Advanced Engineering Technology and Application
An International Journal

http://dx.doi.org/10.18576/aeta/130105

Zinc Oxide Thin Films and Potential Applications

Temesgen Geremew[1*]

[1] Graduate Institute of Applied Science and Technology, National Taiwan University of Science and Technology, Taipei 106335, Taiwan.

Received: 27 Jul. 2024, Revised: 2 Aug. 2024, Accepted: 5 Aug. 2024.
Published online: 1 Sep. 2024.

Abstract: ZnO is currently receiving a lot of attention in the semiconductor industry due to its unique characteristics. ZnO is widely used in solar cells, heat-reflecting glasses, optoelectronic bias, and detectors. In this composition, we provide an overview of the ZnO thin flicks' packages, methods of characterization, and implicit operations. They consist of Transmission spectroscopy, Raman spectroscopy, Field emigration surveying electron microscopy, and X-ray diffraction. This review content also demonstrates how ZnO thin flicks function in electrical components for piezoelectric bias, optoelectronics, detectors, and renewable energy sources.

Keywords: Zinc oxide, Raman spectroscopy, thin films, Piezoelectric Devices.

1 Introduction

Its electrical and optical properties characteristics, ZnO, a broad straight band-gap oxide semiconductor, having tremendous promise for use platforms for electrical, optical, and information technology devices (Schuler and Aegerter 1999) (Sahay and Nath 2008). Invisible conducting oxides employed through contemporary Solid-state technology, including mirrors that reflect heat, solar panels, and sensors , and optical electronics have successfully incorporated zinc oxide (ZnO) thin films (O'Brien, Nolan et al. 2010). TCOs should have great optical transparency and strong electrical conductivity in the visible range. Due to its strong electrical conductivity and excellent transparency to visible light, ITO, or the most common indium tin oxide widely utilized TCO (Srivastava and Kumar 2013). Under UV irradiation, ZnO thin-film transistors (Tiginyanu, Ghimpu et al. 2016).

ZnO is regarded as a flexible substance with a truly larger scope of parcels those generalized important translucence and strong room-temperature luminescence. ZnO have been a great interest in the multitudinous disquisition groups due to its operation in light transmittance, shaft diodes, emigration bias, gas sensors and solar cells, face audial swells, transparent connections, furthermore thin-film transistor(TFT)(Zhou, Gu et al. 2008). Three distinct varieties of zinc oxide can crystallize: cubic rocksalt, hexagonal rocksalt, and cubic zinc blende. A majority frequent and sturdy framework at a peaceful environment temperature is the structure of wurtzite. Prior to stabilizing this ZnO in zincblende conformation can be elevated on substrates featuring a cubic lattice architecture. These two situations, the zinc and oxide centers are four-sided. Polymorphs are hexagon and zincblende do not exhibit inversion symmetry. The hexagonal and zincblende ZnO exhibit piezoelectricity due to this and additional lattice symmetry features (Zhou, Gu et al. 2008).

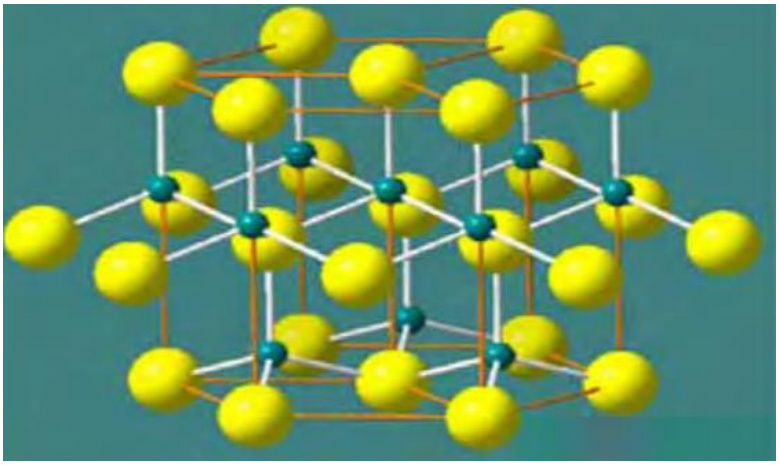

Fig. 1: Wurtzite structure of ZnO.

*Corresponding author e-mail: temeye2024@gmail.com

Natural forms of zinc oxide (ZnO), an oxidic chemical, include the uncommon material zincite, which has a hexagonal wurtzite form when it crystallizes P63mc (Wyckoff 1963).

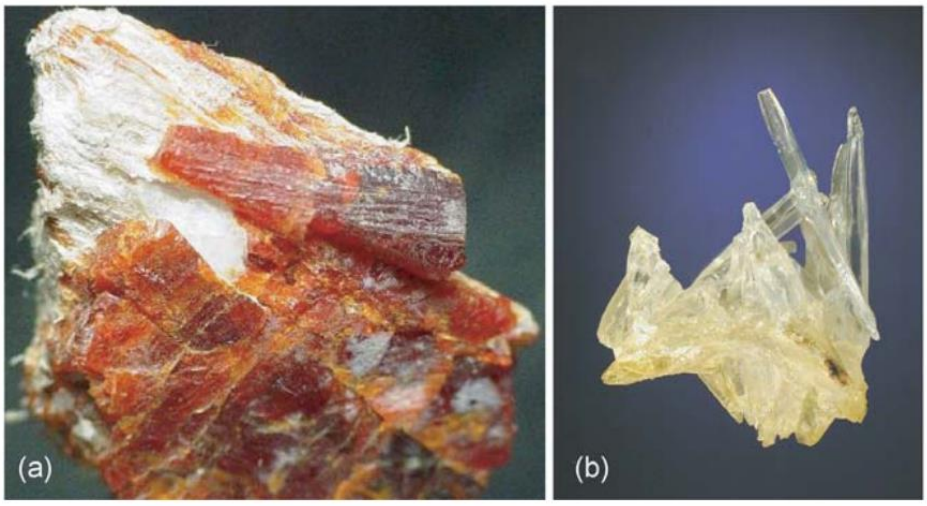

Fig. 2: A manufactured mineralized zinc oxide and (B) Crystal is credited with orange zincite was found in Ogdensburg, USA, in the Sterling Mine. The mineral in (A) is 30× 25 ×6 mm^3 in size.

Manganese impurities commonly give zincite a red or orange tint. In Fig. 2, images of zincite are shown. Crystals of zinc oxide display various common surface orientations. In theory, only Zn atoms may end (0001) planes, whereas only oxygen atoms can terminate $(000\bar{1})$ surfaces. But for these two surfaces, the etching behavior is considerably different (Mariano and Hanneman 1963).

