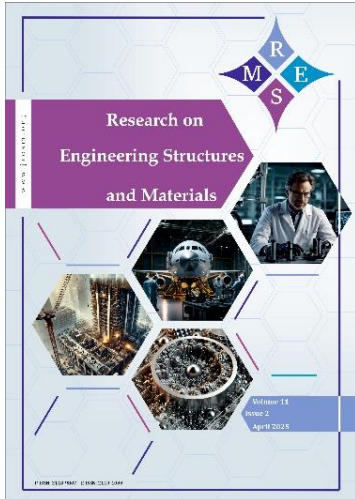




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Experimental investigation of SnS:Cu₂O nanophotonic thin films for enhancing voltage output of solar cell

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Abstract

This paper aimed to find a way that the light could be allowed to react with nano photonic material and enhance the output voltage of the photo cell. SnS:Cu₂O (1:1) was used to produce a thin film nanophotonic material. It was heated at 200 degrees Celsius to create a quantum effect. The results from an X-ray diffraction (XRD) showed the sample had changed from its normal form to become polycrystalline. The size decreased from an average size of 16nm to 12nm and the dislocation density (δ) increased from 0.003906 to 0.010000. Results showed that this material has a high average of optical transmittance greater than 80%. When annealed the optical transmittance was shifted towards lower wavelength. By implementing the prepared nanophotonic thin film into a silicon based solar cell system, a clear increase in produced voltage was observed to increase from 0.0 volts to 2.34 volts when exposed to sunlight. These results show how light and nano particles have a great positive effect on each other when used together. Such results would be considered in the field of optics, solar cells and communications, leading to more advanced technology in the future.

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1. Introduction

As light is one of the fundamental elements of nature, it has played a crucial role in the development of science and technology. With scientific advancements in recent decades, new fields have emerged that rely on exploiting the properties of light at extremely small dimensions, leading to the emergence of nanophotonics. This science represents an intersection of physics, engineering, and applied sciences, where light is used at the nanometer scale to achieve innovative applications in communications, computing, energy, and biomedicine. Nanophotonics is a relatively new but already well-defined field of science and technology that aims to establish and utilize the unusual properties of light and its interaction with matter in various nanostructures. Nanophotonics involves the confinement of light in complex media and electron waves in nano-solids, which determine the various physical phenomena in nanophotonics [1].

The challenge is to control light and its interaction with matter at the nanoscale to obtain new optical properties and functions that go beyond the limits of conventional physics and natural materials. An encouraging approach to these difficulties is to employ quantum dots. Quantum dots can respond precisely to light and by controlling their size and shape their optical properties can be tuned. Because quantum dots are very small, containing only a few hundred atoms, they are surrounded by materials with a larger band gap. Here the gap energy is the energy difference between the top of the valence band and the bottom of the conduction band (the minimum energy required to excite an electron). According to quantum theory, the electrons in quantum dots are confined in three dimensions – length, width and height. This three-dimensional confinement gives them a special property of interacting with light with remarkable efficiency. This effect results in drastic changes in the absorption and emission properties of light, depending on the size of the

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quantum dots. In the quantum dots the electrons are confined to a small volume. The energy levels go up. The energy gap between the ground and excited states goes up. So, when illuminated the quantum dots absorb the light energy and the electrons jump to a higher energy level then fall back to their original energy level by emitting photons. The emitted light's wavelengths depend on the size of the quantum dot, so the same dot can be different colors depending on its size. The rapid progress of modern technology and the huge potential to control light and its interaction with matter at nanometer scale has made nanophotonics an important area of research. Research in this field aims to realize new optical properties and functions beyond the limits of traditional physical materials. Considering the difficulties of this field, like the overcoming of the limits of traditional light diffraction and the design of advanced optics, several solutions have been developed, including the use of quantum dots and their integration with conventional devices. This work explores the essential role of light in nanophotonics, from the theoretical principles that govern the interaction of light at the nanoscale to the practical applications that are revolutionizing fields such as communications and renewable energy. The research also addresses the latest developments in metamaterial design and mechanisms for integrating them with light to achieve unconventional control over optical properties. This research aims to study the role of light in nanophotonics, focusing on the fundamental physical mechanisms and promising applications [2].

Fig. 1 shows the photonic crystals or optical crystals as a visible representation. The color bar on the top of the image represents the square magnitude of the E-field normalized to an arbitrary number. It will be dynamically normalized to values between 0 and 1 where 0 is no intensity of electric field or dark black/ red and 1 would be high intensity of electric field bright white/yellow. y-Axis in microns (μm) from 0-12. X-Axis is on the same space scale as the y-axis, so, also in (μm) from 0-20 and over.

