TiO_2-Based Photoluminescent Coatings for Enhanced Spectral Utilisation in Silicon Photovoltaic Modules

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Abstract:
In the ultraviolet (UV) spectrum, silicon photovoltaic (PV) modules display limited spectral response. They do not use high-energy photons efficiently, thus contributing to thermalization losses and material degradation of the modules. This study looks into the development of photoluminescent coatings using titanium dioxide (TiO_2). These coatings can be used for luminescent down-shifting (LDS) applications in PV systems. An acid-catalysed sol–gel method was used to synthesize TiO_2 nanoparticles. The nanoparticles were thermally treated to control phase composition. X-ray diffraction (XRD) analysis was used to confirm the formation of anatase and rutile phases. It was observed that phase evolution was strongly dependent on annealing temperature. Because of its impact on defect-mediated photoluminescence, a mixed anatase–rutile system was found to be a viable configuration. The intrinsic defect states, like oxygen vacancies and Ti^{3+} centers in the material, make visible emission from UV excitation possible. The results provide a materials-level basis for TiO_2-based LDS coatings intended to enhance spectrum use in silicon solar cells. But device-level efficiency evaluation is still in progress.
Keywords — photoluminescent coatings, titanium dioxide nanoparticles, TiO_2, luminescent down-shifting, LDS coatings, silicon photovoltaic modules, UV spectral response.

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I. Introduction
Silicon photovoltaic technology dominates the global solar energy landscape due to its maturity and reliability. However, when it comes to the ultraviolet (UV) region, its spectral response is less than ideal. This is because photons with wavelengths shorter than 400 nm are absorbed close to the surface, and this causes significant recombination losses. This results in ineffective energy conversion. Material deterioration also speeds up when exposed to UV light for extended periods of time.

To overcome this obstacle, non-invasive optical technique such as luminescent down-shifting (LDS) can be utilized. It works by using a luminescent substance to absorb high-energy photons in LDS systems and reemit them at longer wavelengths. These longer wavelengths more closely resemble silicon solar cells' external quantum efficiency. These coatings can also act as UV filters to improve module longevity.

Among various LDS materials, titanium dioxide (TiO_2) is a particularly attractive option. This can be attributed to its wide band gap, chemical stability, environmental safety, and compatibility with existing photovoltaic architectures. Importantly, it has defect states which enable visible photoluminescence, making it a good candidate for converting UV-to-visible spectrum. This study focuses on the synthesis and structural characterization of TiO_2 nanoparticles. The goal is to evaluate their potential for photoluminescent coating applications in photovoltaic systems.

II. Photoluminescence Mechanisms in TiO_2

TiO_2 is a wide-band-gap semiconductor. This material has two forms: anatase and rutile. Anatase has a band gap of 3.2 electron volts and rutile has a band gap of about 3.0 electron volts. Its photoluminescence arises primarily from defect-mediated electronic states rather than direct band-to-band recombination.
Key contributors include:

- **Oxygen vacancies (VO)**: Introduce localized states within the band gap
- **Ti^{3+} centres**: Act as electron traps enabling radiative recombination
- **Surface states**: Especially significant in nanostructured TiO_2

These defect states in the material allow recombination pathways that emit photons in the visible region. This is critical for LDS applications. However, an important constraint is that increasing defect density can introduce **parasitic absorption and scattering losses**. This reduces overall optical efficiency of the material. Therefore, **controlled defect engineering** is essential.

III. Materials and Methods

A. Synthesis of TiO_2 Nanoparticles

TiO_2 nanoparticles were synthesised using an acid-catalysed sol–gel method :

1. Titanium precursor dissolved in ethanol
2. Water and nitric acid are added to control the hydrolysis and the pH is kept 1.
3. Formation of a stable gel
4. Drying followed by thermal annealing
5. Phase evolution from anatase to rutile controlled via temperature

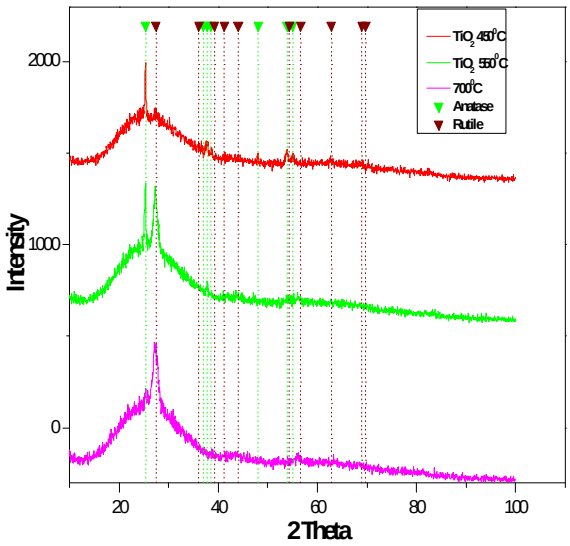
This method offers:

- Low cost
- Good phase control
- Tunable particle size and crystallinity

B. Structural Characterisation

X-ray diffraction (XRD) was used to determine phase composition.

IV. Results and Discussion



A. Phase Evolution and XRD Analysis

The XRD findings show:

- At lower annealing temperatures, the predominant anatase phase
- The rutile phase gradually forms as the temperature rises.
- Enhanced crystallinity at elevated temperatures

This validates thermal treatment-induced regulated phase transition.

B. Role of Mixed Anatase–Rutile Phase

This study's main finding is that photoluminescent applications are better suited for a combined anatase–rutile system.

This can be clarified by:

- Improved A higher density of defect states at interfaces

- A higher density of defect states at interfaces
- Better equilibrium between:
    - UV absorption (anatase)
    - Optical stability and refractive properties (rutile)

The published literature trends on TiO_2 heterophase systems are in good agreement with this synergistic effect.

C. Photoluminescence Implications

Photoluminescence in TiO_2 arises from:

- Oxygen vacancies
- Ti^{3+} defect centres
- Surface defect states

These defects enable:

- Absorption of UV photons
- Re-emission in visible range

This supports the LDS mechanism where emitted photons are better matched to silicon absorption.

D. Relevance to Photovoltaic Applications

The proposed coating serves two primary functions:

1. **UV Filtering:** Prevents PV materials from deteriorating
2. **Spectral Conversion:** Transforms a portion of the UV spectrum into visible light that can be used.

However, it is crucial to state clearly:

Photoluminescence at the material level does not automatically ensure increased efficiency at the device level.

Loss mechanisms include:

- Losses from optical coupling
- Mismatch in refractive index
- Absorption of encapsulation
- Degradation of the environment

V. Research Gap and Future Work

Current work is limited to:

- Nanoparticle synthesis
- Structural characterization

Critical next steps include:

- Photoluminescence spectroscopy
- UV–Vis absorption studies
- Thin-film coating development
- Integration with silicon PV modules
- Device-level efficiency testing

Additionally, optimization is required for:

- Coating thickness
- Transparency
- Defect engineering
- Long-term UV stability

VI. Conclusion

Sol-gel-synthesised TiO_2 nanoparticles show potential for use in photoluminescent coatings in solar energy applications. Controlling defect states and optical characteristics is largely dependent on phase engineering between anatase and rutile. Because of its enhanced defect-mediated photoluminescence, a mixed-phase system seems to be interesting to a great degree.

Even though the work done so far lays a basis at the material level, more research is needed to convert these attributes into quantifiable gains in photovoltaic performance. This work underscores the significance of combining materials design with device-level concerns for real-life applications of TiO_2-based LDS coatings.

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