2 Principle and Theoretical Aspects of Diffraction of X-rays and Raman spectroscopy

2.1. X-Ray Diffraction

A quick and effective method for studying crystalline materials' phases, a single-cell lattice characteristics, crystal orientation, crystal structure, and crystal sizing is diffraction of X-rays (XRD). XRD is frequently employed to describe unidentified crystalline minerals. X-rays' constructive interference with crystal clear material underlies the operation of the XRD technology. Atoms in a crystal arrange themselves uniformly in space, forming crystal lattices(Rodriguez-Mozaz, Marco et al. 2004).

The structure of crystals and Bragg's law are very important to experimentally or computationally for XRD patterns' foundation. High partial pressure as well as concomitant lead monoxide while sintering, evaporation occurs, which causes a modification to fiber's composition of the crystalline phase during heat treatment over 1000^0C, provide a significant challenge for fabricating PZT materials (Heiber, Clemens et al. 2005).

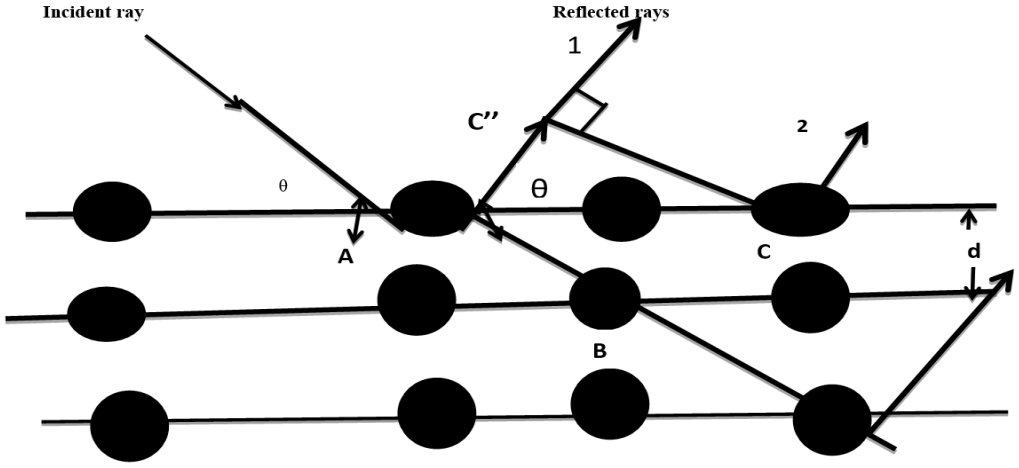

Fig. 3: X-ray diffraction.

The reflected shifts from consecutive plane should intrude constructively.

Hence, from the above Figure the path different are given by:

$$\Delta d = d\sin\theta = n\lambda \quad (1)$$

Regarding the above Figure. 3 that equation 2 can be written as

$$\overrightarrow{AB} + \overrightarrow{BC} = \frac{d}{sin\theta} \quad (2)$$

$$\overrightarrow{AC} = \frac{2d}{tan\theta} \quad (3)$$

$$\overrightarrow{AC'} = \overrightarrow{AC}\cos\theta = \frac{2d\,cos\theta}{tan\theta} \quad (4)$$

$$\overrightarrow{AC'} = \frac{2d\,cos\theta}{sin\theta}\cos\theta = \frac{2d\,cos^2\theta}{sin\theta} \quad (5)$$

putting everything together we get

$$n\lambda = \frac{2d}{sin\theta} - \frac{2d}{tan\theta}\cos\theta = \frac{2d}{sin\theta} - \frac{2d}{sin\theta}\cos^2_\theta \quad (6)$$

$$n\lambda = \frac{2d}{sin\theta}(1-\cos^2\theta) = \frac{2dsin^2\theta}{sin\theta} \quad (7)$$

$$2d\sin\theta = n\lambda \quad (8)$$

Equation 8 represented as Bragg law.

2.2. Raman Spectroscopy

A nondestructive spectroscopic technique is Raman spectroscopy method for observing rotating, vibrating, and different a system's low-frequency modes and offers details on the material's orientation, crystallographic condition, and phase composition. Those method is a tool that can be used for fingerprinting substances based on them distinctive spectrum characteristics (Lusiola and Clemens 2016).

To find and investigate an accouterment's structure, it is crucial to characterize it. An important and non-destructive tool for characterizing 2D accessories is Raman spectroscopy. Characterizing the structural components of 2D accessories is one of its capabilities, along with the ability to identify subcaste consistency, band structures, strain goods, doping type, attention, electron-phonon coupling, and interlayer coupling. An overview of Raman's characterization of sweats for 2D accessories and how they work is shown in Figure 4.

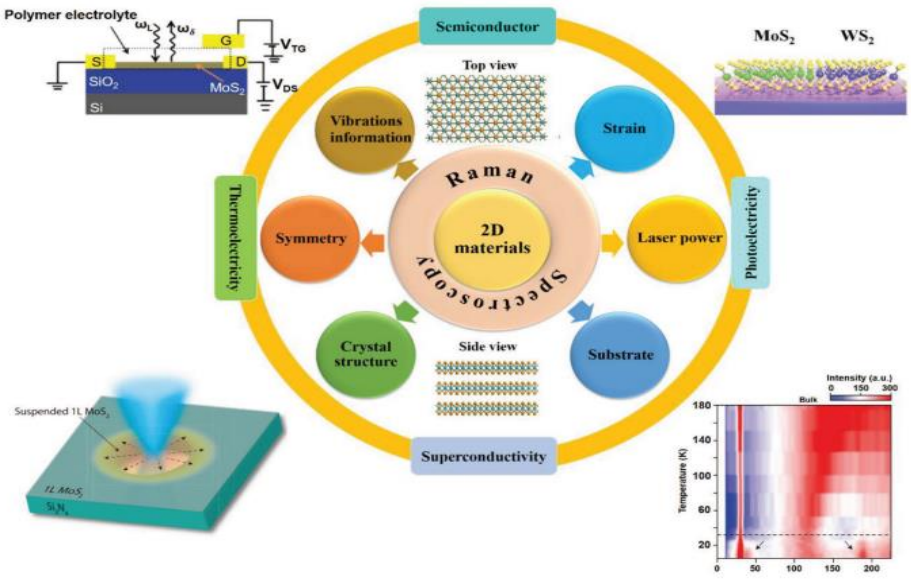

Fig. 4: This figure's upper left inset was taken from "(Solé, Bausa et al. 2005)" with permission. "American Physical Society Copyright 2012." Permission to use the top right inset is granted by "(Williams, Carter et al. 2009)". 2014

American Chemical Society copyright. The bottom right inset is taken from (Kingery, Bowen et al. 1976) with permission.

