Applied Innovative Research
Vol. 1, September-December 2019, pp. 184-193

A comprehensive review: SnO_2 for photovoltaic and gas sensor applications

Priyanka Gupta*& Vandana Rathore
School of Engineering and Technology, Jagran Lakecity University, Bhopal 462 044, India

Received 9 October 2019; Accepted 10 December 2020

Tin oxide is remarkable material in today's research era due to its unique properties in electrical and optical fields. Due to its wide band gap (3.6 eV), it has been used as a core material in many important applications in the field of optoelectronics, spintronics, photovoltaic, thin-film transistors, photocatalysis, dielectrics, sensors and transparent electronic devices. Thin film technology provides many advantages towards photovoltaic area which includes low cost, less material and energy consumption and easy to access. Fabrication of photovoltaic cells by SnO_2 thin films can open the different technological routes for future generation with excellent conversion efficiencies which may range 15% to 20%. It is one of the best candidates for gas sensor applications too with highest sensitivity and selectivity behavior, good oxidizing power, strong chemical bonding, non toxicity and unique transport properties. Tin oxide thin films with various combinations of materials can be synthesized by chemical and physical routes. The detailed advancement in various preparation methods and characterization techniques including X-ray diffraction, atomic force microscopy and X-ray photoelectron spectroscopy have been presented and discussed by authors. Characteristics measurement by Valence Band Structure, Photoluminence Intensity and Scanning Electron Microscope has been also reported with their performance, effect of solar energy conversion efficiency and quick response time in case of gas sensors. Prospective areas of SnO_2 research for photovoltaic and gas sensor applications has been discussed and summarized by the authors. The obtained results will illustrate the possibilities of scheming Physical, chemical, magnetic and optical properties of SnO_2 for sensing devices and photovoltaic applications.

Keywords: Tin oxide, Photovoltaic, Thin film, Gas sensors

1 Introduction

Material science is the systematic study of any material to find out its various characteristic and properties. It includes range of applications from manufacturing nanotechnology devices to constructing new materials at atomic level. In recent scenario we are facing many issues related to conventional sources of energy, global warming, contamination of soil and water, climate change, sanitations etc. Our centre of concern is to reduce these problems by introducing new technologies using advance materials. Nanotechnology and thin films are playing an important role to deal with such type of problems. With the help of this, performance of existing materials can be improved and new functional materials can be developed as discussed by[1], different types of materials are being used these days which have the potential to prevent and remove pollutants from environment, act as cleaner for industrial waste, advance sensing, photo-catalytic and photovoltaic properties. They can be also use as good chemical reactors in water splitting, organic material in pigments, to improve antimicrobial effect[2] and photocatalytic degradation. Metallic nanomaterials have fascinated researchers due to its potential applications in the field of biomedical sciences and engineering. Metal cation and oxide anion forms metal oxide. A strong covalent bond is visible in those metals which have high oxidation states. Transition metal (TM**)** oxides play an important role in catalytic activity and semiconductor properties. It has an extra ordinary potential as base materials in rising new technologies like optoelectronics, spintronics, photovoltaics, thin-film transistors, Photocatalysis, dielectrics, sensors and other transparent electronic devices[3-7]. TM oxides are the most useful multifunctional materials which have unique surface properties, high transmittance in the ultraviolet-visible region and semi-conductivity[8]. Presently most of research work is based on these metals to enhance their applications in different field because it not only provides good scopes to study the optical, electrical and thermal properties in quantum-confinement, but also offers important insights for understanding the functional units in fabricating electronic, optoelectronic, and magnetic devices of nano scale

---

*Corresponding author: (E-mail: priyanka.gupta@jlu.edu.in)

dimensions[9]. Wide band gap and remarkable transport properties makes metal oxides as an emerging material nowadays. The most investigated metal oxides are ZnO, TiO_2 and SnO_2 due to its exclusive worldwide useful applications. Tin oxide is the most usable candidate for photovoltaic studies due to earth-abundant, inexpensive and non-toxicity. Centre of investigation of this research work is to explore more about functionality of SnO_2 and to find out possible areas of research work for future applications in photovoltaics and gas sensors.

2 Overview of Tin Oxide and its Properties

From the past few decades Semiconducting (Metal) oxides such as ZnO, TiO_2 and SnO_2[10] have been proved to be an important class of transparent conducting oxides (TCO) for applications in solar cells and gas sensors. Due to their low electrical resistivity and high transmittance in the visible range, Tin Oxide is the most familiar material for optoelectronic applications[11]. The wide band gap (3.6 eV) and high excition binding energy (130 MeV) makes Tin Oxide a suitable candidates for these applications. It is the only oxide of group IV which displays good conductivity and transparent in visible range[12-14] (300 nm- 800 nm). Bulk SnO_2 cannot attain efficient ultraviolet (UV) emission due to the dipole-forbidden rule. Where as pure SnO_2 generally exhibit strong n-type conduction and the lack of p-type conduction. To understand the optical activity and UV emission of this material, some researchers preferred to use doping methods to modify its rutile tetragonal type structure and electronic structure. Figure 1 shows the tetragonal structure of pure and TM doped SnO_2 thin films[15]. The authors have prepared pure SnO_2 and Mn (5%) doped SnO_2 thin films by Pulsed Laser Deposition (KrF excimer) Si substrate (001). Pellets have been prepared under 160 KN pressure with the help of solid state reaction technique. Laser energy density was kept at 2 J/cm^2 and the pulse repetition rate was kept 10 Hz for both the samples. Structural morphology of material is clearly visible by AFM measurements as shown in Fig.1.