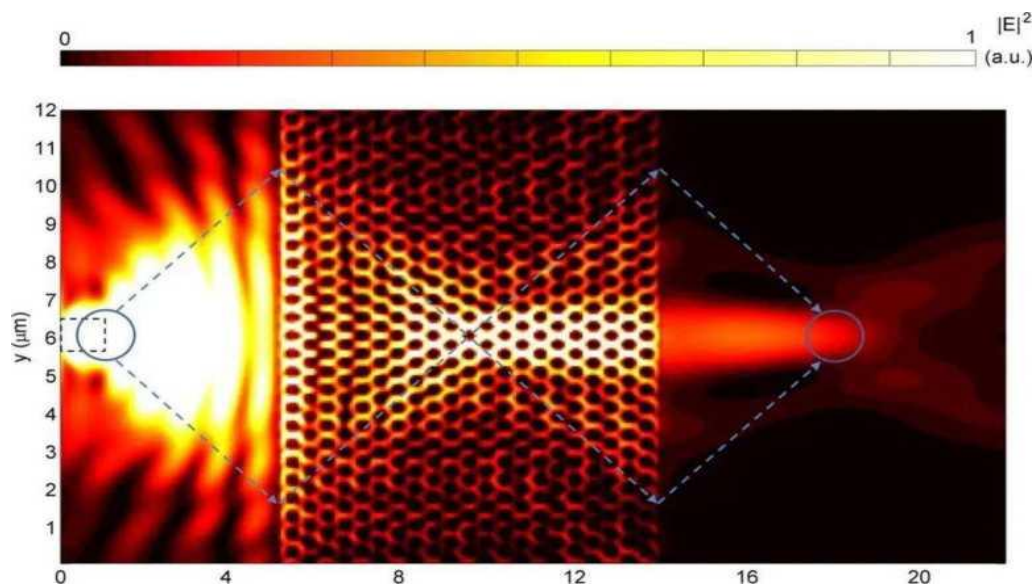


Fig. 1. Photonic crystals or optical crystals [3]

1.1 Nature of Nanophotonics

Nanophotonics can be defined as the science and technology of confining the light waves and electrons in the nanophotonic scale. Electron confinement effect on the optical properties of matter especially on semiconductors and insulators has been a matter of concern for study. These effects phenomena are generally called quantum confinement phenomena, because they are a manifestation of the wave properties of the electrons. These effects show up optically in size dependent optical absorption spectra, emission spectra and transition probabilities of structurally engineered solids of the order of a few nanometers. Their possible applications are various optical elements with certain shapes and sizes can be changed (emitters, filters, lasers, optical elements and switches, photoelectric modulators, and more). This area of nanophotonics has been studied in depth since the 1970s, and several study books have been written about it.

In a different area of nanophotonics, light waves are limited in structurally designed insulating materials. This includes the idea of photonic solids, which control the movement of light waves in the same way that solids control the movement of electron waves [4]. To put it simply, this area of nanophotonics is very traditional. It only uses wave optics and does not go beyond Maxwell's equations. The main thing that is done in this field is making new photonic parts, such as high-quality optical cavities and cavities in superintegrated and other devices. The study of how light and matter combine in nanostructures is a third area of nanophotonics. This includes changing the spontaneous emission and scattering of light. Optical engineering of photonic frequencies can make spontaneous photon emission and scattering stronger or weaker. Recently, in nanophotonics [5], it has become possible to trap light and matter states in microcavities and optical cavities. If you look at the basics of nano-optics, you can see that optical effects at the nanoscale level are possible and not limited by any basic rules. The way light moves through space is controlled by the dispersion relation $\omega = c \cdot k$. This relation links a photon's wave vector $k = \sqrt{k^2x + k^2y + k^2z}$ to its angular frequency ω through the speed of propagation c . For photons, Heisenberg's uncertainty principle says that the product of the uncertainty in where a tiny particle is in space in a certain direction and the uncertainty in its momentum component in that direction cannot be less than h^* . This leads to the following connection:

$$\Delta(hk_x) \cdot \Delta x \geq \frac{h}{2} \quad (1)$$

which can be rewritten as

$$\Delta x \geq \frac{1}{2\Delta k_x} \quad (2)$$

The interpretation of this result is as follows: The constraint depends on the spatial constraint achievable for photons is inversely proportional to the extent of the wave vector components' propagation in the opposite spatial direction, x . Such propagation of wave vector components occurs, for example, in a light field converging towards a focal point, such as behind a lens. The field can be represented by a local superposition of plane waves propagating at different angles, where the wave vector in the opposite direction is k_x . The total length of the wave vector in free space is $k = 2\pi/\lambda$, and this leads to:

$$\Delta x \geq \frac{\lambda}{4\pi} \quad (3)$$

which is consistent with the widely recognized expression for the Rayleigh diffraction limit. Note that the achievable spatial constraint is limited only to the extent of the wave vector components' propagation in a given direction. To increase the extent of the wave vector components' propagation, a mathematical stratagem can be employed. If two perpendicular orientations in space that are arbitrarily chosen for example, x and z , one of the wave vector components can be increased to values exceeding the total length of the wave vector, provided that the wave vector in the perpendicular direction becomes purely imaginary. If this is the case, then the requirement for the total wavevector length can be satisfied [6].

