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# Synthesis and Characterization of Iron-Doped Tin(IV) Oxide Nanoparticles: A Systematic Review of Structural and Optical Properties

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**Abstract- Iron-doped tin(IV) oxide (Fe-doped $SnO_2$) nanoparticles have attracted considerable attention owing to their tunable optical, structural, magnetic, and electronic properties. This review synthesizes findings from recent studies investigating Fe-doped $SnO_2$ synthesized through sol–gel, hydrothermal, co-precipitation, combustion, and sputtering techniques. The literature demonstrates that Fe incorporation significantly influences crystallite size, oxygen-vacancy concentration, morphology, photoluminescence behavior, and band-gap energy. Most studies report retention of the rutile tetragonal phase with minimal impurity formation. The review highlights the relationship between synthesis conditions and material properties and discusses potential applications in photocatalysis, gas sensing, optoelectronic devices, and energy-storage systems.**

**Keywords- Fe-doped $SnO_2$; nanoparticles; nanotechnology; metal oxides; optical properties; semiconductor materials.**

## I. INTRODUCTION

Research in nanoscience is of great scientific interest due to the wide applications of nanoparticles in the fields of optics, medicine, electronics etc. Nanotechnology is the study of particles of sizes about 0.1 to 100nm, with absolutely different properties and functions as that of their bulk counterparts. The term 'nano' originated from the Greek word 'nanos', which means dwarf. The concept of nanotechnology was first introduced by Richard P Feynman in his lecture series giving the famous statement that "There is plenty of room in the bottom".

Nanomaterials are larger than single atoms but are smaller than bacteria and cells. One of the first known, synthesized nanoparticles was of gold in colloidal solution, which was used in ancient times for paintings on glasses, vases etc. Nanoparticles can be of two types which are non- intentionally made nanoparticles (usually produced during a volcanic eruption, proteins, and viruses.) and intentionally fabricated nanomaterials, which are created in labs by different processes. Gold in nano size appears red in transmitted light and green in reflected light and is found to be useful as sensory probes, therapeutic agents, medical applications and in beauty creams. Such findings led scientists to study Nanotechnology has emerged as a transformative field of science and engineering involving materials with dimensions typically between 1 and 100 nanometers. Metal-oxide nanoparticles constitute an important class of nanomaterials because of their unique physical and chemical properties. Tin(IV) oxide ($SnO_2$) is a wide-band-gap semiconductor widely employed in gas sensors, solar cells, transparent conducting electrodes, and catalytic systems. Doping $SnO_2$ with transition metals such as iron enables tailoring of its optical and electronic properties, making it suitable for advanced technological applications.

## II. LITERATURE REVIEW

Recent investigations reveal that Fe doping affects crystallite size, magnetic ordering, optical absorption, and defect formation in $SnO_2$ nanoparticles. Sol–gel synthesized samples generally retain the rutile phase while exhibiting enhanced oxygen-vacancy

concentrations. Hydrothermal and combustion methods produce nanoparticles with high crystallinity and controllable particle size. Several studies report a reduction in band-gap energy with increasing Fe concentration, whereas others observe slight increases depending on synthesis conditions. Photoluminescence analyses consistently indicate that oxygen vacancies play a critical role in determining optical behavior.

## III. METHOD OF REVIEW

This article is based on a qualitative review of published studies referenced in the source document. The selected studies focus on Fe-doped $SnO_2$ nanoparticles synthesized using different preparation routes and characterized through X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), Raman spectroscopy, photoluminescence spectroscopy, and UV–Visible spectroscopy.

## IV. RESULTS AND DISCUSSION

The reviewed literature demonstrates that Fe ions can be successfully incorporated into the $SnO_2$ lattice without significantly altering the rutile crystal structure. Structural characterization confirms particle sizes ranging from approximately 5 to 30 nm. Doping influences oxygen-vacancy formation, which subsequently affects photoluminescence intensity and optical band-gap values. Many studies report enhanced magnetic behavior and improved photocatalytic or sensing performance following Fe incorporation. Variations among reported results are primarily attributable to synthesis conditions, dopant concentration, and post-synthesis treatment procedures.