2.2.1. Basic ideas behind spectroscopy using Raman

A scattering technique is Raman spectroscopy. A slight percentage attributed to dispersed radiation has a different frequency than monochrome incoming light, according to the Raman Effect, which forms the basis of this phenomenon. Its foundation is the incoming radiation's inelastic scattering caused by interactions with vibrating molecules. It looks at how molecules vibrate "(Varnes and Settle 1997)" "(CHALMERS, EDWARDS et al. 2012)".

The Raman effect is based on the fundamental idea when the tiniest form of light travels using any material, a light dispersed by additional molecules changes change in frequency. This indicates that it is the Raman effect created molecules vibrate, and this can therefore be described in terms of energy(Jones, Hooper et al. 2019).

The inelastic collision that causes the Raman effect happens during photons strike molecules from a perspective of quantum physics. If the molecule is initially in its ground state, it will get energized or enter a virtual state when excited light interacts with it. Then, the virtual state of the electrons and molecules will leave the heightened state, producing sporadic lighting.

An ecstatic photon will transmit giving the molecule energy throughout during this process, the photon itself loses energy. The substance that enters the excited state at this point gains energy.

When the direct sunlight frequency low, the prevailing dispersed a light referred to as Stokes Line; when it is high, it is referred to as the inverse Stokes Line (Jones, Hooper et al. 2019). Rayleigh scattering is the process by which photons interact with molecules to modify the direction of the collision rather than the energy between them (Bumbrah and Sharma 2016). Although it might be eliminated applying methods example is fitting polynomial baselines, RS typically has a significant background fluorescence that could distort originally, a spectrum and impair the quality of bacterial identification (Wei, Chen et al. 2015).

RS produces several when measuring a spectral signal lines specific cross section, with the Laser change being the difference in frequency between aforementioned Rayleigh the shards of light and the Raman sporadic lighting (Cialla-May, Schmitt et al. 2019).Inside of biological samples, certain particular chemicals should have distinctive peaks and level of consolidation quantity could have been given the specimen's molecules would have been impact on its molecule brightness (Figure 5).

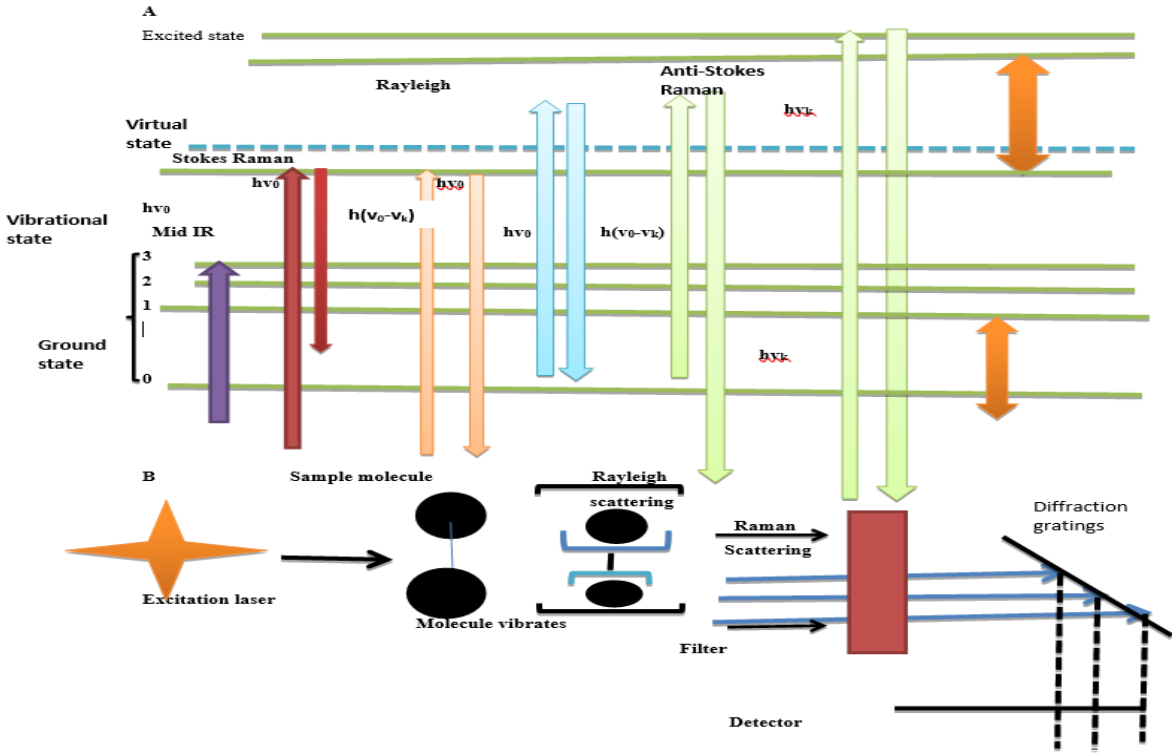

Fig. 5: level of consolidation quantity

3 Applications for thin films of ZnO

3.1 Electronic Properties of Thin Films of ZnO

With a 3.3 eV band gap at ambient Group II–VI semiconductor ZnO has large band gap and the reasonably high energy that binds exciton of 60 meV at standard temperature (Ozgur 2005).

The luminescence phenomena, namely photoluminescence, which is the creation of light in response to the electromagnetic spectrum, is also present in ZnO. This is utilized in televisions and other FED (field emission display) technology, because of this feature. It is better than the more common materials, compounds containing phosphorus and sulfur that display beams, due to its stronger electrical conductivity and greater UV resistance. The size of the compound's crystals, flaws in the crystalline structure, temperature, and other factors all affect zinc oxide's photoluminescent capabilities (Lima, Sigoli et al. 2001) (Tang, Wong et al. 1998) (Kim, Nam et al. 2012) (Khranovskyy, Lazorenko et al. 2012) (Soares, Whitten et al. 2008).

Pure zinc oxide (ZnO) has recorded concentrations attributed to 1016 to 1020 per cm^3 in high quality material, making it an intrinsic n-type semiconductor.

