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Article

Construction and development of an ultrasonic spray pyrolysis system for semiconductor thin films deposition to photovoltaic applications

Construcción y desarrollo de un sistema de rocío pirolítico ultrasónico para el depósito de semiconductores en películas delgadas para aplicaciones fotovoltaicas

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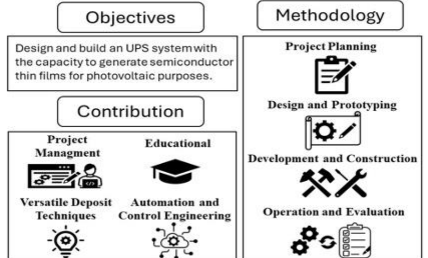
Abstract

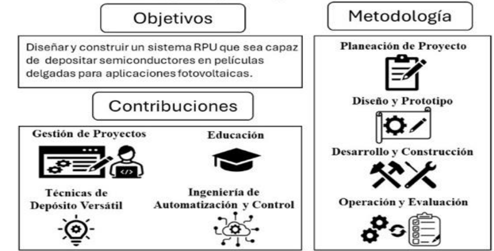
The ultrasonic spray pyrolysis (UPS) technique is an efficient method for depositing high-quality thin films, offering advantages over traditional methods. This paper presents the construction and development of a USP system designed for semiconductor thin films used in photovoltaic applications. It provides an overview of the technique, including the setup, material preparation, and process control. The results demonstrate the system's ability to produce uniform, high-quality films, underscoring its potential to advance semiconductor research and inspire new applications in photovoltaics.



Deposition thecniques, Spray pyrolysis, Thin films

Resumen

La técnica de pirolisis por ultrasonido (USP) es un método eficaz para depositar películas delgadas de alta calidad, con ventajas sobre los métodos tradicionales. Este artículo muestra cómo se construyó y desarrolló un sistema USP para películas delgadas de semiconductores en aplicaciones solares. Se explica de manera sencilla cómo funciona la técnica, desde la preparación de materiales hasta el control del proceso. Los resultados confirman que el sistema puede producir películas uniformes y de buena calidad, lo que lo convierte en una herramienta valiosa para mejorar la investigación en semiconductores.



Tecnicas de depocisión, Rocio pirolitico, Laminas delgadas

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Introduction

Material investigation advancement has focused on semiconductor technology for many decades (Sze, S. M. 2002). Their electrical properties make the semiconductor suitable for energy networks and power electronic applications (Baliga, B. J. 1996). Specifically speaking, these materials play a vital role in the advancement and efficiency of renewable energy technologies. <

Their unique optoelectronic properties are essential in converting and managing energy from renewable sources such as solar (Green, M. A. 2000), wind (Son, J.-Y. et al. 2017), and hydroelectric power (Nababan, S. et al. 2012).

Notably, the photovoltaic field requires semiconductors since these play a crucial role, serving as the foundational materials for solar cells that convert sunlight into electricity. Their unique electrical properties, which allow them to conduct electricity under certain conditions while acting as insulators under others, make them ideal for capturing and converting solar energy efficiently.

Silicon, the most widely used semiconductor in PV cells, has been instrumental in achieving significant improvements in the efficiency and cost-effectiveness of solar panels (Green, M. A. 2005).

Innovations in semiconductor materials and technologies have enabled the development of high-efficiency solar cells, which are essential for increasing the adoption of solar energy (Green, M. A. et al., 2019). By enhancing the performance and reducing the costs of PV technology, semiconductors contribute significantly to the global transition towards sustainable energy sources, helping to mitigate climate change and reduce dependence on fossil fuels.

Unsurprisingly, their development has allowed these materials to go through different manufacturing processes, from their implementation in bulk to their execution in thin films and nanotechnology. Most bulk semiconductors are typically obtained through a series of processes that involve the purification, crystallization, and doping of materials, like silicon, due to its abundance.

However, obtaining semiconductors through thin film deposition techniques has made it possible to generate high-quality materials. These techniques allow precise control over the material's physical properties, such as its thickness, electrical and morphological characteristics, to name a few examples (Chen, Z. et. al. 2012).

Thin film deposition techniques play a critical role in a new generation of solar cells, depositing fragile semiconductor material layers onto a substrate, forming the essential optoelectronic properties (Chopra, K. L. et al. 2004).

