APPLICATION OF ULTRASONIC SPRAY PYROLYSIS TECHNOLOGY IN THE DEVELOPMENT AND OPTIMIZATION OF SOLAR CELLS

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Annotatsiya. Ushbu tezisda energiya ta'minotiga global talabning ortib borishi va an'anaviy yoqilg'ilarning atrof-muhitga ta'siri sababli qayta tiklanuvchi energiya manbalarining ahamiyati ko'rib chiqilgan. Quyosh energiyasi, uning mo'lligi va katta energiya ehtiyojlarini qondirish salohiyati tufayli, alohida e'tiborga sazovor bo'lgan. Fotovoltaik energiya konversiyasi, ya'ni quyosh nurini elektr energiyasiga aylantirish jarayoni, quyosh batareyalarini samarali va tejamkor ishlab chiqarishga bog'liq. Tezisda quyosh batareyalarining ishlashini yaxshilash va narxini pasaytirishga qaratilgan turli materiallar va ishlab chiqarish usullari o'rganilgan.

Kalit so'zlar: qayta tiklanuvchi energiya, quyosh energiyasi, fotovoltaik energiya konversiyasi, quyosh batareyasi, energiya samaradorligi

Аннотация. В данной работе рассматривается важность возобновляемых источников энергии в связи с растущим глобальным спросом на энергию и воздействием традиционных видов топлива на окружающую среду. Солнечная энергия выделяется как особо значимая благодаря ее обилию и потенциалу удовлетворения значительной части мировых энергетических потребностей. Фотоэлектрическое преобразование энергии, процесс преобразования солнечного света в электрическую энергию, зависит от эффективного и экономичного производства солнечных батарей. В данной работе исследуются различные материалы и методы производства, направленные на улучшение производительности и снижение стоимости солнечных батарей.

Ключевые слова: возобновляемая энергия, солнечная энергия, фотоэлектрическое преобразование энергии, солнечная батарея, энергоэффективность

Abstract. This thesis examines the importance of renewable energy sources due to the increasing global energy demand and the environmental impact of traditional fuels. Solar energy is highlighted as particularly significant due to its abundance and potential to meet a substantial portion of global energy needs. Photovoltaic energy conversion, the process of converting sunlight into electrical energy, relies on the efficient and cost-effective production of solar cells. The thesis explores

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various materials and manufacturing techniques aimed at improving the performance and reducing the cost of solar cells.

Keywords: renewable energy, solar energy, photovoltaic energy conversion, solar cell, energy efficiency

Introduction

With the global increase in energy demand and the environmental challenges associated with fossil fuels, renewable energy sources have emerged as a top priority in efforts toward sustainable development. Among these sources, solar energy stands out due to its abundance and its potential to meet a significant portion of the world's energy needs.The process of converting sunlight into electricity, known as photovoltaic energy conversion, primarily relies on the efficient and cost-effective production of solar cells. Various materials and manufacturing techniques have been explored to enhance the performance and reduce the cost of solar cells. These range from traditional silicon-based technologies to emerging thin-film and organic solar cells, each with their own advantages and limitations.As the field continues to advance, innovative deposition techniques are playing a critical role in achieving improvements in efficiency, stability, and scalability of production. This report focuses on one such promising technique — Ultrasonic Spray Pyrolysis (USP) — and its application in solar cell manufacturing.In USP, a specialized ultrasonic atomizer (typically operating at 20–100 kHz) generates fine aerosols from a solution of chemical precursors. When these aerosols are sprayed onto a heated substrate, the solvent evaporates and the target material is synthesized via pyrolysis.As a result, a uniform, highly crystalline thin film is formed on the substrate surface. This technology has shown great promise for large-area deposition of perovskite,

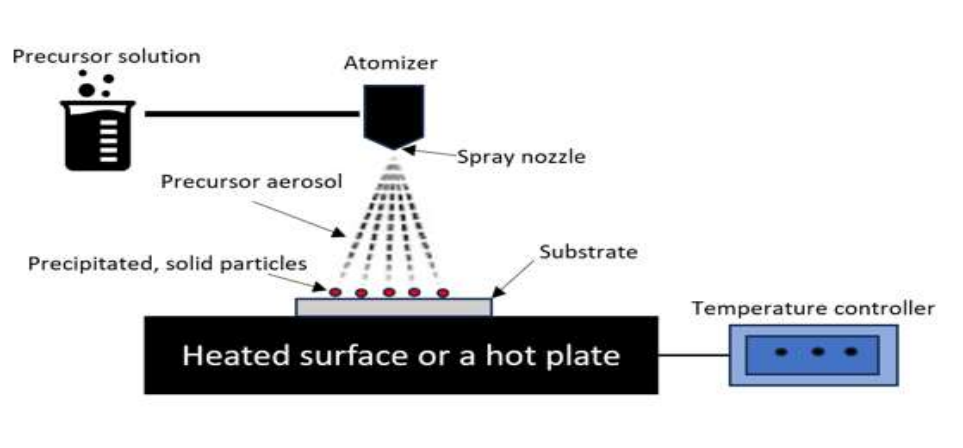


Figure.1. Schematic representation of the ultrasonic spray pyrolysis (UPP) technology process

chalcogenide, titanium dioxide, and other semiconductor layers.

