation techniques to enhance resilience under real-world operating conditions.

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