$k = \sqrt{(k^2x + k^2y + k^2z)}$ to be $k^2\pi$. The range of wavevectors that can be used in the x -direction grows as the wavevector gets bigger. And Eq (3) is no longer the only thing that limits light. The rise in the wavevector component in the opposite direction, on the other hand, must be completely imaginary. Putting this wavevector that is only imaginary into the formula for a plane wave gives us $\exp(ik_z z) = \exp(-|k_z|z)$. In one direction, this leads to a field that shrinks exponentially, which is called a declining wave. In the other direction, however, the field grows exponentially. Since fields that grow exponentially don't matter in real life, the method described can be safely ignored in order to find a solution. Also, keep in mind that Eq (3) is always true in empty space. Still, this argument only works when there is an infinite amount of empty room. If you split unlimited free space in half and give each half a different refractive index, the field that is exponentially decreasing can exist in one half of space without the field that is exponentially increasing in the other half. In the other half of space, there may be a different answer that meets the border conditions for the fields at the interface. These simple reasons show that Rayleigh's limit for light confinement is no longer strictly

true when there is spatial variation. However, it is possible for light to be confined indefinitely, at least in theory. This insight is what nano-optics is built on. One important question in nano-optics is how to change the structure of materials to get the best optical confinement that is possibly possible. Another question is what the physical effects are of fields that are both exponentially decaying and tightly contained [7].

1.2 Properties of Nanophotonics

One of the most prominent properties of nanophotonics is the ability to utilize photonic crystals and plasmons to guide and control light propagation in innovative ways. For example, this technology can be used to develop optical materials with unique properties such as a negative refractive index, which opens the door to the design of advanced applications such as optical devices that transcend the limitations of conventional photonics, such as perfect lenses and cloaking devices [8].

1.3 Nanoscale and Its Effects

Nanotechnology is a contemporary technology with numerous applications in the production of molecules or particles at the nanoscale. It is a sophisticated domain of science and engineering that concerns the production, processing, and application of minuscule units, structures, devices, and systems. Nanoparticles are characterized as individual particles with size not exceeding 100 nanometers. The surface structure, size and chemical nature are related to the unique features and properties of nanoparticles. This has led to a substantial increase of medical and industrial applications. Hence, the unique properties and physical modifications of different materials at the nanoscale have facilitated the development of industrial products with enhanced characteristics. The widespread use of nanotechnology products and nanomaterials has resulted in the presence of nanoparticles in the environment. [9]

1.4 Photonic Interaction at the Nanoscale

Photonics is the science of generation, absorption, emission, collection and control of light, and of its application in technology. Light is the visible portion of the electromagnetic spectrum to the human eye with wavelengths from about 400 to 700 nanometers. Moreover, ultraviolet and near-infrared extensions are usually added to reproduce the electromagnetic radiation spectrum, from 100 nm to 1-2 μm , which is the domain of photonics [10]. The propagation of light waves in a medium with inhomogeneities of the order of the wavelength of light is modified by many interferences and scattering effects. Vision is enabled by light scattering and interference, phenomena also observed in soap bubbles and the iridescent film of gasoline on a wet road after it rains, producing bright colors. The changes in space due to the changes in the conditions of the light propagation are small with respect to the wavelength of the light. They are particularly important in the size range from 10 to 100 nm to several micrometers. The space variations of light waves are connected with the differences of the dielectric permittivity. All matter is made of atoms. Nuclei and electrons make up atoms. The first electron shell of the basic hydrogen atom is at a radius of 0.053 nanometers. Atoms can bond to form molecules and solids. A typical molecule is on the order of 1 nm across. Typical crystalline solids have a lattice period on the order of 0.5 nm. There is a decrease in the light-matter interaction of processes directly related to the electron system in molecules and solids. Hence, a detailed study of the properties of electrons is required to understand the interaction of light with matter. Electrons have wave-like properties. They possess wave characteristics, like wavelength, as well as particle attributes, such as mass and charge. The kinetic energy of an electron confined by a potential energy due to its mobility in an electric field produced by an atomic nucleus is equivalent to the typical value of $k_B T = 27 \text{ meV}$ at room temperature. Dependent upon the temperature (T) and the Boltzmann constant (k_B), the characteristic thermal de Broglie wavelength of electrons in solids is approximately 10 nanometers under these conditions [12].

