# Nickel Oxide (NiO) Devices and Applications: A Review

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***Abstract*- The prospects for using nanomaterials with diameters of <100 nm in number of applications is being widely researched today across multiple domains such as biology, physics, chemistry, cosmetics, optical components, pharmaceutical drug manufacture, polymer science, mechanical engineering, and toxicology. In recent years, nanostructured materials have received steadily growing attention as a result of their peculiar and fascinating properties and applications. The electrical, optical, magnetic, thermal and mechanical properties of materials is often important when materials selection and processing decisions are being made during the design of a device. The applications of Nickel oxide (NiO) today is found in semiconductors, capacitor–inductor devices, tuned circuits, transparent heat mirrors, thermistors and varistors, batteries, micro-supercapacitors, electrochromic and chemical or temperature sensing devices. It is used in preparation of nickel cermet, plastics and textiles, in nanowires, nanofibers and specific alloy and catalyst applications. It is also used as an antiferromagnetic layers, accelerators and radar absorbing materials, aerospace and active optical filters. In this paper, current and future device applications of NiO is reviewed**.

***Key Words*-Nickel Oxide, Device, Applications**

## I. INTRODUCTION

The prospects for using nanomaterials in number of applications is being widely researched today across multiple domains such as biology, physics, chemistry, cosmetics, optical components, pharmaceutical drug manufacture, polymer science, mechanical engineering, and toxicology. In recent years, nanostructured materials have received steadily growing attention as a result of their peculiar and fascinating properties and applications. Among the various nanomaterials, metal oxides (with NiO inclusive) have attracted increasing technological and industrial interest. This interest has mainly to do with their properties (optical, magnetic, electrical, and catalytic properties) associated with general characteristics such as mechanical hardness, thermal stability or chemical passivity (Mohammad and Leila, 2014). Nickel oxide is a prominent example among metal oxides and can be manufactured by thermal decomposition of freshly prepared nickel hydroxife by sol gel route at 300°C (572°F). It has a melting point of $1955^0$C and a density of 6.67g/cm$^3$ (AzoNano, 2013).

Nickel oxide (NiO) is an attractive semiconductor, because its properties are very useful for various photocatalytic, battery, electrochromic and chemical sensing applications (Thomas *et al*., 2014). Nio is also an attractive material for applications in preparation of nickel cermet for the anode layer of solid oxide fuel cells, in lithium nickel oxide cathodes for lithium ion microbatteries, in electrochromic coatings, plastics and textiles, in nanowires, nanofibers and specific alloy and catalyst applications. It is also used as a catalyst and as antiferromagnetic layers, in light weight structural components in aerospace, in active optical filters, in cathode materials for alkaline batteries and materials for gas or temperature sensors, such as CO sensor, H sensor, and formaldehyde sensors (AzoNano, 2013).

Al-Kuhaili *et al.* (2015), deposited Nickel oxide thin films by thermal evaporation and observed the desired properties that are necessary for their utilization in the energy-saving transparent heat mirror multilayer structures. This was manifested by their smooth and dense surfaces that had a sub-nano-meter surface roughness, and oriented crystalline growth. According to Baptiste *et al.* (2016), NiO is used for making electrical ceramics such as thermistors and varistors e.g. ferrites (nickel zinc ferrite), Pigments for ceramic, glasses and glazes. Gold doped nickel oxide films can be used as transparent electrodes in optoelectronic devices.

## II. MICRO-SUPERCAPACITOR

Micro scale supercapacitors enable novel applications in wireless microsensors and microelectronics devices (Richard and Travis, 2011). Jing *Et al.* (2018), proposed a rational design of thin film, flexible micro-supercapacitors with in-plane inter-digital electrodes, where the electrodes were fabricated using the oblique angle deposition technique to grow oblique Ni/NiO nanowire arrays directly on polyimide film. The obtained electrodes are observed to have a high specific surface area and good adhesion to the substrate compared with other in-plane micro-supercapacitors. Meanwhile, the as-fabricated micro-

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supercapacitors have good flexibility and satisfactory energy-storage performance, exhibiting a high specific capacity of 37.1 F/cm$^3$, a high energy density of 5.14 mWh/cm$^3$, a power density of up to 0.5 W/cm$^3$, and good stability during charge-discharge cycles and repeated bending-recovery cycles, respectively as shown in Fig. 2.1. They therefore concluded that, the obtained micro-supercapacitors can be used as ingenious energy storage devices for future portable and wearable electronic applications.