3 Methodology

There are numerous deposition techniques used to grow SnO_2 films either doped or undoped including chemical vapor deposition, spray pyrolysis, thermal evaporation, sol-gel, and sputtering. Recently, pulsed-laser deposition (PLD) has been used to grow various high-quality thin films for photovoltaic and gas sensor applications[16-17].

3.1 Chemical deposition technique

3.1.1 Chemical vapor deposition (CVD)

CVD is a chemical procedure of Vacuum deposition method in which the gaseous precursors is moved into a chamber with the substrate. Through the chemical reaction between the precursor and the substrate, the thin film of required thickness can be obtained at high temperature. This is a popular process in semiconductor industry to fabricate high quality and high performance semiconductors[18]. There are many CVD methods to fabricate thin films including thermal chemical vapor deposition, APCVD (Atmospheric-pressure CVD), MOCVD (Metalorganic chemical vapor deposition), PECVD (Plasma-enhanced chemical deposition), LCVD (Laser Assisted Vapor Deposition), and PACVD (Photo-assisted chemical vapor deposition).

3.1.2 Atomic layer deposition (ALD)

Atomic layer deposition method it is also a vapor phase deposition method. In this method the reaction between gaseous precursors and substrate happens consecutively one at a time. For this reaction two or more gaseous precursors are used to obtained thin film of desired thickness. ALD is a stepwise procedure, precursors react only with the available substrate and no more reaction occurs after the surface is saturated .Therefore it is slower process but has the advantage of precise thickness control of film even on lower temperature[19-20].

3.1.3 Sol-gel method

Sol-Gel is a chemical solution deposition method in which precursor material form a solution called ‘sol’. This ‘sol’ has been deposited on the substrate

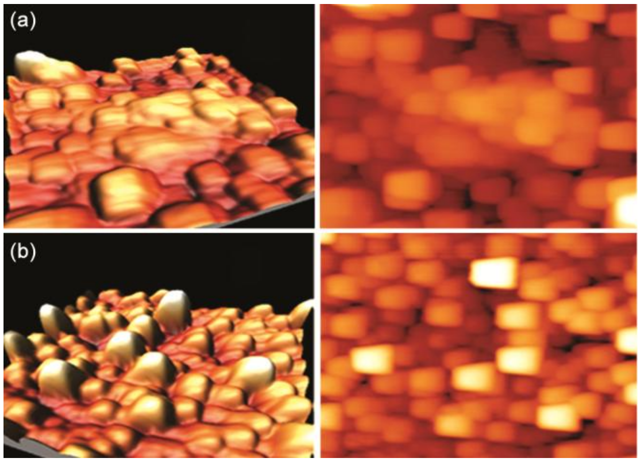

Fig. 1 – 3D AFM images of (a) pure SnO_2 and (b) doped $Sn_{0.095}Mn_{0.005}O_2$ thin films.

through highly controlled process. Sol-Gel method involves gelation process, where the precursor material transfers from a liquid ‘sol’ to solid ‘gel’ form[20]. This solution is known as a sol-gel which is a constant combination of suspended precursor particles and substrate. Spin coating, dipping and spraying these methods comes under the Sol-gel method. A brief description of different methods to synthesis a thin film for its useful applications is shown in tabular form in Table 1.

3.2 Physical deposition technique

3.2.1 Molecular beam epitaxy (MBE)

MBE has the advantages of both chemical and physical methods for thin film fabrication. In MBE the films are deposited on single-crystal substrates by slowly evaporating the material onto substrates held at a temperature appropriate for epitaxy, chemical reaction, and re-evaporation of excess reactants. In this method, the deposition of target material is completed in the form of layers but one layer at a single time. Layer by layer growth finely controlled by high speed shutters and can be monitor desired thickness of thin film[21-22].

3.2 .2 Sputtering

Sputtering is a physical thin film deposition method in which surface atoms are released by bombarding of ions on surface of a target material and then it come to rest on the substrate. In this deposition method Nobel gas Argon is taken as a target material at low temperature. Normally Nobel gas is less reactive so it behaves neutral for any chemical reaction in the chamber, because of this it is a fast and an authentic method. Sputtering is clearly an etching procedure, so it is useful for surface cleaning application[22]. We classified process of sputtering in the following terms: Diode Sputtering, Reactive Sputtering, Bias Sputtering and Ion-Beam Sputtering. Diode Sputtering: In Diode sputtering material is to be deposited (cathode) on the target substrate (electrode) in a glow discharge vacuum chamber. Usually thin films pure metals can be deposited in the presence of noble gas (Ar) with metal targets. Radio Frequency (RF) Sputtering: This is suitable for the dielectric (electrically non-conducting) material and insulating targets. If the frequencies are less than about 50 kHz then electron (cathode) and ions (anode) can be move easily in plasma. In the case of frequencies above about 50 kHz then ions can be unable to move in plasma. Generally a frequency of 13.56 MHz is used which is radiate a certain amount of energy without interfering with communications[23]. Magnetron Sputtering: In the magnetron sputtering process the magnetic fields converts into the electric fields. Strong magnets are use to confine the glow discharge. Sputtering with a transverse magnetic field generates several important alterations of the basic processes. Ion-Beam Sputtering: Sputtering of Ion beams generates in and extracted from glow discharges from the surface. This is very useful method for deposition of special materials on desired small substrate area.

3.2.3 Thermal evaporation

In thermal evaporation, the material is heated in a vacuum chamber until its surface atoms have sufficient energy to leave the surface. The evaporated material then condensed on the substrate for synthesis of thin film of desired thickness.