## V. APPLICATION OF NANO TECHNOLOGY

- MEDICINE: Customized nanoparticles, the size of the molecules, can deliver drugs directly to diseased cells in our body. It is a method that reduces damage treatment such as chemotherapy.
- ELECTRONICS: Use of nanotechnology can help increase capabilities of electronics devices while reducing their weight and power amplifications.
- FOOD: Nanotechnology can impact many aspects of food science, from how food is grown to how it is packaged. Companies are developing nanomaterials that will make a difference not only in the taste of food, but also in food safety, and in health benefits that food can bring forth.
- FUEL CELLS: Reduction in the cost of catalysts used in the fuel cells to produce specific ions and to improve the efficiency of its working is also achieved with the use of nanotechnology know-how.
- SOLAR CELLS: Today companies develop solar cells at a significantly lower cost than conventional solar cells.
- SPACE TECHNOLOGY: Use of nanomaterials to make lightweight spacecraft is a norm these days. This allows for reduced requirement of rocket fuel, leading to lower cost of space programmes.

## VI. NANOPARTICLES

Generally, nanoparticles are just several atoms or molecules bonded together. Nanoparticle clusters are at times indistinguishable from molecules. Nanoparticles can be obtained either by assembling individual atoms or by dividing bulk materials. The fabrication of a nanoparticle is as important as selecting the component material since the properties of a nanoparticle are highly size dependent. For a bulk material, most of the properties can be derived from the electronic properties of the constituent material. This is averaged over size, losing its dependency on size of the material at large scale. The surface to volume ratio is much larger for a nanoparticle in comparison with that of its bulk and this factor plays a significant role in defining its properties due to the changes in the electronic structure of a system. This is because on reducing the dimension scale the wave like properties of the electrons

become significant, resulting in quantum mechanical effects playing an important role. As the size of the particle approaches the de 'Broglie wavelength, the discreteness of the energy levels increases. This can ensue in change in the bandgap thereby changing the properties of the samples.

**Dimensionality of Nano structures**

The materials' dimensionality sets the structure of it. The word 'Nano' means one in a billion. Based on the dimension of the particles, materials are classified as Zero-, One-, Two- and Three-dimensional nanostructures as shown in figure 1.

**Zero Dimensional Nanostructures ( 0D)**

Materials in which all three dimensions are of the Nano scale are called zero-dimensional nanostructures. Nanoparticles can be zero-dimensional nanostructures. An example of 0-D nanostructures is quantum dots.

**One Dimensional Nanostructures (1D)**

These structures are those which have one of their dimensions larger than the nano size. Nanowires, nanotubes and nanorods are 1-D nanostructures.

**Two Dimensional Nanostructures (2D)**

These are structures where two of the dimensions are not confined to the nanoscale. These are nanolayers, nanofilms and nano coatings which can be single or multilayers. They are termed as quantum wells.

**Three Dimensional Nanostructures (3D)**

When no dimension of the material is confined to the nanoscale, the material is a 3-D nanostructure. But these materials possess nanocrystalline structure and are of nanoscale features. They can be bundles of nanowires, multianalytes etc.

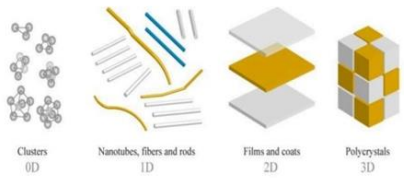


**Figure 1**

**Different types of nanoparticles**

(https://images.app.goo.gl/MHqG1Cp22b15i68W6)

**Oxide Materials**

**Metal Oxides**

Oxides are stable materials under atmospheric conditions with a range of crystal structures also possible on altering the physical and chemical environments they exist in. Oxides also exist in various states of matter and can still be very stable.

Metal – oxygen (M-O) bonds are strong; Hence such materials are used for various applications under atmospheric conditions. ZnO, $TiO_2$ , $CeO_2$ , $SnO_2$ are just some of the metal oxide materials explored for various properties as their band gaps can easily be manipulated with addition of dopants or change in the sample preparation conditions. One such interesting material that has been studied for its various properties is $SnO_2$

**Tin (IV)Oxide**

**Figure 2 Tin Oxide** https://en.wikipedia.org/wiki/Tin(IV)_oxide

Tin oxide (stannic oxide), with chemical formula $SnO_2$ , is obtained from its ore cassiterite. A diamagnetic insulator at room temperature with a band gap of 3.6 eV, $SnO_2$ has different stable structures with a change in the

temperatures it exists in. SnO2 has various applications as gas sensors, electrodes for electric glass melting furnaces, solar cell applications etc. With a change in the dopant type the properties of this material can be altered for desired ones.