According to the defect equations below (see Equations 9 and 10), the chemistry is flawed causing the n-type characteristics to have non-stoichiometric ratios as a result (Zn1+δO or ZnO1-δ), respectively.

$$\text{null} \overset{ZnO}{\longleftrightarrow} V_0^{00} + 2e' + Ox_o \quad (9)$$

$$\text{null} \overset{ZnO}{\longleftrightarrow} Zn_i^{00} + 2e' + Ox_o \quad (10)$$

Depending on the Aluminum or Gallium Equation 11 also can be written as.

$$Al_2O_3 \overset{ZnO}{\longleftrightarrow} 2Al^o_{Zn} + 2e' + 3O^x_o \quad (11)$$

According to Li, Na, and K (Equation 12) and as N, P, and as (Equation 13) can be written as.

$$Li_2O \overset{ZnO}{\longleftrightarrow} 2Li'Zn + 2h^o + O^x_o \quad (12)$$

$$N_2O_5 \overset{ZnO}{\longleftrightarrow} 2N'''_o + 6h^o + 5Ox_o \quad (13)$$

Applications of ZnO as p-n junctions in electronics and optoelectronics have been constrained due to the low capacity for p-doping.

3.2. ZnO thin films are essential Semiconductor Materials for Optoelectronics

Semiconductor materials can be categorized into two groups based on their band gaps: materials using a tighter energy gap and those by means of a wider band gap. Materials including an indirect energy gap and those with a direct band gap can also be separated from one other. Materials with a narrower band gap and a direct band gap are favored for (IR) visible/infrared optoelectronic devices, materials that have a large and direct energy gap have recommended with UV/blue optical electronics. Significant research has been done on larger bandgap group III-nitrides for photonic devices based on semiconductors including lasers and UV/blue LEDs because of their unique features (Ramanathan, Contreras et al. 2003).

Because of its remarkable material qualities and compatibility with traditional processing, Si is well known for being the dominant material in the semiconductor industry. Si's indirect bandgap, however, severely restricts the use of this material in optoelectronic components. In order to create optical electronics such as LEDs, as well as other extremely fast III-V substances, such as arsenide gallium indium, electronic devices, and aluminum Arsenic gallium, as well as GaAs, a direct bandgap material with a highly elevated mobility electron (>8500 $cm^2\ V^{-1}\ s^{-1}$) are used (Patil, Kajale et al. 2011). GaAs and its related materials are ideal for very fast electrical and optoelectronic devices in the near-IR range and have a number of benefits.

3.3. Piezoelectric Devices Using ZnO

Piezoelectric crystals lack symmetric cells, which characterize most other crystals. The asymmetrical character of the crystal structure gives rise to piezoelectricity. In particular, when a clear structure lacks a symmetry center, electric dipoles were present, resulting in the formation of two equivalents. Additionally distinct point charges in the cell with overlapping centers (Fig.6) (Liang, Yan et al. 2019). Because the neighboring with a negative charge balance piezoelectric, removing the positive charge crystals maintain their electrical neutrality in spite of the uneven Atom

arrangement within the lattice. On the other hand, the atoms in a piezoelectric crystal shift when it is stretched or compressed.

As a result, Similar to zinc oxide wurtzite, a net charge accumulates throughout the crystal, with electronegative and net positive charges appearing around opposing sides as well as exterior shell.

In this wurtzite ZnO clear crystal structure, where Zn^{2+} and O^{2-} are tetrahedrally coordinated, centrosymmetry is absent. Both positive and negative ion centers intersect, and there is no spontaneous polarization across the whole crystal. The initial atomic locations of the O^{2-} and Zn^{2+} are moved in relation to one another when the unit cell is under stress, which causes those unit cell to acquire dipole moments. As a result of the charges in the piezoelectric crystal's whole cell being collectively polarized, the crystal develops a piezo potential.

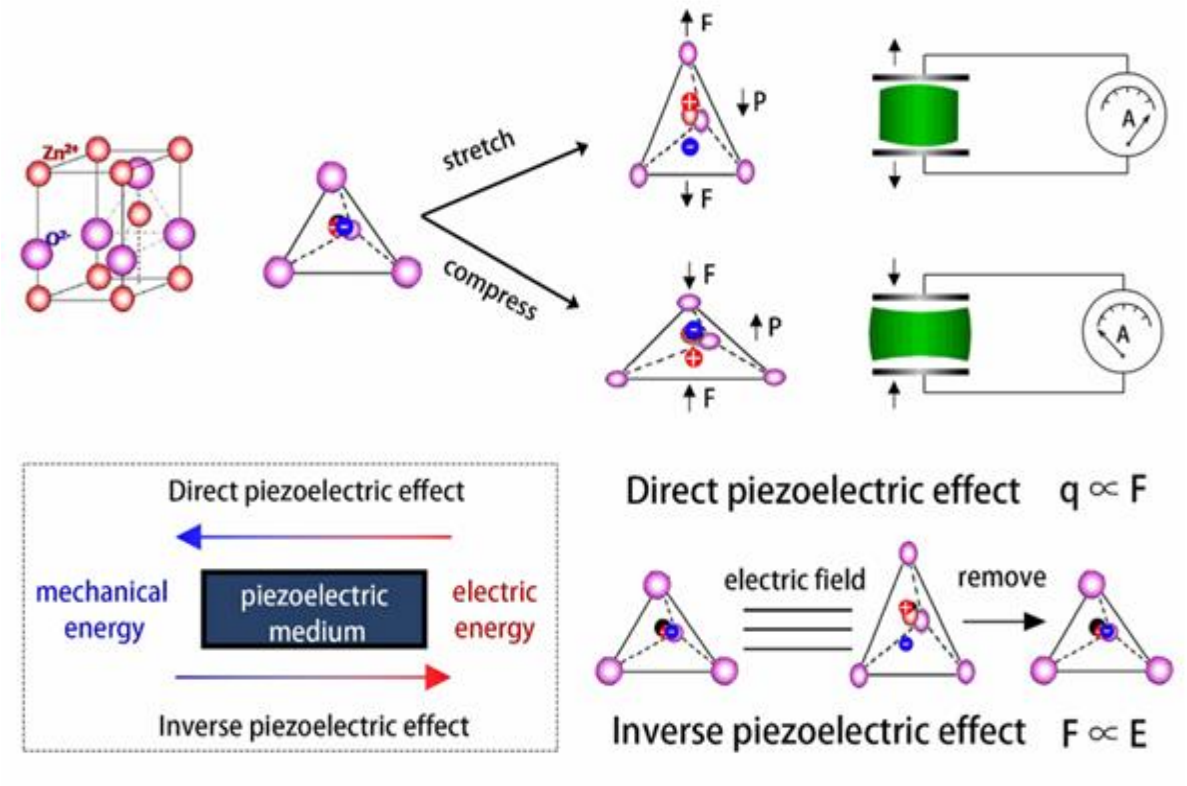

Fig. 6: Mechanism of the piezoelectric effect(Li, Zhao et al. 2020)

Since the early 1970s, the use of ZnO has been utilized due to its usefulness for thin-film piezoelectric devices mild coefficients of coupling and simplicity of settling.