1.5 Quantum Confinement and its Effects on Quantum Dots

Quantum dots are one of the most well-known forms of nanomaterials. They are extremely small particles or three-dimensional, semiconducting nanostructures with dimensions ranging from 2 to

10 nanometers (10 to 50 atoms in diameter), and a volume ranging from 100 to 100,000 atoms in a single quantum dot. They are called quantum dots because they are very small particles of matter effectively concentrated in a single point with zero dimensions [13]. Fig. 2 shows a schematic of the thermal evaporation system working with the quantum point basis.

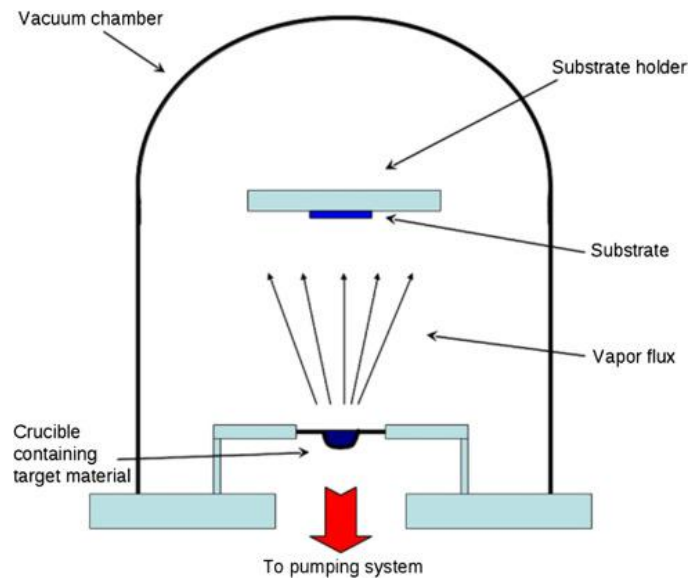


Fig. 2. The phenomenon of thermal evaporation in a schematic [14]

In quantum physics, quantum confinement occurs when electrons in a material are confined to such narrow boundaries that the effects of quantum mechanics become pronounced. The quantization of energy levels is brought about by this confinement in quantum dots, which means that electrons can only occupy certain energy values, instead of moving freely across a wide range of energies as in larger materials. This results in a phenomenon known as the quantum size effect.

These special properties make quantum dots ideal candidates for building solar cells. Solar cells are devices that convert light energy into electrical energy by the interaction between photons and electrons. Photons are absorbed, electrons are released, and a flow of electrons is created, which we call an electric current. The efficiency of light absorption and energy conversion can be optimized by designing quantum dots to a specific size [15]. Size dependence of electronic and optical properties of quantum dots This is dictated by quantum mechanics. They are under quantum confinement. Quantum confinement constrains the conduction band electrons and valence band holes, or excitons (bonded pairs of conduction electrons and valence holes). When exposed to an external light source, such as ultraviolet radiation, these dots cause their atoms to absorb this light, which is then emitted as different colors of different wavelengths [16].

The quantum confinement in quantum dots leads to novel phenomena in light-matter interactions, and new possibilities for innovative technological applications in the fields of energy, electronics and medicine. For example, quantum dots can be used in medical imaging applications because they can emit light of different wavelengths when treated with certain light sources. These properties can be used to develop more precise imaging devices and less invasive imaging devices. Moreover, quantum dots can be employed in the fabrication of optical sensors. Quantum dots can be tuned to respond to specific wavelengths, which gives them high sensitivity to changes in their environment. This opens up possibilities for applications such as pollution detection or monitoring biological processes in living organisms. Consequently, nanoscale interactions between light and matter play a prominent role in technological progress and quality of life with a multitude of applications in different fields. leading to a better understanding of quantum physics and its practical utilization [17].

1.6 Manipulating Light at the Nanoscale

For more than half a century, scientists have endeavored to guide and affect light at the nanoscale. Early theoretical investigations during the 1950s and 1960s at first intended to confine

electromagnetic radiation inside nanometer-scale structures. However, intensive experiments in the 1970s and 1980s ended in frustration as researchers endeavored to effectively detect and manipulate these optical interactions at the nanoscale utilizing the manufacturing capabilities accessible at that period. Persistent setbacks in this field have led some to question the relevance of nanooptics. The trend began to shift in the 1990s with the development of new nanoprinting techniques that enabled the characterization of subatomic features at wavelengths of light between 400 and 700 nanometers. Furthermore, new scanning microscopes allowed for the characterization of optical properties in real space at the nanometer level. Researchers were finally able to access the nanoscale to elucidate the behavior of light and the optical properties of materials at these minuscule length scales [18].