3.2.4 Spray pyrolysis deposition

In Spray pyrolysis the deposition of thin film can be occurred by spraying a solution onto a heated surface. Spray pyrolysis consists of the chemical dissociation or evaporation of droplets containing a solute of the desired nanomaterials[24]. Hence it has been follow by both gas-phase and liquid-phase methods. Spray pyrolysis method is based on forming an aerosol from various precursor solutions, which could be a solution of metallic salts or a colloidal solution[25]. It is a Non-reversible process which provides high efficiency.

3.2.5 Laser evaporation

The laser evaporation technique is used as the thermal source to vaporize or removing materials

Table 1 – A glance of various preparation methods of thin film deposition of SnO_2 material.

Thin Films Deposition Techniques

Chemical Process (Nonequillibirium reaction)	⇩		Physical Process (Equillibirium reaction)	⇩
Plating	Sol Gel	CVD	Evaporation	Sputtring
Electroplating	Dipping	MOCVD	Ion Plating	RF
Electrolusis	Spraying	PECVD	MBE	DC
Flame Hydrolysis deposition (FHD)	Spin Coating	ALD	Laser ablation & Electron Beam	Magnetron

from a solid surface, and preparation of thin film. The laser evaporation is high vacuum technique, where the source of powder is kept outside the vacuum system. Usually, laser ablation refers to removing material with a pulsed laser, but it is possible to ablate material with a continuous wave laser beam if the laser intensity is high enough[26].

3.2.6 Pulsed laser deposition (PLD)

Pulsed laser deposition uses energy from a laser source to excite the target surface. The electronic excitation, heating and physical ablation of the surface atoms and molecules occurs due to high energy. The molecules which are ablated from the surface form a plasma plume which is directed to the substrate where deposition process takes place. The change in chemical and physical parameters which take place at target and substrate depends on the type of target material, energy of laser light, intensity, and distance between the target substrate[21].

4 Tin Oxide as Photovoltaic Cell

The working of PV materials for photovoltaic application is based on the photo-electric effect. In this effect the exposed PV material converts electromagnetic energy (Sunlight) to Electric energy. Photovoltaic cell is the most demanding renewable sources of energy[27]. It has lots of advantages compared to other forms of energy like fossils fuels and petroleum. It is a promising and sustainable energy source for the high energy demand without any harm in our atmosphere. Ke *et al.*[28] have discussed about SnO_2 ETLs in perovskite solar cell. They used the unique properties of SnO_2 like wide band gap, high electron mobility and good antireflection to get excellent PCE of 16.02%. SnO_2 ETLs Synthesized by spin coating of $SnCl_2.2H_2O$ precursor prepared at a room temperature and followed by thermal annealing in air at 180 ^oC for 1 h. They summarized in their study that low-temperature solution-processed SnO_2 is an excellent ETL material for high performance perovskite solar cells. Bouras *et al.*[29] reported on the structural, optical and electrical properties of Nd-doped SnO_2 thin films deposited by the RF magnetron sputtering at different temperatures. Through XRD and XPS analysis they showed the crystallinity and phase composition of the films. The polycrystalline rutile structure of the films is improving with increasing the growth temperature and the layers exhibit a SnO_2 structure. PL measurements showed that the films exhibit very strong and well defined emission peaks characteristics of Nd atoms whose the XPS 3d core level revealed the 3þ ionic state. PLE spectroscopy revealed an efficient resonant energy transfer from the SnO_2 host matrix to the Nd$_{3\text{þ}}$ ions as well as direct excitation lines allowing us identification of some energy levels of Nd$_{3\text{þ}}$ ions. The down-shifting functionality was concluded. The electrical properties of the films performed by the Hall Effect measurement showed the n-type character of the films and improvement of the carrier concentration, resistivity and mobility with deposition temperatures upto300°C. The optimum condition enabling the best electrical conductivity and the highest PL intensity was found for deposition at 300 °C. The application of this Nd–SnO_2 optimized layer to CIGS solar cells showed the highest short circuit current density, and overall the best cell efficiency, which can be attributed to good TCO properties and photon conversion process provided by the Nd-doped tin oxide films. Zhu *et al.*[30] successfully exploited the solution processed SnO_2 nanocrystals to develop as an efficient ETL in the inverted thin film Photovoltaic solar cell. They suggested that due to some novel properties SnO_2 is more compatible than ZnO and TiO_2. In this paper they first prepared highly crystalline SnO_2 NCs with hydrothermal method and then applied it as an ETL in PVSCs. Due to their high crystallinity it forms a thick layer and preserve the device from O_2 and Water. So it improves the stability of device with the high PCE 18.8%. Ikhmayies[31] presented a review of TCOs prepared for use in solar cells. Thin films of SnO_2, SnO_2:F, ZnO and ZnO:Al were prepared and characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM), current–voltage (I–V) characteristics and transmittance spectroscopy. Huang *et al.*[32] have compared the performance of individual SnO_2 Thin film and TiO_2 Thin film with the composite SnO_2-TiO_2 thin film. They resulted that composite layer of thin film is giving best Power Conversion Efficiency 14.80%, which is higher than PCEs of devices based on individual SnO_2 layer and sintered TiO_2 layer.