Functions for its MEMS and NEMS stand for micro- and nano-electromechanical systems., filters, and sensors, as well as Surface and bulk acoustic wave resonators (BAW and SAW). On semiconductor substrates like Si (Visser, Vellekoop et al. 1989), GaAs , and InP, Thin sheets of piezoelectric ZnO have been utilized to implement acoustic wave instruments. Other materials used include non-piezoelectric substances with high acoustic velocity and minimal loss during propagation, like sapphire (Koike, Tanaka et al. 1995) (Lu, Emanetoglu et al. 2006) and diamond (Yamanouchi, Sakurai et al. 1989), weakly piezoelectric materials like quartz, and inexpensive amorphous materials like glass (Lu, Emanetoglu et al. 2006).

Understanding highly integrated piezoelectric devices requires an understanding of piezoelectric skinny flicks. Structures made of wurtzite and perovskiteare the two main crystallization in thin films (Liang 2011). The wurtzite crystal structure of nonferroelectric piezoelectrics like ZnO and AlN makes them suitable for high frequency resonator applications. Nonferroelectric piezoelectric thin films have lower piezoelectric coupling coefficients, which makes them less suitable for displacement actuators. Due to their considerably greater piezoelectric coefficient, thin layers of ferroelectric and piezoelectricity enable actuators' low voltage functioning and highly sensitive detector. Using a piezoelectric constants ferroelectrics made of perovskite are produced via a number of methods, such as domain wall motion, polarization rotation, and extension of polarization (Park and Shrout 1997).

Piezoelectric electroactive cellulose and piezopolymer film (PVDF) sheets there had been used in energy collection, actuation, sensing, and other functions because of their flexibility and biodegradability (Tanaka, Tanaka et al. 2008) (Kim, Yun et al. 2011) .

3.4. ZnO Thin-Film Transistors for Flexible Electronics at a Low Cost

The transistor, which was first conceived in 1947 at Bell Laboratories, has grown to be one of the keystones of technological advancement. Transistors are used in a multitude of applications nowadays, including data storage, computers, telecommunications, and sensor networks.

In recent times, the Internet of Everything, or IoE, and the Web of Things (IoT) have forecast mass connection in the future, which has elevated the transistor to a key position in both scientific and commercial advancement. As a result, it is anticipated that Si-based devices will be used in practically every application across almost all industries. The fundamental driver behind the usage of silicon considering those dominant fast semiconducting in microelectronics, the material was the availability of silicon dioxide (SiO_2), an excellent and stable oxide. Gordon Moore predicted in the 1960s that the quantity of components on a chip would be quadrupled by the semiconductor industry every two era (Moore 1965).

In order to keep up with this trend, the industry has been pushing the frontiers of technology continually. Thus, various technical modifications to the architectures of Silicon MOSFETs, or metal-oxide-semiconductor field-effect transistors, made, despite the fact that the MOSFET's core has not changed over time.

It is possible to integrate billions of transistors with effective computing capability on a single chip thanks to advancements in microelectronic technology, however, not all applications need excellent accomplishment and great material density. These application sectors for juggle are expanded by the ability to build electronics operating vast area substrates that employ low heat techniques as long as by investigating those features of the materials in a larger range. Applications including chemical and biological sensor networks, RFID tags, wearable and flexible electronics, and flexible matrix components for driving pixels in screens have all benefited from this method. Transistors with thin films are the essential components of the system's tidal currents for these purposes.

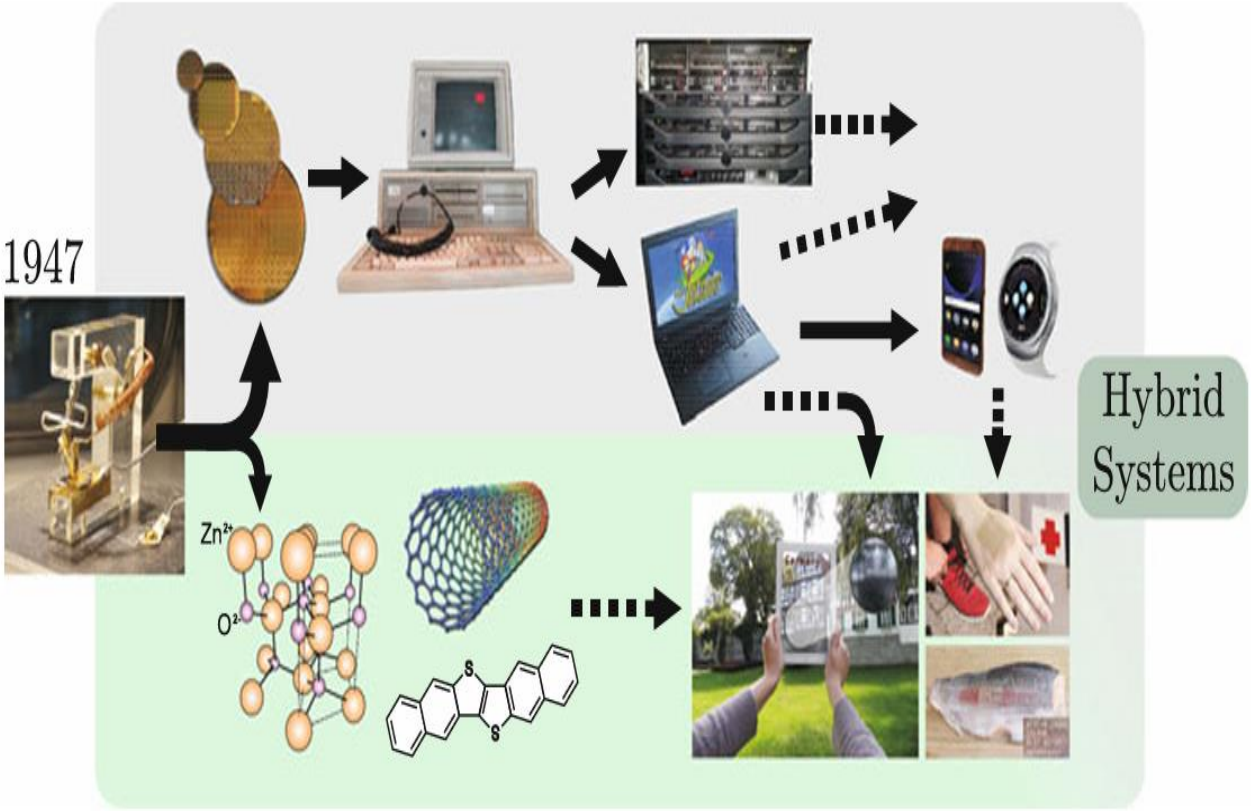

Fig. 7: ZnO transistor technology's evolution as well as applications.