There is a wide variety of techniques capable of depositing thin films. Still, the vast majority can be classified as completely chemical, entirely physical, or a combination of both in different stages (Kern, W. et al. 2001). Among the most frequently used deposit techniques are the implementation of Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), and Atomic Layer Deposition (ALD).

These techniques offer distinct advantages and are selected based on the desired material properties and applications.

PVD, including methods like sputtering and evaporation, allows for the deposition of metals, insulators, and semiconductors, providing high-purity films with excellent adhesion and uniformity. On the other hand, CVD is advantageous for its ability to produce high-quality, conformal films over complex geometries, making it ideal for applications in microelectronics and nanotechnology.

ALD stands out for its precision, enabling atomic-level control over film thickness and composition, which is critical for advanced electronic and optical devices (Kern, W. et al. 2001, M. N. Chaudhari 2021). The choice of deposition technique directly influences the thin films' microstructure, crystallinity, and chemical composition, thereby determining their electrical, optical and morphological properties. Furthermore, many of these techniques have modifications or variants in their deposition trajectory, allowing the method to generate specific characteristics in the thin film that may not be visualized in films obtained using the original technique.

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As a result, understanding and selecting the appropriate deposition method is essential for tailoring material characteristics to specific technological applications (Bunshah, R. F. 1982).

Ultrasonic Spray Pyrolysis (USP) is categorized as a vapor chemical technique. It does not require strict growth environments such as low pressures or vacuums, making it a relatively simple and economical technique compared with other physical and chemical methods. Likewise, the USP results in homogeneous growth for forming thin films (Patil, P.S. et al. 1999), converting it into a versatile and attractive technique to produce semiconductor materials.

The USP technique involves producing atomic species, the material to be deposited in a micrometric format (generally droplets), using an ultrasonic nebulizer or atomizer.

The nuclear species generated are transferred with a carrier gas that can be oxygen, nitrogen, argon or another type of gas, depending on what is required to be deposited.

The micrometric droplets collide with the surface where you want to grow the thin film (usually a substrate). The growth environment must be subjected to adequate temperatures provided by a reactor or thermal chamber.

The temperature decomposes the droplets, allowing the thin film to form with the accumulation of particles on the substrate, leaving only the supplied materials that want to be deposited; this is known as pyrolysis (Mwakikunga, B. W. 2013). Figure 1 shows a general diagram of the technique.

Box 1

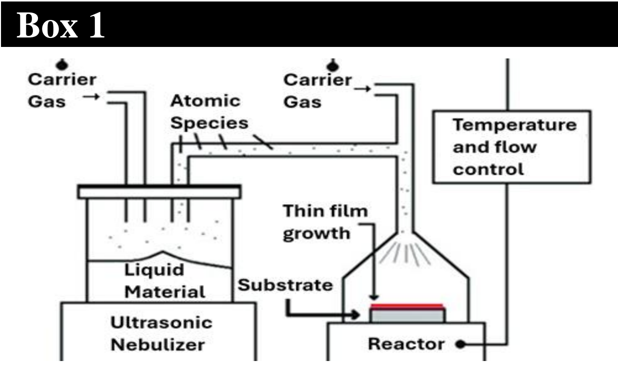

Figure 1
General diagram of the USP technique
Source: Mwakikunga, B. W. 2013

This paper plans to document the construction and development of a USP system capable of depositing semiconductor thin films. The article's structure includes an introduction in section I, the experimental development of the system in section II, the obtained results, and finally, the conclusions for sections III and IV, respectively.

Methodology

The design and construction of the USP system are guided by the diagram presented in Figure 2.

Box 2

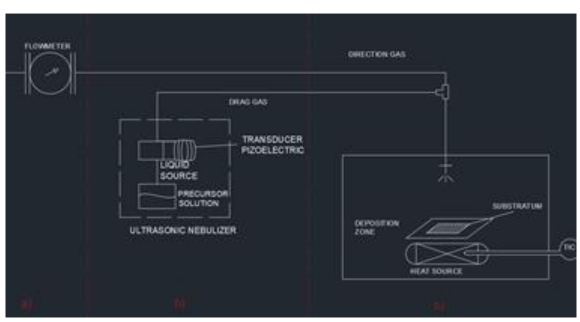

Figure 2
Diagram of USP system made in AutoCAD 3D. Section a) corresponds to the carrier and directional gas distribution and the gas source. Section b) pertains to the ultrasonic nebulization and precursor solution. Section c) covers the deposition area, heat source, and temperature control.