More fast progress has been made thanks to new ideas in related fields like making semiconductors, electron imaging, and quantum materials. New things like surface plasmon resonances, photonic band gaps, and metamaterials have been found that show that optical devices can work at the nanometer scale. Nanophotonics uses ideas from optics, quantum physics, and materials science to change how light and matter interact at the nanoscale level. Nanophotonics is a very active area of study thanks to advances in fabrication techniques and a deep understanding that has grown over many years. Nanophotonic elements, like photonic crystals, plasmonic surfaces, and metamaterials, are being used by scientists to get more precise control over how light is absorbed, scattered, emitted, and spread. Revolutions in a variety of application domains are being driven by the nanoengineering of light-matter interactions. Transformative capabilities, including invisible cloaking and single-molecule recognition, are now facilitated by nanophotonic components. As researchers keep improving light control at the nanoscale, nanophotonics anticipates a novel future in the renewable energy, fields of healthcare, communications, and information processing [19], [20].

1.7 Applications and Technologies

The unparalleled manipulation of light enabled by nanophotonics is resulting in advancements across several critical technologies and applications. Optical communications consist of the following:

1.7.1 Nanophotonic Components Such as Photonic Crystals

The optical functions can be integrated via optical modulators and plasmonic guides onto the chips to develop the nanophotonic integrated circuit. This makes it possible to process and transmit information more quickly by utilizing light rather than electrons. Nanophotonics is essential for the development of optical computers, communication technologies and optical-on-chips [21].

1.7.2 Renewable Energy

Nanodesigns markedly enhance the light absorption and emission efficiency of photovoltaic cells and illumination devices. Nanophotonic solar cells, LEDs, and lasers offer enhanced sustainability and cost-effectiveness in energy solutions. Quantum dots and luminous nanomaterials promote wavelength conversion for improved light harvesting.

1.7.3 Biomedicine

Nanoparticles and plasmonic surfaces facilitate the precise detection and quantification of biomarkers, including individual molecules. Nanophotonic technologies are propelling advancements in quick diagnostics, precise medicine, and the imaging of diminutive biological structures. Nanoparticle agents facilitate targeted phototherapies [22].

1.7.4 Quantum Technology

Confining and manipulating light at the nanoscale results in exceptional control over quantum states. This results in novel quantum light sources, modeling methodologies, and sensing materials. Nanophotonics will play a crucial role in the progression of quantum computing, information technology, and communications [23].

1.7.5 Right Beam

The propagation of light within the photonic crystal is obstructed by the propagation gap; hence, typical plane waves are reflected and do not readily infiltrate the crystal. The right beam directs incoming waves deep into the crystal by bending them, allowing for the concentrating of light at any specified depth within the obstructed gap [24].

1.7.6 Recent Developments

Nanophotonics is a rapidly evolving field, with new discoveries constantly expanding the possibilities for controlling light at the nanoscale. Among the most notable recent discoveries are:

- **Photonic Crystals:** Photonic crystals allow for the customization of light flux through dielectric structures with nano-patterns. Recent advancements have enabled the dynamic management of reconfigurable circuitry and the direction of propagation. Chip-sized photonic dielectrics based on photonic crystals can reduce the device footprint [25].
- **Nanolasers:** Minuscule nanolasers with wavelengths less than that of visible light can facilitate ultra-dense optoelectronic integration. Researchers have recently showcased room-temperature nanolasers constructed from two-dimensional semiconductors like molybdenum disulfide, which are optimal for on-chip applications [26].
- **Quantum Dots:** These nanocrystals could produce single photons for quantum technologies. New approaches are being developed to fabricate improved quantum dots that are deterministically placed in photonic crystal cavities, paving the way for scalable quantum photonics [27].
- **Nanoplasma:** With surface plasmons on metallic nanoparticles, light can be focused beyond the limit of diffraction at the nanoscale. Biosensing, high-resolution microscopy, and next-generation data store densities are all getting better thanks to progress in this area. This field is moving forward very quickly as new nanophotonic materials and production methods are created. Because of these improvements, it is now possible to get visual effects and qualities that were not possible before. Nanophotonics has a bright future ahead of it, with big changes coming to technology and health care [28].