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Application Stages of Ultrasonic Spray Pyrolysis (USP) Technology In ultrasonic spray pyrolysis, the process begins with preparing a solution containing a metal precursor. This solution is then atomized into fine droplets using an ultrasonic atomizer. A carrier gas—typically air or nitrogen—is introduced to transport the resulting aerosol towards the substrate. The substrate is heated to a specific temperature (usually between 200–500°C), and upon impact, the solvent within each droplet evaporates while the remaining material undergoes pyrolytic decomposition and solidifies on the substrate. In this process, each droplet essentially acts as a miniature chemical reactor. The characteristics of the resulting thin film can be optimized by controlling various parameters such as the substrate temperature, solution concentration, gas flow pressure, and the distance between the spray nozzle and the substrate. [3]

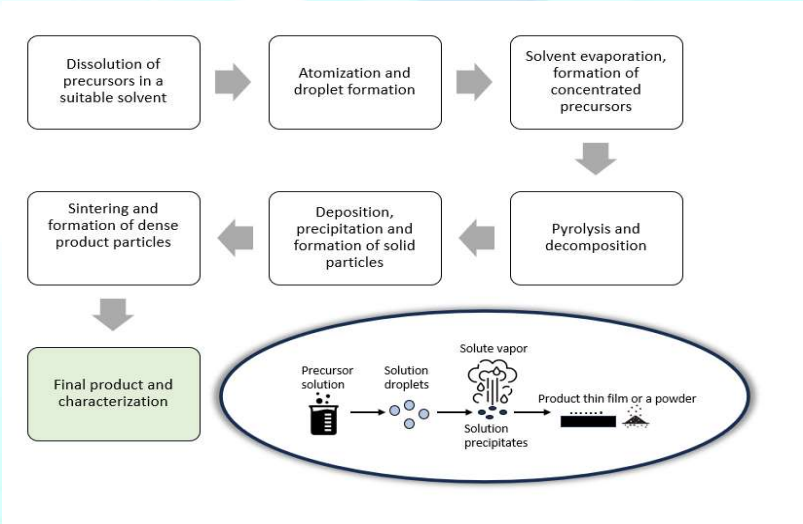


Figure. 2. Stages of Ultrasonic Spray Pyrolysis (USP) Technology: Sequence of Physicochemical Processes

Various layers for solar cells have been fabricated using Ultrasonic Spray Pyrolysis (USP) in recent studies. For instance, there have been attempts to utilize USP in the formation of coated solar cells based on materials such as CdTe and $Cu(In, Ga)Se_2$ [4].In recent experiments, tin sulfide (SnS) perovskite layers were successfully deposited via ultrasonic spraying. By adjusting the precursor solution's flow rate, researchers could control the film thickness and crystallinity. Moreover, deeply compensated Sb_2S_3 layers produced through USP have been integrated into semi-transparent solar cells, demonstrating high open-circuit voltages and relatively good conversion efficiencies.

Review of Scientific Literature

According to scientific literature, various solar materials have been successfully synthesized using Ultrasonic Spray Pyrolysis (USP) technology. For instance, Hernández-Pérez and colleagues reported the successful fabrication of

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Fe_2O_3-based films using the USP method, achieving high solar absorption performance [5]. Similarly, Eensalu et al. developed Sb_2S_3-based solar cells with a reported power conversion efficiency (PCE) of 5.5% [6].Furthermore, Sultana and co-workers identified an optimal Sn concentration of 1.8 mM in CZTS films, which yielded the best optical and crystalline properties [7]. Another notable contribution comes from Batyrbekov and colleagues, who investigated π-SnS coatings synthesized via USP and demonstrated improvements in film characteristics by controlling the solution flow rate.It is also noteworthy that USP-synthesized Ga_2O_3–Cu_2O devices showed significant enhancement in open-circuit voltage due to process automation. Overall, current scientific findings affirm the advantages of USP technology in terms of process simplicity and compatibility with a variety of materials. From this perspective, unconventional materials such as ZnMgO are also being synthesized via USP to replace toxic CdS layers with more environmentally friendly alternatives [8].Research in the field of organic photovoltaics also supports the wide applicability of USP. For example, Bisen et al. (2024) investigated optoelectronic processes in organic devices fabricated by ultrasonic spraying and reported a power conversion efficiency of 11.7% with the incorporation of diphenyl ether (DPE) [9]. Rodríguez-Gómez and colleagues (2023) successfully fabricated Li-doped NiO thin films via USP for use as hole transport layers in light-emitting diodes (LEDs). These films exhibited a cubic structure, 60–77% transmittance, and low haze. In another study, Ledesma-Mancilla et al. (2023) examined the optical, morphological, and structural properties of MnPc films synthesized at low temperatures using USP. Their results indicated an optical bandgap ranging from 3.58 to 4.46 eV, with thermal treatment inducing molecular structural rearrangements.Additionally, Eensalu and co-workers (2019) fabricated semi-transparent Sb_2S_3 thin films via USP and tested them in solar window applications, achieving a PCE of 5.5% under 1 sun illumination and 7.4% under 0.1 sun. Remarkably, the films retained 70% of their efficiency after one year of storage. Kärber et al. (2016) also reported efficiencies ranging from 1.3% to 1.9% in TiO_2/Sb_2S_3/P3HT hybrid cells on smaller active areas.More recently, USP-prepared ZnO:F films have demonstrated an electrical resistivity of R = 0.016 Ω·cm and a significantly improved Haacke figure of merit (FOM) [13].Based on new research published in 2025 by Springer, Ag-doped SnS materials showed an increase in bandgap energy (Eg) from 1.84 eV to 2.47 eV. Likewise, another Springer article from 2024 provided data on SnS-based heterostructures, highlighting the variability in film density, Eg, and photovoltaic response as a function of deposition flow [14].