Component Description

This implies the construction and application of specific elements to carry out the technique.

A.- Ultrasonic Nebulizer

A YUE HUA ultrasonic nebulizer WH-2000 model (Figure 3) with an ultrasonic frequency of 1.7 MHz was coupled to the system. This element contains the integrated piezoelectric transducer where the precursor solution is placed once prepared.

The ultrasonic nebulizer is the most significant element of the USP technique; in addition, the magnitude of the frequency allows the size of the droplets to be regulated, improving the deposition of the thin film.

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Box 3

Figura 3
Ultrasonic nebulizer WH-2000 (YUE HUA)
Source: Global Sources Official Website

B.- Reactor Chamber

The reactor is characterized by providing the thermal energy necessary for the pyrolysis process. It is also the instrument where substrates are placed so thin films can be deposited by the atomic species transferred from the nebulizer. For that matter, specific requirements must be formulated.

On the pyrolysis part, it is required for the substrate to be able to vary its temperature, allowing the study and investigation of the temperature influence in thin films (Afify, H.H. et al. 1991). In addition, different materials can be deposited at various temperatures, thus expanding the range of possibilities planned for thin films that are intended to be deposited.

Even so, the USP technique is characterized by maintaining low temperatures compared to other chemical techniques, so handling temperatures of 400 °C are usually considered high (Patil, P.S. et. al. 1999).

For the place where the substrates are placed inside the reactor, a bowl-type container was sized with measurements of 10 cm as a diameter and depth of 6 cm; this allows several substrates to grow thin film samples with identical deposit conditions and allows the possibility of carrying out destructive-type techniques to analyse specific properties.

Lukoschus et al. consider this requirement, as well as temperature management, to be one of the significant points in generating an efficient system for the deposition of thin films (Lukoschus et al. 2001).

For the heat source, a liquid tin melting system was designed to prevent the Leidenfrost effect, which causes droplets to bounce on the hot surface, returning to the deposition substrate.

A pair of 980W tungsten resistors from ECOGLASS were used to generate sufficient heat for the melting process. These resistors were embedded in a carved refractory brick, mimicking the shape of domestic heaters, to avoid contact with the metal surfaces of the bowl-type container.

Figure 4(a) illustrates the refractory brick designed in Solidworks, while Figure 4(b) shows the physical counterpart and the resistors used.

Box 4

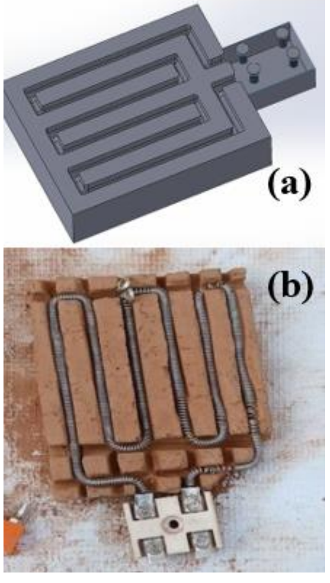

Figure 4
First designed (a) and physical (b) refractory brick
Source: Author

The heat source brick was placed in a heat-resistant stainless-steel box lined inside with a high-temperature ceramic fiber.

A custom-fitted lid with a prepared opening conduit was placed on the metal frame, through which the tin melting process will be carried out inside a small stainless-steel dish (see Figure 5)

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Box 5

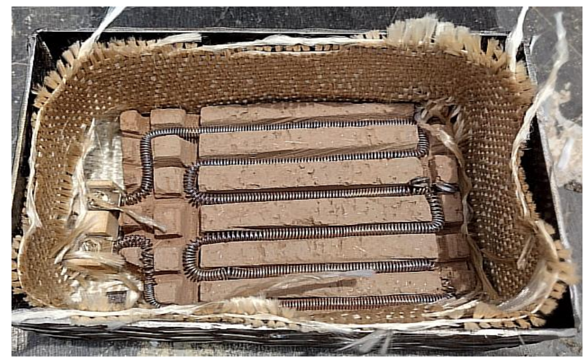

Figure 5
Tin melting prototype

Source: Author

A K thermocouple connected to a PID controller from TECNEU that regulates the current input to the resistances was implemented for the temperature control system.