**Structure**

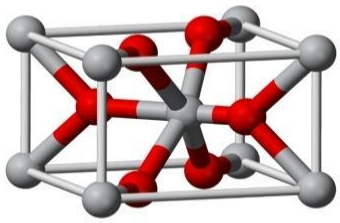

**Figure 3 Structure of Tin Oxide**

Tin(IV) oxide crystallises in the brookite, anatase or rutile structure. The rutile structural phase (shown in the fig 3) forms at higher temperatures of sample preparation. In this phase the tin atoms are arranged with a coordination number six and the oxygen atoms with a coordination number of three. In its stable state, SnO2 is observed as an oxygen-deficient n-type semiconductor. SnO2 is insoluble in water. It is amphoteric, with its ability to dissolve in concentrated basic or acidic solutions easily. SnO2 has uses in various applications in pigmented ceramic glasses, for polishing different kinds of materials, gas sensors, solar cells etc.

## VII. REVIEW AND FINDINGS

The most recent studies on the structural and optical properties of Fe doped SnO2 are presented. The effect of the dopant and the changes brought about due to the sample synthesis procedure selected are explored. A conclusion to this effect will be sought following the review of these papers. Single phase rutile structured Cr and Fe doped SnO2 prepared by the sol-gel method was studied for their magnetic and emission properties by Duhan et al [1]. The crystallite size was found to decrease slightly from 15 nm for pure SnO2 to 8 nm for the doped samples from the X-ray diffraction (XRD) analysis. The transmission electron microscopic (TEM) results corroborated that the particle sizes were in the range of 5 – 10 nm, while the scanning electron microscopic (SEM) studies showed agglomeration of grains with dopant addition. While the pure SnO2 samples were diamagnetic, the doped samples were found to exhibit room temperature ferromagnetism (FM) owing to the presence of oxygen vacancies. Photoluminescence (PL) peak at ~425 nm with a change in the peak confirmed the presence of oxygen vacancies in the samples with the introduction of the dopant. Sambasivam and Obaidat present the structural and magnetic properties studies on the sol-gel prepared Sn1-xFexO2 (x = 0.0, 0.1, 0.2, 0.3) [2].

The XRD patterns showed that the crystallization of the samples occurred in the rutile structure with no impurity peaks visible. The particle sizes increased with an increase in the Fe content. The raman studies confirmed the structure of the samples observing the Eg , A1g , and B2g peaks and with characteristic active modes found at 320 and 690 cm-1 . The broadening of the Eg mode was attributed to oxygen vacancies and nanosize effects. The broad, low intensity electron spin resonance (ESR) spectra obtained at room temperature were attributed to the presence of Fe 3+ in all samples. The anisotropy in the non- spherical particles as well as the enhanced dipolar magnetic interactions with Fe 3+ concentrations were attributed for the shift in the ESR peak to lower fields and to the increase in the line width. The change in the line width also indicated the presence of FM in the samples with increasing Fe content.

Spherically shaped nanostructures of Fe, Cu and Zn doped SnO2 were prepared by Asaithambi and co-workers to study the influence of doping concentration on the structural, optical, functional and morphological properties of the samples [3]. The XRD studies showed the samples to be in the cassiterite rutile tetragonal structure with no impurity phase being formed

on doping with the transition metal ion. The average crystallite sizes were in the range of 20 – 30 nm. The presence of the Sn, O, Fe, Cu and Zn ions was confirmed from the electron dispersive x-ray spectroscopic results. The UV-Visible spectroscopic results showed a decrease in the band gap with the introduction of the transition metal (TM) ion due to the to the formation of delocalized energy states/mid energy levels within the energy band gap as oxygen vacancies and metal interstitials were produced and sp-d hybridization interaction between the band electrons.

The PL spectra revealed emission peaks pertaining to pure and TM-doped SnO2 nanoparticles. The peaks observed were at 360 nm and 378 nm (UV emission region), at 411 nm and 438 nm (due to structural defects and electron recombination with shallow level defects) and at 520nm (due to singly ionized oxygen vacancies). The increase in the PL intensity of the doped samples was attributed to the formation of oxygen vacancy, defects and electron transition from TM ions to SnO2 host lattice.