2. Materials and Methods

A thin film of SnS:Cu₂O Nanophotonics was prepared by mixing an equal ratio (1:1) of tin sulfide (SnS) and Cuprous Oxide (Cu₂O) with (0.01) gm for each compound and evaporated onto glass and silicon substrates [29]. Preparation on glass substrates was carried out using a physical thermal evaporation technique with an Edwards Auto 306 coating plant. The glass substrates were ultrasonically cleaned with acetone, ethanol and distilled water. Deposition was performed under high vacuum of about 1×10^{-7} mbar with deposition rate of about 0.3 nm/s for desired thickness of 50nm. After deposition the films were annealed at 200°C for 2 hours. The XRD analysis of samples was done with Shimadzu-6000 X ray diffractometer. Optical properties were studied using SCINCO MEGA2100-SCINCO UV-Vis spectrophotometer from 300 to 1200 nm. Fig. 3 shows the Cuprous Oxide Cu₂O: SnS Nanophotonics glass thin film. This thin film was used to demonstrate the interaction between light and nanophotonic materials. The film was placed in front of a silicon solar cell under direct light of an incandescent 20-Watt CFL lamp with 1,200 lumens situated at a 15 cm distance to produce 1.21 mW/cm². The solar cell was connected to a voltmeter to observe the interaction between the film material and light considering I-V characterization for standard performance analysis of the solar cell. Measuring the pattern of X-ray diffraction for a Cu₂O:SnS Nanophotonic film was carried out with Cu-K α radiation ($\lambda \approx 0.15418$ nm), and a scanning range (2θ) of 20° to 40° adopted

3. Results and Discussion

For the film grown on a glass substrate, as depicted in Fig. 4, one peak can be noticed by referring to the (020) plane at angles of $2\theta = 31.169^\circ$ as a preferred orientation as compared to values of the card (JCPDS Card No. 01-079-2193). After the annealing process, it is possible to observe three

main peaks at angles of $2\theta = 19.673^\circ$, 31.673° and 35.637° . So, the preferred orientation at $2\theta = 19.673^\circ$ where the polycrystalline structure of the thin films is displayed in Fig. 4.

The lowering in the peak intensity of Cu₂O:SnS exhibits similar behavior to that obtained by Devika et al (2006) [30]. Scherrer's formula Eq. (4) was utilized to determine the crystallite size of the Cu₂O:SnS thin films.

$$D = \frac{0.9 \lambda}{\beta \cos \theta} \quad (4)$$

where λ stands for the wavelength, β is the FWHM and θ represents Bragg angle. From Table 1, the average crystal size of Cu₂O:SnS films are decreased after the annealing process at 200°C from 16 nm to 12 nm. The observed reduction in crystallite size down to the nanoscale restricts the exciton Bohr radius, thereby inducing quantum confinement effects. The apparent reduction in crystallite size following thermal annealing at 200 °C cannot be attributed to crystal splitting. Instead, it is highly likely driven by severe thermal mismatch stress between the Cu₂O:SnS film and the glass substrate. This induces severe lattice microstrain and structural defects, which manifests as diffraction peak broadening in the XRD spectra, artificially reducing the calculated Scherrer crystallite size. When the temperature of annealing offers the least amount of thermal energy needed to move the particles or atoms, the particles undergo diffusive motion, which reduces their size.

Using the Williamson-Hall equations, the density of dislocation (δ) Eq. (5) and micro-strain (ε), Eq. (6) values of each sample were determined where they are inversely proportional to the variation in crystalline size.

$$\delta = \frac{1}{D^2} \quad (5)$$

$$\varepsilon = \frac{\beta \cos \theta}{4} \quad (6)$$

As indicated in Table 1, an increase in the dislocation density of Cu₂O:SnS nanostructure thin films may be ascribed to a rise in the grain boundaries as a result of a change in the crystallite size. This may have been caused by the annealing process, which included raising the temperature [29, 31].