Dong *et al.*[33] reported in their paper study of compact SnO_2 ESL and compact TiO_2 ESL and their PCEs. Fabrication of thin films based on sol-gel method. They applied various characterizations on films like SEM, J-V Curves, PL, XRD, IPCE. Wang *et al.*[34] discussed that low temperature processed tin oxide (SnO_2) is an outstanding material for fabricating Perovskite solar cell. They performed experiment on SnO_2 ESLs to receive high device efficiency by PEALD process at below 100C temperature and get

100°C PCEs approximate 18%. They applied Spin coating and ALD method to prepare SnO_2 ESL thin film. Xiong *et al.*[35] investigated in this paper that the HTP SnO_2 with suitable Mg doping is the very good alternative ESL for Photovoltaic application. This process enhances the power conversion efficiency of solar cell approximately 14.60% and nearly 92.8% enhancement compared to that with undoped SnO_2. Roose *et al.*[36] have summarized in their paper about the UV instability of Perovskite solar cell using my TiO_2. They adopted the conclusion that this instability can be replaced by using m-SnO_2 thin film. In their experiments they achieved the high efficiency approximately 16.4%. Solar cell is fabricated by Ga doped SnO_2 film. Ren X *et al.*[37] concluded that Nb doped SnO_2 ETL enhance electron mobility, surface morphology, conductivity, electron extraction and also achieved a higher PCE of 17.57%. Sinha[38] has successfully fabricated ZnO-SnO_2 composite thin film by pulsed laser deposition (PLD) technique and find this technique very suitable for fabrication due to uniformity of film, Precise thickness of film, multi component target, smooth surface, etc. He applied various characterization on that composite film like GIXRD, XRD, SEM, XPS and resulted that it is very low cost and highly effective method for Solar cell to enhance its efficiency. As discussed by the Lee *et al.*[39] SnO_2-TiO_2 composite layer thin film is capable to produce efficiency near about 19.80%, same result is concluded by Song *et al.*[40] they claimed the highest PCE of 21.10%. The authors have been reported the approximate PCE upto 23% for perovskite solar cell with the spin coating method and sole gel methods for deposition of SnO_2 thin films and investigation of its properties by Comparing thermally annealed SnO_2 TF (T-SnO_2) and P-SnO_2 TF[41-42]. Abdullah N *et al.*[43] performed an experiment with Sno_2 thin film solar cell in t four consecutive sunny days and resulted the highest solar radiation is 18.9%. Yang *et al.*[44] has been chosen EDTA to modify the SnO_2 to improve its performance. It is apparent that the unmodified EDTA and SnO_2 samples are transparent, while EDTA-treated SnO_2 turned into milky white. They developed an effective E-SnO_2 ETL by spin coating with the increased PCE of 21.60% with negligible hysteresis, This is the highest reported value for planar-type PSCs so far. They also fabricated solar cell at low temperature processing for E-SnO_2 ETLs, with high PCE of 18.28%. S Dolai *et al.* [45] fabricated Glass/F: SnO_2/CdS/CuO/Ag structure heterojunction solar cell with power conversion efficiency in between 2.0% and 2.1%. The authors used direct current (d.c.) magnetron sputtering and thermal evaporation technique for fabrication of solar cell. Liu R *et al.*[46] reported a high power efficiency of 16.85%. They used AZO substrate for fabrication of solar cell with addition of rGO in SnO_2 material. A brief description of SnO_2 material (photovoltaic application) is summarized in below Table 2.

5 Tin Oxide as Gas Sensors

Nowadays Gas sensors is the most fascinating research area because it is useful in monitoring environment issues according to the need for physical, chemical and biological systems in Earth’s atmosphere. Researchers are working to enhance its durability, quick responsive, highly sensitive. Gas sensors playing an important role in the field of environment monitoring, medical applications, breath analysis for medical diagnoses, industrial applications, food processing, etc.[47]. Mainly the applications of gas sensors are to discriminate odor, to detect gas or to monitor changes in the particular gas in atmosphere. The selection of material is highly affected to performance of gas sensors. Metal oxide based gas sensors are the subject of research for last few decades because of its novel characteristic like band gap, electro conductivity, type of conductivity, oxygen diffusion etc. With strong oxidizing power, good chemical inertness, low cost, nontoxic, large surface area and unique optical property, nanostructured SnO_2 offer great potential for energy and environmental applications including gas sensing[48]. The analysis of many parameters of Tin oxides including different characterization is showing here in the below in Table 3.

Ryo Tanuma *et al.*[49] investigated that directly or indirectly CO_2 is affecting our daily life, so it is compulsory to have knowledge about concentration of CO_2 gas. To fulfill this purpose they developed CO_2 gas sensor having advantages of small size, low fabrication cost, better reliability, easy mass production etc. Ammonia (NH_3) is a very harmful gas, which directly affected human health. Fluctuation of Ammonia gas can cause different diseases in human body like irritation in eyes, skin and human respiratory system, lung disease, blindness, kidney failure etc. Therefore, Beniwal A *et al.*[47] investigated a SnO_2 sensor for low concentration ammonia detection at room temperature. They prepared SnO_2

Table 2 – A review of SnO_2 materials on preparation methods, characterization technique and photovoltaic application.