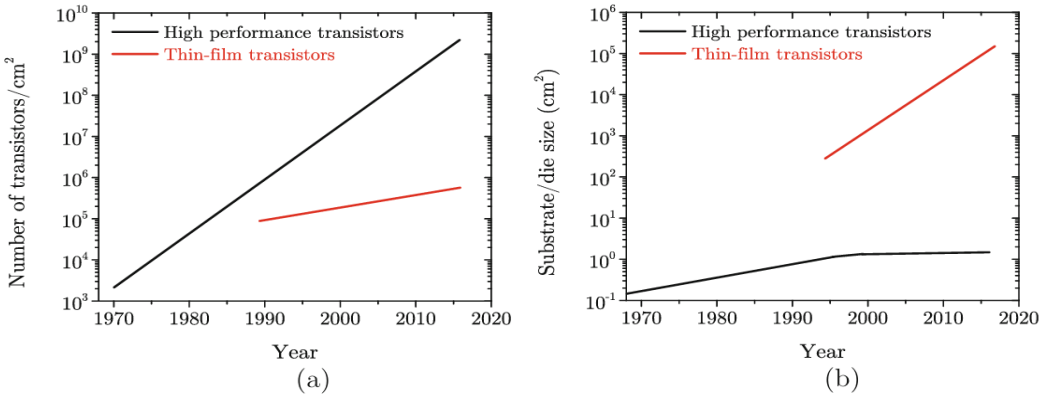

Fig. 8: The MOSFET and TFT technologies are compared with respect to (a) the amount of transistors per square meter, and (b) the foundation/diesize through time. Moore's law and the most recent MOSFET data (Hruska 2014) and TFTs, which are display-based industry) (Street 2009) are approximated in plots. Taken from (Franklin 2015).

Fig. 7 shows their usage in situations where high performance is not the primary need, as they are less expensive than MOSFETs. Furthermore, it is not intended for these types of transistors to replace transistors based on crystal silicon are found in high-performance applications. One of those major uses is to use this technology construct hybrid systems by adding new functionality to both freshly produced and currently existing goods and applications. In this sense, flexible and transparent TFTs complete the data collecting and user interface characteristics, while high-performance transistors handle the primary data management.

There exists another distinction in between the TFT and MOSFET markets concerning the density based on integrated devices per area unit. Figure. (8a) shows how both technologies have changed over time. While the number of transistors in high-performance MOSFETs continues to double in line with Moore's law every few years, the key goals of TFT technology have been substrate-independent fabrication process stability, repeatability, and cost reduction.

It is the other way around when it comes to substrate/die size. In order to optimize yield and cut costs, a single chip's die size has not much risen, despite the contemporary MOSFET production process requiring wafers with diameters of around three hundred mm. On the other hand, the TFTs' integration gains originating from the advancement based on procedures appropriate for broad substrates; as one result, a sharp rise in substrate size over time is noted (Fig. 8b).

3.5. Applications of ZnO in Solar Cells

The fundamental goal of the hunt for clean, ecologically acceptable energy sources has been to reduce the usage of fossil fuels and the gaseous pollutants they produce. Consequently, methods for converting solar radiation into electrical energy have taken center stage in the worldwide energy sector. Recently, zinc oxide has been investigated as a potentially very useful substitute material for solar cells sensitive to dyes and other cells with photoelectrochemistry.

In 1990, (O'regan and Grätzel 1991) created dye-sensitized solar plasma, which had a photoconversion efficiency of 11%–15% (Shi, Zhan et al. 2010). Photoelectrochemical cells, in contrast to traditional solar cells like silicon-based solar cells, primarily work by means of kinetic competition among the interfaces that comprise the tool. As instance, those idea behind the solar cells with dye-sensitized operation was that charge separation and light absorption happen in distinct ways. A chemically deposited dye monolayer covering the semiconductor material's surface absorbs light. Fig. 9 depicts the overall kinetic process of color-sensitive solar cells.

Although the formation of a pair of electrons and holes, all charge transportation processes—the processes of photogeneration, separation, and recombination predominantly only at the solar cell that is dye-sensitized surfaces. Consequently, in contrast to traditional n-p cells, interface characteristics are crucial; that is, the semiconductor's bulk property is lower significant (Gregg 2003). Retamal et al. claim that zinc oxide may obtain produced with a large surface area in a variety of shapes. In ZnO, morphology and electron transport are also connected (Feng 2012).

Research on ZnO material has increased primarily because of two factors: (1) a bandgap of 3.2 eV, similar to that of TiO2, and (2) substantially greater electronic mobility of 115–155 $cm^2\ V^{-1}\ s^{-1}$ compared to Titania anatase (TiO2), which is stated to be $10^{-5}\ cm^2\ V^{-1}\ s^{-1}$ (Zhang, Chou et al. 2008).

On the other hand, yet ZnO can be readily nanoarchitected with one variety about forms, which allow enhance its capacity for light collecting and electron transport, thus improving overall efficiency.

On the other hand, ZnO can be easily nanoarchitected in a variety of forms, which should enhance its capacity for light collecting and electron transport, thus improving overall efficiency.

A link between the conversion and the photoelectrode morphology performance of solar cells with dye sensitization may be observed by comparing the nanostructures.