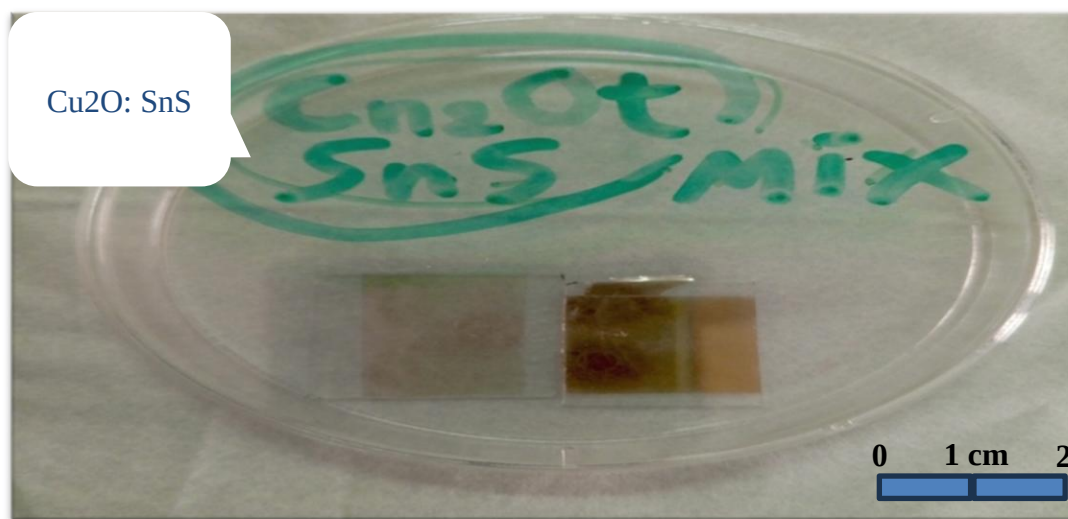


Fig. 3. Cuprous oxide Cu₂O: SnS nanophotonics glass thin film prepared

The measurement spectrum of optical transmission (T%) of Cu₂O: SnS Nanophotonic films in the 300-1100 nm range, the average of T% in the visible region for deposited films is roughly more than 80%, for annealed samples. It is clear that the process of annealing influences optical transmittance and shifts it toward shorter wavelengths (blue shift). Due to the effect of the quantum confinement brought on by the reduction in the size of nanoparticles and dimensional structure, a strong blue shift can be seen as displayed in Fig. 5.

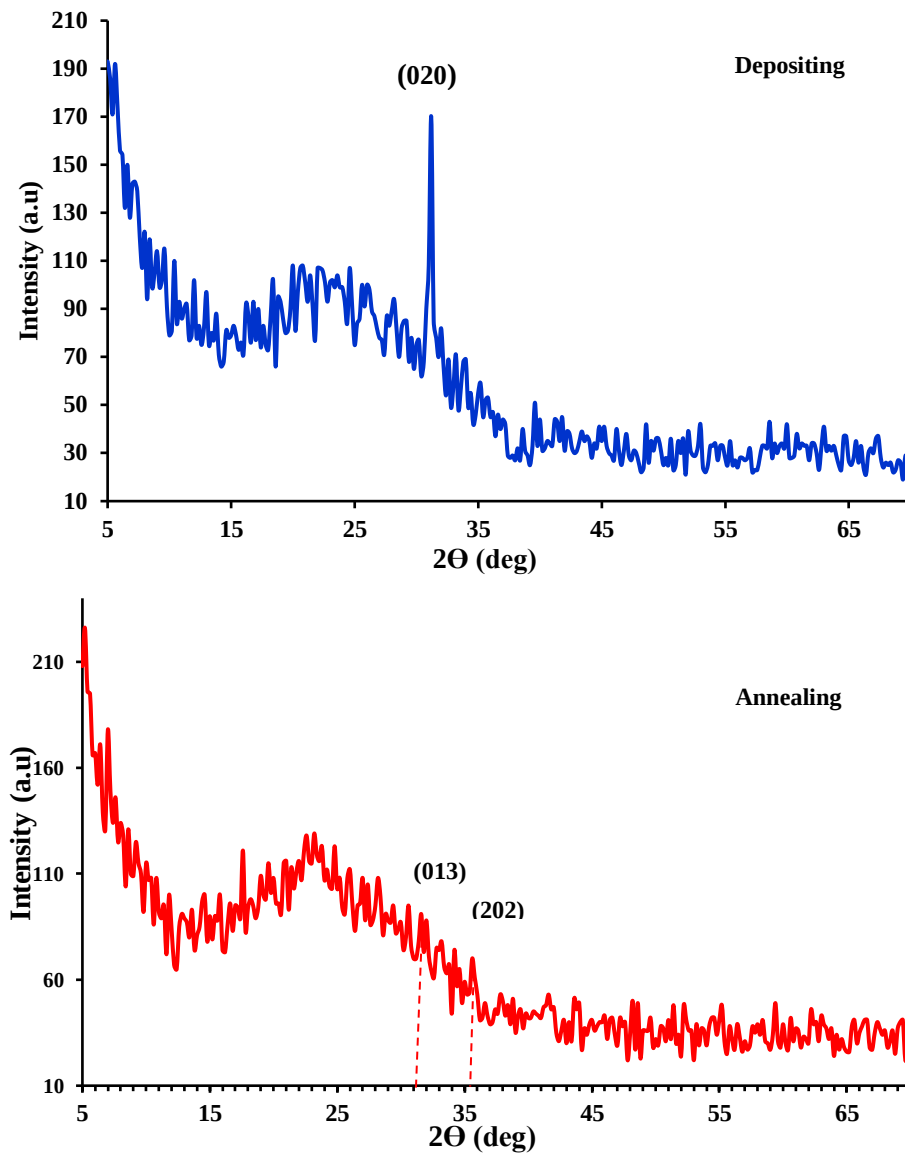


Fig. 4. The X-ray diffraction for a Cu₂O:SnS nanophotonic of thin films

Table 1. Obtained X-ray results of Cu₂O: SnS nanophotonics samples as growth and annealed