The presence of oxygen vacancies enhanced the intrinsic electron conductivity of the samples thereby increasing the energy storage capacity of the samples. From the electrochemical performance of the samples it was seen that the Fe doped SnO2 electrode had a favorable specific capacitance of 270 F/g at a current density of 0.5 A/g. The sample also had good cycling stability of 98% retention over 2000 charging discharging cycles. Sujatha et al used the co-precipitation method with water as the solvent to synthesize pure, Fe-doped and surfactant-assisted (CTAB, SDS and Triton) Fe-doped SnO2 nanoparticles [4]. All the samples were of the rutile structure, with the XRD peaks shifting position with the addition of Fe. A decrease in the crystallite sizes of Fe-doped and surfactant-assisted Fedoped SnO2 samples were found. The SEM and High resolution TEM studies revealed spherical morphology of the grains. The band gap energies were 3.487, 3.741, 3.845, 3.783 and 3.552 eV for pure, Fe-doped, cetyltrimethylammonium bromide, sodium dodecyl sulphate and Triton (surfactants) assisted Fe-doped NPs, respectively. An increase in the band gap was attributed to the addition of the Fe ion in the SnO2 sample. The samples were studied for their photocatalytic activity and confirmed that the pure SnO2 samples significantly photo-degraded methylene blue dye under sunlight when compared with the activity of the Fe doped samples. A report by Kumar et al reports the electronic, structural and optical behavior of Sn1-xFexO2 nanoparticles synthesized using co-precipitation assisted hydrothermal method [5].

The structural properties depicted proper phase formation of all the samples, with crystallization occurring in the tetragonal rutile phase. With increase in the dopant content the crystallinity kept decreasing. The average crystallite sizes varied in between 7 and 10nm. The expansion and contraction of the lattice constants are ascribed to the dopant added into the lattice giving rise to oxygen vacancies. The near edge x-ray absorption fine structure spectroscopy (NEXAFS) studies establish that Fe ions are situated at the Sn sites with dominant Fe content in the 3+ state and a minor Fe 2+ content present. The UV-Vis spectral studies indicate good transparency of the samples to visible light while ultraviolet radiations were absorbed. The band gap varies asymmetrically between the values of 3.1 and 3.6 eV. The authors assign this to the casual distribution of Fe ions inside the host SnO2 crystal texture.

Fe-doped SnO2 quantum dots (QDs) synthesized by solution combustion synthesis was studied for their various properties by Rao and coworkers [6]. All these tetragonal structured samples possessed a particle size of below 5nm, with a slight decrease in the particle size being observed with increase in the Fe content. The HRTEM and corresponding selected area electron diffraction (SAED) results confirmed the findings from the XRD studies, while the x-ray photoelectron spectroscopic studies affirmed the existence of SN in the 4+ state and Fe in the 3+ state. Tuning of the energy bandgap (decrease of it with increase in

Fe) facilitates increased absorption of SnO2 with increase in Fe doping. The XPS study clearly confirms the existence of Fe in 3+ state. With respect to the pure SnO2 samples the quantum dots exhibited three additional characteristic bands in the visible range. The ESR studies indicated that the Fe species occupied the distorted octahedral sites in SnO2 quantum dots. These properties of the samples make them potential candidates for optoelectronic devices and photocatalysis.

Rutile structured, sol-gel synthesized Sn1 – xFexO2 , (x = 0.05, 0.10) nanoparticles exhibited compressive strain in the lattice indicating the influence of grain boundary formation in the lattice [7]. The features in the PL spectrum highlight radiative recombination and quenching and a shift in the optical band gap estimated from UV-visible spectrum confirm the influence of the grain boundaries. Studies on the Raman spectrum and the morphological studies performed using the Field Emission SEM (FESEM) too point to the formation of grain boundaries. The impedance of the samples increases with an increase in the doping concentration while a decrease in the loss factor at high frequencies is also noted. Guillen-Baca et al present their studies on undoped and Fe-doped SnO2 dc sputtered polycrystalline films grown on glass substrates [8]. The as prepared samples were amorphous in nature while annealing the films rendered them crystalline. The Fe-doped films showed a (101) preferred orientation, a preference enhanced with film thickness. The SEM studies revealed the columnar structure of the films deposited. The UV-Vis spectrum showed a monotonous decrease in the band gap of the films with an increase in the film thickness. This result is evaluated on the basis of the change of the residual strain. The results are also in good agreement with the XRD results.