S.No.	Thin Film Material	Preparation Method	Characterization	Solar Cell	PCE	References
1.	LTP NCs SnO_2	Spin Coating $SnCl_2.H_2O$	SEM, TEM, SAED, XPS, AFM, XRD	Perovskite	16.02%	Ke W. et al (2015) [28]
2.	Nd Doped SnO_2 Thin Film	Magnetron Sputtering	XRD, XPS, RBS, Hall Effect, TEM, PL	CIGS Solar cell	10.4% at (100- 400^0C)	Bouras K. et al (2016) [29]
3.	SnO_2 Thin Film	Sol- gel	XRD, SEM, TEM , PL	Perovskite	18.80%	Zhu Z. et al (2016) [30]
4	SnO_2 and F doped SnO_2 Thin Film	Thermal evaporation & SP tech	XRD, SEM,I-V characteristics, TS	CDS & TCO Solar cell	High	Ikhmayies S. J.(2017) [31]
5	SnO_2 -TiO_2 composite layer	Spin Coating	XRD, AFM , XPS, SEM	Perovskite	14.80%	Huang X.et al (2017) [32]
6	SnO_2	Sol- gel	SEM, J-V Curves, PL, XRD,IPCE	Perovskite	12.18%	Dong Q. et.al (2015) [33]
7.	SnO_2	ALD	XRD, AFM , PL, SEM, TRPL	Perovskite	17.16%	Wang C.et al. (2016) [34]
8.	Mg doped SnO_2	Spin Coating	XRD, SEM, XPS, UPS, Hall effect, IS	Perovskite	14.60%	Xiong L.et al (2016) [35]
9.	Ga doped SnO_2	Sol- gel	XRD, XPS,SEM,	Perovskite	16.40%	Roose B. et al (2017) [36]
10.	Nb Doped SnO_2 Thin film	Spin Coating	XRD,AFM, XPS, SEM, PL	Perovskite	17.57%	Ren X. et al (2017) [37]
11.	ZnO-SnO_2 thin film	PLD	GIXRD, XRD, AFM, FESEM, XPS	Solar cell	High	Sinha S.K. (2016) [38]
12.	TiO_2-SnO_2 Composite	Spin Coating	XRD, J-V curve, TEM, SEM,PL	Perovskite	19.80%	Lee Y. et al (2017) [39]
13.	TiO_2-SnO_2 Composite thin film	Spin coating	XRD, HR-SEM, HR-TEM, UPS, SCLC, IPCE	Perovskite	21.10%	Song S. et al (2017) [40]
14.	Ta doped SnO_2 thin film	Spin coating	XRD, AFM, SEM, XPS, UVS, SE,	Perovskite	-	Ganchev M et al (2019) [41]
15.	SnO_2 thin film	Sol-gel	XPS, AFM, SPM, EDS	Perovskite	19.56%	Yu H. et al (2018) [42]
16.	SnO_2 thin film	Thermal Oxidation	FESEM, EDX, XRD,SEM,TEM, VLS	Solar cell	18.9%	N Abdullah et.al (2018) [43]
17.	EDTA complexed SnO_2 ETLs	Spin coating	XPS, FTIR, AFM, KPFM, SEM, PL, J-V curves	Perovskite	21.60%	Yang D. et al (2018) [44]
18.	EDTA complexed SnO_2 ETLs	Spin coating	XPS, FTIR, AFM, KPFM, SEM, PL, J-V curves	Perovskite	18.28% At low temp.	Yang D. et al (2018) [44]
19.	F:SnO_2/CdS /CuO/Ag	Sputtering	XRD, FESEM, AFM, SAED,	F:SnO_2/Ag CdS/CuO	2.1%	Dolai S. et.al (2019) [45]
20.	SnO_2-rGO	Spin coating	SEM, AFM, PL	perovskite solar cells	16.87%	Liu R. et al (2018) [46]

thin film from sol-gel method and applied various characterizations on it like XRD, AFM, XPS, SEM. They concluded that it is very promising sensor to detect concentration of Ammonia at very low temperature and this sensor has various applications in future due to its excellent stability, proper recovery time and good response. Gupta P *et al.*[50] suggested that doping of Zn improve the gas sensing properties of SnO_2 like surface morphology, crystallinity, crystal size, etc. They reported that SnO_2 shows enhancement sensitivity for O_2 gas sensing among pure and Zn doped SnO_2. Khuspe G D *et al.*[51] reported in their study about more sensitivity and stability of SnO_2 towards NO_2 gas. They reported higher response of sensor is 19% and stability is 77.90%. Similarly Sharma A *et al.*[2] also investigated and find it highly sensitive. Ozone is an important gas which is using in many applications in today's physical world. Korotcenkov G *et al.*[53] have discussed about monitoring of Ozone (O_3) gas in their paper. They compared SnO_2 and In_2O_3 materials and also shown the advantage and disadvantage of SnO_2 thin film for

Table 3 – A review of SnO_2 materials on preparation methods, characterization technique and gas sensors application.