The entire system was enclosed within an acrylic hood to maintain a closed environment and adapt an extraction system. The final reactor chamber and the interjection pipes of other USP component description areas are shown in Figure 6.

Box 6

Figure 6
Reactor chamber

C.- Carrier gas system

Industrial-grade nitrogen gas was used due to its low reactivity with the chemical components from the precursor substance applied to form thin films.

The gas tank acquired has a pressure regulator used as a flowmeter from WESTON model Z-62900, which allows coordination of the nebula formed by the ultrasonic atomizer, mitigating the turbulence of the deposition velocity in the thin film.

A network of polyurethane pipes was created for the gas transit due to the material's low roughness, preventing turbulence formation within the duct, thus promoting a laminar flow preferred for homogeneous thin film formation.

Results

A prototype of a USP system was built and characterized. The final reactor system consists of three separable modules: The ultrasonic nebulizer, the reactor chamber and the carrier gas system. Figure 7 shows the finalized USP prototype system.

Box 7

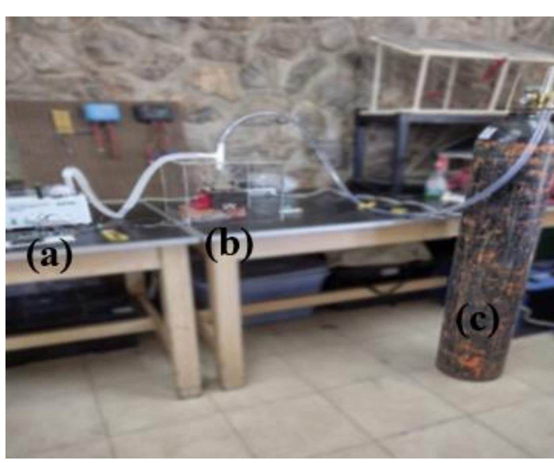

Figure 7
USP prototype system: Ultrasonic nebulizer (a), reactor chamber (b), carrier gas system (c) modules

During preliminary tests, the system achieved temperatures exceeding 300°C, with a peak of 600°C after approximately 15 minutes of exposure.

The use of industrial-grade nitrogen gas for nebulization, along with a network of polyurethane pipes, ensured low reactivity and promoted laminar flow, which is crucial for the formation of high-quality films; this system allows a maximum flow rate of up to 30 liters per minute.

However, for the application of this reactor, flow rate tests were conducted at up to 5 liters per minute, maintaining laminar flow.

Integrating a KJ thermocouple connected to a PID controller allowed precise temperature regulation, contributing to the overall efficiency and reliability of the process.

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The enclosed acrylic hood provided a controlled environment, paving the way for future enhancements with an extraction system. These features collectively contributed to the successful creation of cells within the deposition hood, as evidenced by the stable laminar flow observed during the 10-minute deposition tests.

Conclusions

The construction, development, and implementation of an Ultrasonic Spray Pyrolysis system have been achieved. The system's component integration and preliminary testing have demonstrated significant advancements in the controlled temperature and deposition processes.

The system, composed of three distinct modules, the ultrasonic nebulizer, effectively maintained stable operational conditions for thin film deposition.

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this document.

Author Contribution

Palacio-Sifuentes, David: Contributed to the project idea, research method and technique, and article writing.

Alvarez-Macias, Carlos: He is Project Leader and Supervisor. He carried out the systematization of the background for the state of the art. He supported the design of the methodology and contributed to the writing of the article.

Rodríguez-Castro, Sergio: contributed to the research of the state of the art, the bibliography and the article's writing.

Martinez-Lopez, Ricardo: contributed to the research design, the type of research, the approach, the method, and the article's writing.

Availability of data and materials:

The data obtained and used in this study are sourced from publicly available articles on the platforms Google Scholar and ResearchGate.

The specific articles that served as information sources can be accessed through relevant searches on these platforms.

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Abbreviations

ALD	Atomic Layer Deposition
CVD	Chemical Vapor Deposition
PV	Photovoltaic
PVD	Physical Vapor Deposition
USP	Ultrasonic Spray Pyrolysis

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