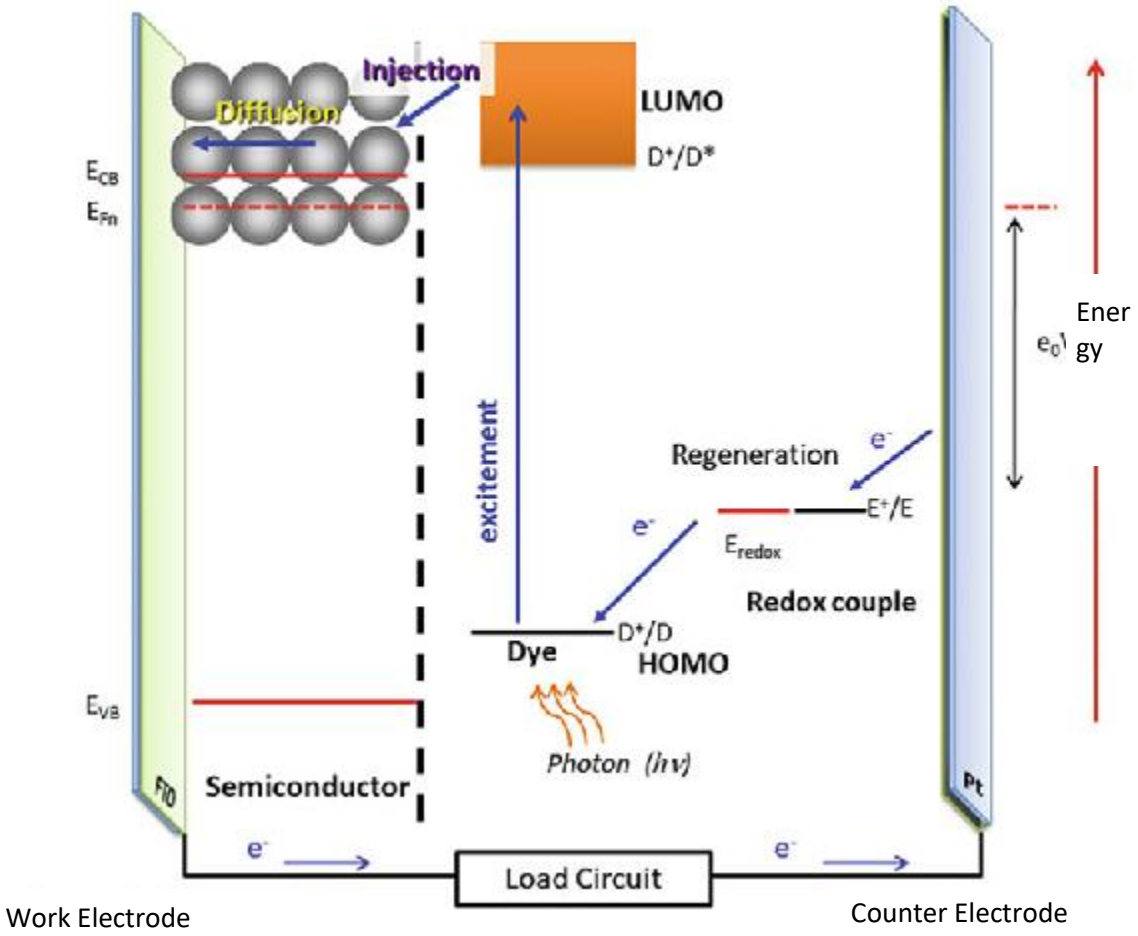

Fig. 9: Scheme of operation for solar cells with dye sensitization. Those ground-state excited dye is D^*, while the oxidized dye is D D^+. An electronic semiconductor's valence band energy is EVB, whereas this conduction band energy is ECB. The semiconductor conduction band's Fermi level is denoted by EFn. The electrolyte's redox power is known as redox. e_oV is the highest possible level.

4 Conclusion and Future perspectives

ZnO, a broad straight band-gap oxide semiconductor, offers excellent potential for use as a platform for electrical, optical, and information technology devices Its electrical and optical properties capabilities. An attainable application of ZnO thin films across several fields, including optoelectronics, sensors, solar cells, and catalysis. This review paper concludes with future perspectives on the review of ZnO thin films, highlighting the need for further studies on their properties and potential applications. We had also emphasized the importance of developing sustainable and eco-friendly synthesis methods for ZnO thin films. Finally, the article discusses the future perspectives of ZnO thin films, including the characterization, the improvement of their properties, and the exploration of new applications. Continued research in this field is expected to lead to the discovery of new properties and applications of ZnO thin films.

Zinc oxide (ZnO) thin films have a larger scope of implementation in the area for optoelectronics, sensing, and energy conversion. In the near future, ZnO thin films are expected game to use a function should be developing for next generation of solar cells, photodetectors, and thin film transistors. Therefore, future studies are required to improve polluting the global environment and causing health problems. The light-emitting diodes are semiconductor devices that

light when an electric current passes through them. LEDs are increasingly being used as a source of lighting in homes and businesses, and for outdoor lighting, traffic signals, and automotive lighting.

Acknowledgments

This review effort has no acknowledgments.

Funding

Finances the absence outside financing in this project.

Conflict of Interests

There are no conflicting interests, according to the author.

Contributions of authors on the review papers of the conception or design of the work, interpretation and revising.

References

[1] Bumbrah, G. S. and R. M. Sharma (2016). "Raman spectroscopy–Basic principle, instrumentation and selected applications for the characterization of drugs of abuse." Egyptian Journal of Forensic Sciences 6(3): 209-215.

[2] Chalmers, J. M., et al. (2012). "Infrared and Raman Spectroscopy in Forensic Science."

[3] Cialla-May, D., et al. (2019). "Theoretical principles of Raman spectroscopy." Physical Sciences Reviews 4(6): 20170040.

[4] Gupta, V., et al. (2006). "Optical phonon modes in ZnO nanorods on Si prepared by pulsed laser deposition." Journal of Crystal growth 287(1): 39-43.

[5] Heiber, J., et al. (2005). "Thermoplastic Extrusion to Highly-Loaded Thin Green Fibres Containing Pb (Zr, Ti) O3." Advanced Engineering Materials 7(5): 404-408.

[6] Jones, R. R., et al. (2019). "Raman techniques: fundamentals and frontiers." Nanoscale research letters 14: 1-34.

[7] Khranovskyy, V., et al. (2012). "Luminescence anisotropy of ZnO microrods." Journal of luminescence 132(10): 2643-2647.

[8] Kim, J., et al. (2011). "Piezoelectric electro-active paper (EAPap) speaker." Journal of mechanical science and technology 25: 2763-2768.

[9] Kim, M. S., et al. (2012). "Photoluminescence studies of ZnO thin films on R-plane sapphire substrates grown by sol–gel method." Journal of luminescence 132(10): 2581-2585.

[10] Kingery, W. D., et al. (1976). Introduction to ceramics, John wiley & sons.

[11] Koike, J., et al. (1995). "Quasi-Microwave band longitudinally coupled surface acoustic wave resonator filters using ZnO/Sapphire substrate." Japanese Journal of Applied Physics 34(5S): 2678.

[12] Liang, Y.-C. (2011). "Growth and structural characteristics of perovskite–wurtzite oxide ceramics thin films." Ceramics International 37(3): 791-796.