S.No.	Thin film material	Preparation Method	Characterization	Gas sensor	Response/ Sensitivity	References
1.	SnO_2 Thin Film	sol-gel	XRD, XPS, AFM and SEM	Ammonia (NH_3) gas	Response 28%	Beniwal A. et.al (2019) [47]
2.	SnO_2 Thin Film	RF sputtering method/ PLD	XRD, Vander Paw tech, optical transmittance	CO_2 gas sensor	Very high	Tanuma R. et.al (2018) [49]
3.	Zn-doped SnO_2	sol-gel	XRD, PL, I-V, R-T, gas sensing measurement	O_2 gas	Sensitivity 37.6%	Gupta P. et.al (2017) [50]
4.	SnO_2 thin films	sol-gel	XRD, FESEM, TEM,IS, SAED	NO_2 gas	Response 19%	Khuspe G.D. et.al (2013) [51]
5.	SnO_2 thin film	RF sputtering method	XRD, AFM, XPS, SEM	NO_2 gas	Response $2.20\text{x}10^4$	Sharma A. et.al (2013) [52]
6.	SnO_2	spray pyrolysis	XRD, XPS, AFM and TEM	Ozone gas	Very high	Korotcenkov G. et.al (2012) [53]
7.	ZnO–SnO_2 composite	Spin coating	XRD,XPS, SEM, EDX	Hydrogen gas	Response 90% and high sensitivity	Mondal B. et.al (2013) [54]
8.	SnO_2 thin film	RF sputtering method	XRD, SEM	SO_2 gas	56	Tyagi P.et.al (2015) [55]
9.	Cu doped SnO_2 thin film	RF sputtering method	XRD,AFM, XPS, SEM	H_2S gas	response 10.1 & recovery time 42.4S	Zhang S. et.al (2014) [56]
10.	Ni & Zn doped SnO_2	screen-printing technique	XRD,XPS,SEM	CO gas	Response Ni -7.28 Zn- 5.90	Zhou Q. et.al (2017) [57]
11.	SnO_2 thin film	PLD	XRD, SEM,	CO & NO_2 gas	Response CO -5-50 ppm NO_2- 0.5-1 ppm	Preiß M.E. et.al (2015) [58]
12.	SnO_2 nanocrystalline thin film	LB technique	FESEM, XPS, XRD	toxic gas	_	Betty C.A. et.al (2016) [59]
13.	Pd – SnO_2 thin film	RF Sputtering	XRD, UV-Visible	Methane gas	High response ~97.2%	Haridas D. et.al (2012) [60]
14.	SnO_2 thin film	Spray Pyrolysis	XRD, SEM, UV-Visible	NO_2 gas	_	Kamble D. L. et.al (2017) [61]
15.	Pt-doped SnO_2 thin film	RF sputtering	TEM, HRTEM,	HCHO, Toluene, and CO gas		Kang J. et.al (2017) [62]

Ozone gas sensor. Mondal B *et al.*[54] investigated ZnO-SnO_2 composite material based hydrogen sensor. It showed good selectivity and outstanding response of 90%. They also performed experiments on methane and Carbon-mono oxide gas but it showed good sensitivity for hydrogen gas. Tyagi P *et al.*[55] discussed in their paper about monitoring and deduction of most toxic and harmful gas SO_2. They fabricated SO_2 gas sensors using SnO_2 thin film integrated with different metal oxide catalyst. Most highest response showed by the NiO_2 catalyst with SnO_2 thin film. For monitoring and deduction of toxic and inflammable gas Hydrogen Sulphide (H_2S) S. Zhang *et al.*[56] resulted that Cu doped SnO_2 thin film is very suitable and promising alternative. It shows very high sensitivity, fine reproducibility, Quick response and short recovery time. Zhou Q *et al.*[57] reported rapid recovery and response time of Ni and Zn doped SnO_2 gas sensors as compared to particular Zn doped or Ni doped SnO_2 nanomaterials. They applied various experiments on concentration of toxic CO gas and find better sensitivity and stability. Preiß E M *et al.*[58] performed their experiments on Tin Oxide films deposited at higher oxygen background pressure by PLD method to enhance sensor signal to CO. Author's resulted the response of sensors are 5-50 ppm for CO gas and 0.5-1 ppm for NO_2 gas at different operation temperatures and relative humidity. Betty C A *et al.*[59] reported in their paper that the gas sensitivity by nanocrystalline SnO_2 film sensor has been shown a visa-versa relationship with temperature for toxic gases such as H_2S and SO_2 Haridas D *et al.*[60] investigated a high response of 97.2 % for detection of Methane gas. For sensor the thin film of SnO_2 material with Pd doping is synthesis by Rf- sputtering method. Kamble D L *et al.*[61]

experimented the nanocrystalline tin oxide (SnO_2) thin films were synthesized with varing precursor concentrations of the solution by spray pyrolysis technique for NO_2 gas detection. They applied XRD, SEM, UV-Visible and two probe resistivity characterization measurements on the prepared thin film. Kang J *et al.*[62] have performed experiment with Pt doped SnO_2 thin film for CO, HCHO, and toluene gases. They concluded that on the 25 ppm toluene and HCHO gases are giving good selectivity response but CO gas is not showing any response

6 Results and Discussion

In the present work, the authors have studied current development on tin oxide. A study on different methods to prepare SnO_2 thin films in pure form, composite form as well as doping with transition metals to display its structural and electrical properties have been put forward. Different Preparation methods of synthesis SnO_2 films to highlight their utilities and drawbacks, various innovations and their unique effects, and potential applications especially towards photovoltaics and gas sensors have been discussed here. With so many useful applications of SnO_2 thin films we are focusing only highly demanding application of photovoltaic and sensing application. Photovoltaic application is the most interesting application due to its specific advantages as a renewable energy source. It is very ecofriendly application which has no pollution and no green house gas emission. SnO_2 has excellent properties of charge collection in Solar cells and having an effective and progressive scope in future green energy technology. Looking forward towards the futuristic aspects of SnO_2 thin films the corresponding collected data as shown in Table 2 and presented by various authors have been also discussed and interpreted. A PCE of 16.02% has been achieved for low temperature nanocrystalline[28] SnO_2. Highest PCE of 19.56% were achieved for pure SnO_2 thin films synthesized by different methods like sol-gel, ALD, spin coating, PLD and sputtering[42]. With the doping of Transition metals like Nb doped SnO_2 thin film, Mg doped SnO_2 thin film and Ga doped SnO_2 thin film, the PCE's are 17.57%, 14.60%, 16.40%, respectively[35-37]. The investigation shows in case of Composite thin film of SnO_2-TiO_2 the achieved PCE[40] is 21.10%, which is the highest efficiency in all experiments. SnO_2 as gas sensor application it is observable from the collected data as shown in Table 3 that pure SnO_2 gas sensor fabricated by Sputtering method is showing very high sensitivity for CO_2 gas[49]. Similarly pure SnO_2 thin films prepared by Sol-gel method are giving 28% response for Ammonia (NH_3) gas and 19% response for NO_2 gas[47, 51, 52]. With doping of Zn in SnO_2 thin film an increased high response and sensitivity of 37.6% for the monitoring of O_2 gas has been notified by the authors[50]. SnO_2 thin film is good for Ozone gas sensing with high response[53]. Cu doped SnO_2 is giving very quick recovery time for H_2S gas[56]. For H_2 gas Authors obtained a very high response approximately 90% and high selectivity with the use of composite thin film of ZnO and SnO_2 material[54]. For the monitoring of CO gas researchers performed their experiments with the doping of Ni and Zn and found the response of 7.28 and 5.90, respectively. SnO_2 thin film fabricated by PLD method shows a response of 5-50 ppm for CO gas and0.5 -1 ppm for NO_2 gas, respectively[58]. An enhanced response (99.2%) for the detection of Methane gas can be obtained by SnO2 thin film in the presence of 10nm Pd clusters at the temperature of 160 ℃[60]. Authors investigated the sensing characteristics to 25 ppm CO, 25 ppm toluene, and 1 ppm HCHO gases at 300-440 ℃. They concluded the Pt-doped SnO_2 gas sensors with the thickness of 120 nm showed the selectivity to 1ppm HCHO gas at 31.5 mW power consumption and to 25 ppm toluene gas[62] at 45 mW.