Using the density functional theory Gao et al studied the electronic structure and magneto-optical properties of Fe-doped SnO2 doped with different concentrations of Fe and oxygen [9]. Here the geometry optimization and energy calculation in accordance with the first-principle generalized gradient approximation + U(GGA+U) method was used. The effects of changes in Fe2+/3+ and oxygen vacancy concentration on the electronic structure, energy, magnetic exchange mode, and optical absorption properties of SnO2 materials were explored. A difference in the Fe 2+ /Fe 3+ concentrations and the oxygen vacancies vary the magnetic moment and the stability of the system. Systems with dopants giving the same magnetic moment were studied further and it was found that Sn22[Fe 3+ ]2O46 system had the best stability and magnetic properties. That SnO2 may be a good photocatalytic material may also be due to the increased static dielectric constant and the red shift of the absorption band edge.

Fe-doped tin dioxide (for 0 – 20% of doping) was prepared using the hydrothermal method and detailed structural studies on these samples is reported by Othmen et al.[10]. The XRD studies confirmed the rutile structure of the samples even for the highest concentration of Fe dopant used. With an increase in the Fe content the grain sizes decreased, leading to a red shift in the band gap. The HRTEM images revealed good crystallinity of the samples. The Raman modes observed confirm the findings obtained from the XRD and HRTEM studies. The morphological transformations with Fe dopants addition is reflected in the Raman A1g mode. This is because an induced local symmetry breaking occurs with Fe addition. From the Raman studies it was also found that forbidden Raman phonon modes were active and the (110) surface oxygen bridging enhanced with Fe addition. This oxygen bridging plays a major role in enhancing the adsorption of hydroxyl groups on the Fe-doped SnO2 surface. The oxidation states of the oxygen vacancies are also affected with addition of Fe, as revealed from the PL studies. The UV-visible band absorption gets affected by the addition of Fe in the sample. The bandgap continuously decreases with the introduction of Fe. These studies indicate that Fe doping into the samples affects the density of singly charged oxygen vacancies.These results point to the possibility

of using Fe doped SnO2 for ethanol and humidity gas sensing.

## VIII. IMPLICATIONS FOR FUTURE RESEARCH

Future investigations should focus on optimizing Fe concentration, controlling oxygen-vacancy distribution, and developing scalable synthesis approaches. Comparative studies integrating experimental and computational methods could further clarify the relationship between defect chemistry and functional performance. Long-term stability and commercial applicability of Fe-doped $SnO_2$ systems also require additional evaluation

## IX. CONCLUSION

The reviewed evidence confirms that Fe-doped $SnO_2$ nanoparticles are promising multifunctional materials with tunable structural and optical properties. Iron incorporation modifies particle size, oxygen-vacancy concentration, magnetic characteristics, and band-gap energy while preserving the desirable rutile phase. These characteristics support their potential use in sensing, photocatalysis, energy storage, and optoelectronic technologies.

The study has been undertaken to look into some of the most recent studies on the structural and optical properties of Fe doped SnO2 . This sample has been chosen as introduction of a magnetic ion into a semiconducting matrix is a typical formula used for dilute magnetic semiconducting materials, which also have prospects for various applications. It is seen that single-phase Fe doped SnO2 nanoparticles can be synthesized by a variety of sample synthesis procedures. All the reviewed work shows proof that the samples crystallize in the rutile structure with no evidence of any impurities in the samples. This can be advantageous as it gives more options for the sample preparation. Other studies like photoluminescence, infra-red spectroscopic studies, HRTEM and SEM studies confirm the results obtained by the XRD studies. The morphological studies also highlight the possibility of obtaining homogenous spread in the sample grain sizes.

The optical properties reported depict how the introduction of Fe in the samples lead to the presence of oxygen vacancies in the samples. This in turn plays a role in defining the energy band gap. It can be confirmed that manipulating the sample preparation conditions the behaviour of the oxygen vacancies and the spread of it in the samples can be controlled to a certain extent to obtain desired properties.

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