Samples	2θ °	FWHM	(hkl)	Average Crystal Size (nm)	$\delta=1/D^2$ (nm ⁻²)
Cu ₂ O NPs:SnS as deposited	31.169	0.514	(020)	16.05 ~16	0.003906
Cu ₂ O NPs:SnS annealed at 200° C	31.673	0.858	(013)	9.62~10	0.010000
	35.637	0.752	(202)	11.10 ~11	0.008264

Through using the system of nanophotonic thin films with solar cell and voltmeter, when an electric light was directed on the thin nanomaterial film after placing it on a silicon solar cell, it becomes evident from the voltmeter reading (output voltage increased from 0.00 to 2.34 V) that the efficiency of the solar cell is changed due to the influence of the nanomaterial used to manufacture the films. Fig. 6 shows output voltage increase of the solar cell due to the effect of nanophotonics thin films and light.

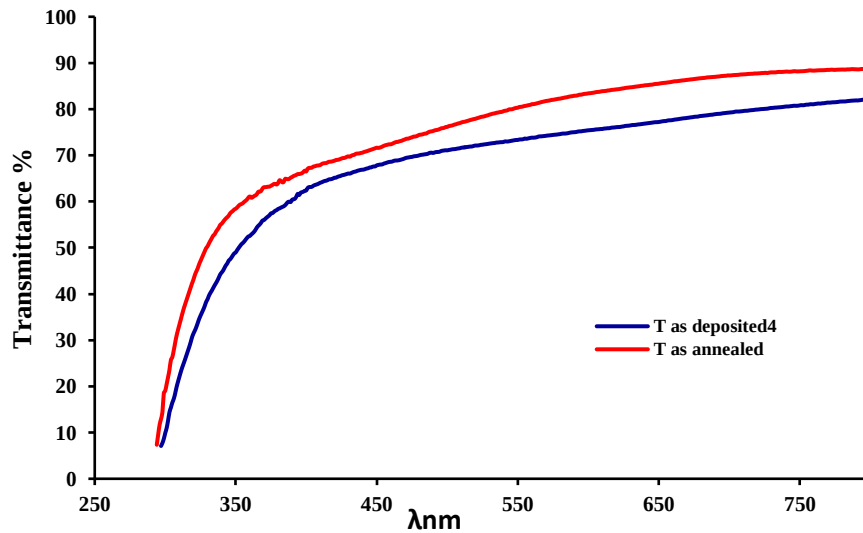


Fig. 5. Transmittance of Cu₂O NPs: SnS nanophotonics thin films before and after annealed at 200°C



Fig. 6. Output voltage increase of a solar cell due to the effect of nanophotonics thin films and light

4. Conclusions

In this paper it has been shown how Cu₂O: SnS nano photonic thin films can be fine-tuned and how they influence light matter interaction. When studying samples prepared through the study, it can be found that the heat treatment of the films at 200°C played a major role in determining the characteristics of the film used through quantum confinement. By using quantum confinement, it is clear to observe changes to the nanostructure of the thin film. Upon annealing it has been observed a shift from having one peak at $2\theta = 31.169^\circ$ (020) to three different peaks which shows that the sample used now has a polycrystalline structure and resulted average size decreased from 16 nm to 10 nm. The splitting that occurred at the grain boundary showed an increased value of dislocation density (δ) going from 0.003906 to 0.010000. It was also possible to observe changes to the optical properties of the thin films used, with a high average of optical transmittance (T%) greater than 80%. When annealed the optical transmittance was shifted towards lower wavelength. By implementing the prepared nanophotonic thin film into a silicon based solar cell system, it was clear to see an increase in voltage. This was shown when the voltmeter reading jumped from 0.0 volts to 2.34 volts under direct light.

According to these findings it can be concluded that there is a way to manipulate nanoparticles to convert more energy from sunlight. With high transparencies and quantum confinement there is great potential for Cu₂O: SnS nanophotonic thin films in the field of optoelectronics, communication and photovoltaic. As the results of this research illustrate the emerging integration between quantum dots and nanophotonics in the design of optical devices, practical applications of such research include optical communications, enhanced solar cells, and precise medical diagnostics using nanoparticles, along with promising potential in quantum computing and communications.

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