[13] Lima, S., et al. (2001). "Luminescent properties and lattice defects correlation on zinc oxide." International Journal of Inorganic Materials 3(7): 749-754.

[14] Lu, Y., et al. (2006). ZnO piezoelectric devices. Zinc oxide bulk, thin films and nanostructures, Elsevier: 443-489.

[15] Lusiola, T. and F. Clemens (2016). "Fabrication of One-Dimensional Ferroelectric Nano-and Microstructures by Different Spinning Techniques and Their Characterization." Nanoscale Ferroelectrics and Multiferroics: Key Processing and Characterization Issues, and Nanoscale Effects: 232-268.

[16] O'Brien, S., et al. (2010). "Zinc oxide thin films: Characterization and potential applications." Thin solid films 518(16): 4515-4519.

[17] Ozgur, U. (2005). "A comprehensive review of ZnO materials and devices." J. Appl. Phys. 98(41301): 1-103.

[18] Park, S.-E. and T. R. Shrout (1997). "Ultrahigh strain and piezoelectric behavior in relaxor based ferroelectric single crystals." Journal of Applied Physics 82(4): 1804-1811.

[19] Patil, G. E., et al. (2011). "Synthesis, characterization and gas sensing performance of SnO 2 thin films prepared by spray pyrolysis." Bulletin of Materials Science 34: 1-9.

[20] Ramanathan, K., et al. (2003). "Properties of 19.2% efficiency ZnO/CdS/CuInGaSe2 thin-film solar cells." Progress in Photovoltaics: research and applications 11(4): 225-230.

[21] Rodriguez-Mozaz, S., et al. (2004). "Biosensors for environmental applications: Future development trends." Pure and applied chemistry 76(4): 723-752.

[22] Sahay, P. and R. Nath (2008). "Al-doped ZnO thin films as methanol sensors." Sensors and Actuators B: Chemical 134(2): 654-659.

[23] Schuler, T. and M. A. Aegerter (1999). "Optical, electrical and structural properties of sol gel ZnO: Al coatings." Thin solid films 351(1-2): 125-131.

[24] Soares, J. W., et al. (2008). "Novel photoluminescence properties of surface-modified nanocrystalline zinc oxide: toward a reactive scaffold." Langmuir 24(2): 371-374.

[25] Solé, J., et al. (2005). An introduction to the optical spectroscopy of inorganic solids, John Wiley & Sons.

[26] Srivastava, A. K. and J. Kumar (2013). "Effect of zinc addition and vacuum annealing time on the properties of spin-coated low-cost transparent conducting 1 at% Ga–ZnO thin films." Science and technology of advanced materials 14(6): 065002.

[27] Tanaka, M., et al. (2008). "Measurement and evaluation of tactile sensations using a PVDF sensor." Journal of Intelligent Material Systems and Structures 19(1): 35-42.

[28] Tang, Z., et al. (1998). "Room-temperature ultraviolet laser emission from self-assembled ZnO microcrystallite thin films." Applied Physics Letters 72(25): 3270-3272.

[29] Tiginyanu, I., et al. (2016). "Strong light scattering and broadband (UV to IR) photoabsorption in stretchable 3D hybrid architectures based on Aerographite decorated by ZnO nanocrystallites." Scientific reports 6(1): 32913.

[30] Varnes, A. W. and F. Settle (1997). Inductively coupled plasma mass spectrometry, Prentice Hall: Upper Saddle River, New Jersey.

[31] Visser, J., et al. (1989). Surface acoustic wave filters in ZnO-SiO/sub 2/-Si layered structures. Proceedings., IEEE Ultrasonics Symposium, IEEE.

[32] Wei, D., et al. (2015). "Review of fluorescence suppression techniques in Raman spectroscopy." Applied Spectroscopy Reviews 50(5): 387-406.

[33] Williams, D. B., et al. (2009). "Other Imaging Techniques." Transmission Electron Microscopy: A Textbook for Materials Science: 511-532.

[34] Yamanouchi, K., et al. (1989). SAW propagation characteristics and fabrication technology of piezoelectric thin film/diamond structure. Proceedings., IEEE Ultrasonics Symposium, IEEE.

[35] Zhou, L., et al. (2008). "Piezoelectric film electro-deposition for optical fiber sensor with ZnO coating." Chinese Optics Letters 6(6): 462-464.

[36] Feng, Z. C. (2012). Handbook of zinc oxide and related materials: volume two, devices and nano-engineering, CRC press.

[37] Franklin, A. D. (2015). "Nanomaterials in transistors: From high-performance to thin-film applications." science 349(6249): aab2750.

[38] Gregg, B. A. (2003). "The essential interface: studies in dye-sensitized solar cells." Molecular and Supramolecular Photochemistry 10: 51-88.

[39] Hruska, J. (2014). Stop obsessing over transistor counts: It'sa terrible way of comparing chips, ExtremeTech.

[40] Li, S., et al. (2020). "Recent advances of ferro-, piezo-, and pyroelectric nanomaterials for catalytic applications." ACS Applied Nano Materials 3(2): 1063-1079.

[41] Liang, Z., et al. (2019). "Piezoelectric materials for catalytic/photocatalytic removal of pollutants: Recent advances and outlook." Applied Catalysis B: Environmental 241: 256-269.

[42] Mariano, A. and R. Hanneman (1963). "Crystallographic polarity of ZnO crystals." Journal of Applied Physics 34(2): 384-388.

[43] Moore, G. E. (1965). "Cramming more components onto integrated circuits Electronics Magazine." Electronic resource]. Access mode: https://newsroom. intel. com/wp-content/uploads/sites/11/2018/05/moores-law-electronics. pdf: 4.

[44] O'regan, B. and M. Grätzel (1991). "A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films." nature 353(6346): 737-740.

[45] Shi, Y., et al. (2010). "Polydisperse Spindle-Shaped ZnO Particles with Their Packing Micropores in the Photoanode for Highly Efficient Quasi-Solid Dye-Sensitized Solar Cells." Advanced Functional Materials 20(3): 437-444.

[46] Street, R. A. (2009). "Thin-film transistors." Advanced materials 21(20): 2007-2022.

[47] Wyckoff, R. (1963). "Interscience publishers, new york, new york rocksalt structure." Crystal structures 1: 85-237.

[48] Zhang, Q., et al. (2008). "Aggregation of ZnO nanocrystallites for high conversion efficiency in dye-sensitized solar cells." Angewandte Chemie 120(13): 2436-2440.