7 Conclusions

There are still substantial scopes in synthesis of SnO_2 thin films by pulsed laser deposition method. It is worth mentioning that, among the other synthesis technologies, PLD method is the most suitable method because of the obvious reasons of accuracy, simplicity, flexibility, homogeneity and Uniformity. However, some of its benefits can be mentioned that by the fabrication of SnO_2 thin film through PLD some important characterization like XPS and VBS study can be performed on the SnO_2 materials. We hope that the study of this characterization technique may explore the new path of photovoltaic and gas sensor applications which can be helpful to achieve the desired efficiencies of solar cell for future aspects as well as excellent performance (gas response, selectivity, stability, sensitivity) in gas sensors.

Acknowledgement

The authors would like to acknowledge to UGC-DAE CSR and RRCAT, Indore for funded research project. We extremely acknowledge Jagran Lakecity

University and grateful to the dignitaries for great motivation and support for research work.

References

1 Brinker C J & Ginger D, *Nanotechnol Res Dir Soc*, 2020 (2011) 261.

2 Zhang L, Xu C & Champagne P, *Bioresource Technol*, 101 (2010) 2713.

3 Du G, Cui Y, Xiaochuan X, Li X, Zhu H, Zhang B, Zhang Y & Ma Y, *Appl Phys Lett*, 90 (2007) 243504.

4 Ogale S, Choudhary R J, Buban J P, Lofland S E, Shinde S R, Kale S N, Kulkarni V N, Higgins J, Lanci C, Simpson J R, Browning N D, Das Sarma S, Drew H D, Greene R L & Venkatesan T, *Phys Rev Lett*, 91 (2003) 077205.

5 Patil M K, Shaikh S & Ganesh I, *Current Nanosci*, 11 (2015) 271.

6 Da Silva L F, M'Peko J C, Catto A C, Bernardini S, Mastelaro V R, Aguir K, Ribeiro C & Longo E, *Sens Actuators B: Chem*, 240 (2017) 573.

7 Shukla T, *J Sensor Technol*, 2 (2012) 102.

8 Babu B, Kadam A N, Thirumala Rao G, Sang W L, Chan B & Shim J, *J Lumin*, 195 (2018) 283.

9 Das S & Jayaraman V, *Prog Mater Sci*, 66 (2014) 112.

10 Chopra K L, Paulson P D & Dutta V, *Prog Photovolt: Res Appl*, 12 (2004) 69.

11 Kim H & Pique, *Appl Phys Lett*, 84 (2004) 218.

12 Kumar S, Chauhan R S, Panchal G, Singh C P, Dar T A, Phase D M & Choudhary R J, *J Appl Phys*, 122 (2017) 125301.

13 Mehraj S, Ansari M S & Alimuddin, *Thin Solid Films*, 589 (2015) 57.

14 Bacol S, Chik A & Yassin F, *J Sci Technol*, 4 (2012) 1.

15 Rathore V, Prakash S, Gupta P, Rathore M K, Rawat R, Choudhary R J & Phase D M *AIP Conference Proceeding*s, 2115 (2019) 030279.

16 Comini E, *Mater Today*, 19 (2016) 559.

17 Kwoka M, Ottavianob L & Szubera J, *Appl Surf Sci*, 401 (2017) 256.

18 Wang J T, *Modern Inorg Synth Chem*, 7 (2011)151.

19 George S M, *Chem Rev*, 110 (2010) 111.

20 Shim E, *Smart Text Protect*, 3 (2013) 87.

21 Gupta P & Rathore V, *Jagran Int J Contemp Res*, 6 (2019) 12.

22 Kern W & Schuegraf K K, (Eds) *Handbook of thin film deposition, Process and Tech*, (Intel Corporation Santa Clara, California) 2002.

23 Sarkar J, *Sputtering Materials for VLSI and Thin Film Devices*, 2 (2014) 93.

24 Ashik U P M, Kudo S & Hayashi J, *Synth Inorg Nanomater*, 2 (2018) 19.

25 Gavrilović T V, Jovanović D J & Dramićanin M D, *Nanomater Green Energy*, 2 (2018) 55.

26 Veiko V P, Skvortsov A M, Huynh C T & Petrov A A, *Tech Phys Lett*, 41 (2015) 701.

27 Grama S, Massachusetts Institute of Technology, System Design and Management Program, (2007).

28 Ke W, Fang G, Liu Q, Xiong L, Qin P, Tao H, Wang J, Lei H, Li B, Wan J, Yang G & Yan Y, *J Am Chem Soc*, 137 (2015) 6730.