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Table 1 presents the changes in key parameters of π-SnS films synthesized via USP. The data demonstrate that increasing the solution flow rate introduces an inverse relationship between film thickness and transparency, directly affecting the optoelectronic performance of the devices.

Table 1

Properties of π-SnS Thin Films

Flow Rate (ml/min)	Film Thickness (nm)	Optical Bandgap (Eg, eV)
4	338	1.83
6	686	1.77
8	1098	1.75

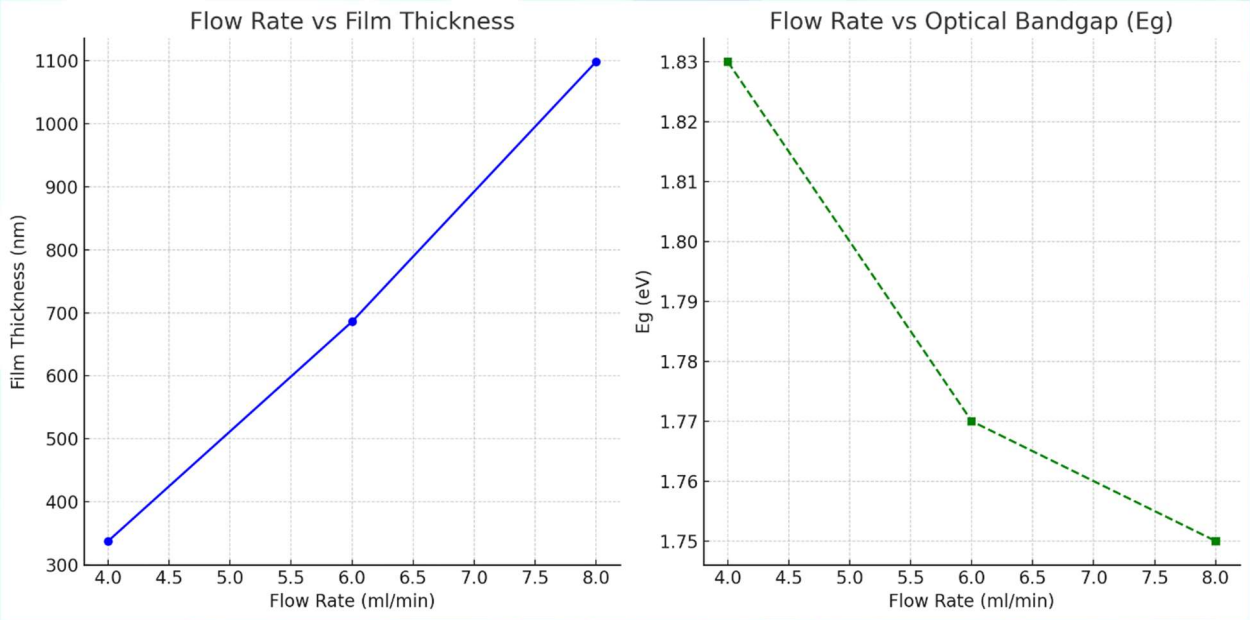


Figure. 3. Effect of Flow Rate on Film Thickness and Optical Bandgap (Eg)

Conclusion

Ultrasonic Spray Pyrolysis (USP) is playing an increasingly important role in modern solar cell manufacturing technologies.One of the primary advantages of this method lies in its ability to operate in an open atmosphere, without the need for vacuum systems, thereby significantly reducing production costs. Additionally, USP allows for the formation of uniform and controllable coatings over large-area substrates, making it highly suitable for industrial-scale applications.Scientific studies have shown that thin films synthesized via USP exhibit excellent surface adhesion, high density, and structural stability. These properties make them essential not only for high-efficiency photovoltaic devices but also for a wide range of optoelectronic systems. In particular, the ability to tune the optical bandgap (Eg), as well as control the film thickness and morphology, positions USP as a

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technologically and scientifically relevant solution. Future research should continue in several key directions to further enhance the efficiency of USP-based processes. These include optimizing process parameters such as temperature, ultrasonic frequency, spray rate, precursor solution concentration, and pH; investigating new classes of semiconductor and oxide materials; and developing fully automated processing systems. From this perspective, USP can be considered a promising and innovative approach for the future production of high-performance, cost-effective, and environmentally friendly solar cells.

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