29 Bouras K, Schmerber G, Rinner H, Aureau D, Park H, Ferblantier G, Colis S, Fix T, Park C, Kim W, Dinia A & Slaoui A, *Sol Energy Mater Sol Cells*, 145 (2016) 134.

30 Zhu Z, Bai Y, Liu X, Chueh C, Yang S & Jen A, *Adv Mater*, 28 (2016) 6478.

31 IKhmayies S J, *Mediterranean Green Buildings Renewable Energy* 70 (2017) 899.

32 Huang X, Hu Z, Xu J, Wang P, Wang L, Zhang J & Zhu Y, *Sol Energy Mater Sol Cells*, 164 (2017) 87.

33 Dong Q, Shi Y, Wang K, Li Y, Wang S, Zhang H, Xing Y, Du Y, Bai X & Ma T, *J Phys Chem C*, 119 (2015) 10212.

34 Wang C, Zhao D, Grice C R, Liao W, Yu Y, Cimaroli A, Shrestha N, Roland P J, Chen J, Yu Z, Liu P, Cheng N, Ellingson R J, Zhao X & Yan Y, *J Mater Chem A*, 4 (2016) 12080.

35 Xiong L, Guo Y, Wen J, Liu H, Yang G, Qin P & Fang G, *Adv Funct Mater*, 28 (2018) 1802757.

36 Roose B, Johansen C M, Dupraz K, Jaouen T, Aebi P, Steiner U & Abate A, *J Mater Chem A*, 6 (2018) 1850.

37 Ren X, Yang D, Yang Z, Feng J, Zhu X, Niu J, Liu Y, Zhao W & Liu S F, *ACS Appl Mater Interf*, 9 (2017) 2421.

38 Sinha S K, *Adv Mater Lett*, 7 (2016) 319.

39 Lee Y, Paek S, Cho K T, Oveis E, Gao P, Lee S, Park J, Zhang Y, Baker R H, Asiri A M & Nazeeruddin M K, *J Mater Chem A*, 5 (2017) 12729.

40 Song S, Kang G, Pyeon L, Lim C, Lee G, Park T & Choi J, *ACS Energy Lett*, 212 (2017) 2667.

41 Ganchev M, Katerski A, Stankova S, Eensalu J S, Terziyska P, Gergova R, Popkirov G & Vitanov P, *IOP J Phys Conf Ser*, 1186 (2019) 01202.

42 Yu H, Yeom H I, Lee J W, Lee K, Hwang D, Yun J, Hwang D, Yun J, Ryu J, Lee J, Bae S, Kim S K & Jang J, *Adv Mater*, 30 (2018) 1704825.

43 Abdullah N, Ismail N M & Nuruzzaman, *IOP Conf Ser: Mater Sci Eng*, 319 (2018) 012022.

44 Yang D, Yang R, Wang K, Wu C, Zhu X, Feng J, Ren X, Fang G, Priya S & Liu S (Frank), *Nature Commun*, 9 (2018) 3239.

45 Dolai S, Dey R, Hussain S, Bhar R & Pal A K, *Mater Res Bullet*, 109 (2019) 1.

46 Liu R, Qiu R, Zou T, Liu C, Chen J, Dai Q, Zhang S & Zhou H, *Nanotechnology*, (2018) 119039 R2.

47 Beniwal A, Srivastava V & Sunny, *Mater Res Express*, 6 (2019) 4.

48 Das S & Jayaraman V, *Progress Mater Sci*, 66 (2014) 112.

49 Tanuma R, Haga H & Sugiyama M, *Jpn J Appl Phys*, 57 (2018) 115503.

50 Gupta P & Sharma S K, *Mater Res Express*, 4 (2017) 065010.

51 Khuspe G D, Sakhare R D, Navale S T, Chougule M A, Kolekar Y D, Mulika R N, Pawar R C, Lee C S & Patil V B, *Ceram Int*, 39 (2013) 8673.

52 Sharma A, Tomar M & Gupta V, *Sens Actuators B*, 181 (2013) 735.

53 Korotcenkov G, Brinzari V & Cho B K, *J Sens*, 1 (2016).

54 Mondal B, Basumatari B, Das J, Roychaudhury C, Saha H & Mukherjee N, *Sens Actuators B*, 194 (2014) 389.

55 Tyagi P, Sharma A, Tomar M & Gupta V, *Sens Actuators B: Chem*, 224 (2017) 282.

56 Zhang S, Zhang P, Wang Y, Ma Y, Zhong J & Sun X, *ACS Appl Mater Interf*, 6 (2014) 14980.

57 Zhou Q, Chen W, Xu L, Kumar R, Gui Y, Zhao Z, Tang C & Zhu S, *Ceram Int*, 44 (2018) 4392.

58 Preib E M, Rogge T, Kraub A & Seidel H, *Procedia Eng*, 120 (2015) 88.

59 Betty C A & Choudhury S, *Sens Actuators B: Chem*, 237 (2016) 787.

60 Haridas D & Gupta V, *Sens Actuators B: Chem*, 166 (2012).

61 Kamble D L, Harale N S, Patil V L, Patil P S & Kadam L, *J Anal Appl Pyrolysis*, 127 (2017) 38.

62 Kang J, Park J S & Lee H J, *Sens Actuators B: Chem*, 248 (2017) 1011.