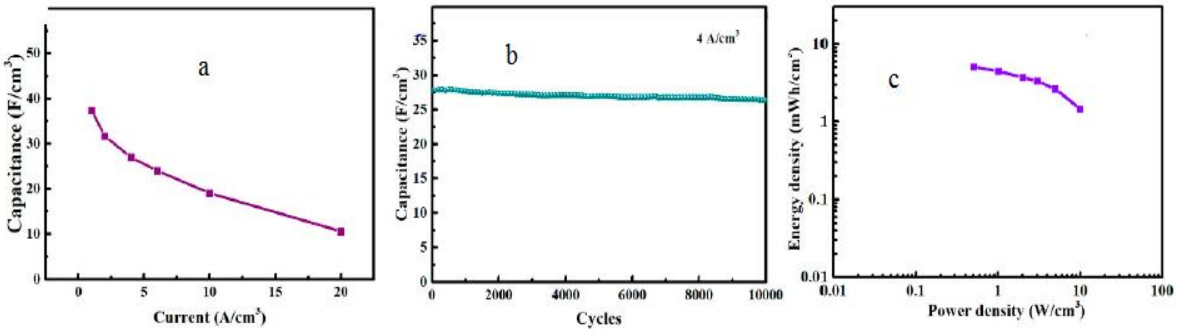

Fig. 2.1: (a) comparison of capacitances of the micro-supercapacitors devices at varied galvanostatic charge-discharge current densities; (**b**) capacitance retention on cycle number at a current of 4 A/cm$^3$; (**c**) energy and powder densities of the micro-supercapacitors devices (Jing *Et al.*, 2018).

## III. DIELECTRIC-BASED DEVICES

A material is classified as “dielectric” if it has the ability to store energy when an external electric field is applied. The dielectric material increases the storage capacity of the capacitor by neutralizing charges at the electrodes, which ordinarily would contribute to the external field (Richard and Travis, 2011). Ahmad *et al*. (2017), in their study highlighted the development of microwave-absorbing material from NZF by adding natural fibres, Oil Palm Empty Fruit Bunch (OPEFB) and polycaprolactone (PCL). They prepared Nickel–zinc ferrite material using the conventional solid-state reaction technique. A Thermal Hake blending machine was used in blending the powder structure of NZF + OPEFB + PCL, which made it homogeneous. The composite was characterised and the effective permittivity and effective permeability was obtained over a broad frequency range from 8 to 12 GHz at room temperature. It was observed that the values of effective permittivity and permeability increased as the content of NZF increased.

Raju and Murphy (2012), reported that, for a composite; nickel–zinc ferrite + paraformaldehyde, increase in the volume of paraformaldehyde decreases the permittivity, permeability, and dielectric and magnetic loss. Such magnetic composites are candidates for capacitor–inductor integrating devices such as electromagnetic interference filters in RF communications. .

Ravi *et al.* (2012), prepared Ni-Cu ferrites of different compositions by a conventional double sintering ceramic technique. They investigated the electrical conductivity of Ni-Cu ferrites of various compositions from room temperature to well beyond the Curie temperature. Composition and frequency dependent dielectric properties of mixed Ni-Cu ferrites have been measured at room temperature in the frequency range 1 to 13 MHz using a HP 4192A impedance analyser. They reported that, among all the ferrites, the composition $Ni_{0.8}Cu_{0.2}Fe_2O_4$ exhibits the highest value of dielectric constant, dielectric loss tangent and complex dielectric constant.

Gaurav *et al.* (2015), studied the improvement in dielectric and optical properties of nematic liquid crystal (NLC) by doping of nickel oxide (NiO) nanoparticles. They observed the dielectric and optical properties of pure and doped cells in order to understand the influence of NiO nanoparticles in the pure NLC. Detailed studies of dielectric parameters such as dielectric permittivity, dielectric loss and dielectric loss factor as a function of frequency with temperature were carried out. It has been observed that on doping the nanoparticles in NLC, the value of dielectric parameters (dielectric permittivity, dielectric loss and dielectric loss factor) decreases.

Hayati (2018), reports on the electrical and nanostructural properties of polymer-based materials in corporation with NiO (Nickel oxide) in weight concentrations of 0.2%, 0.4%, and 0.8% of PVA (polyvinyl alcohol) polymer. The permittivity value of NiO/PVA dielectric is found to be higher than for other presented samples, and therefore, it can be introduced as a good gate dielectric material.

Banerjee *et al., (*2012), synthesized Barium strontium titanate (BST) ceramics $(Ba_{0.6}Sr_{0.4})TiO_3$ by solid state sintering using barium carbonate, strontium carbonate and rutile as the precursor materials. The samples were doped with nickel oxide in different proportions and their dielectric properties are studied. It was observed that the dielectric properties of BST were modified significantly with nickel oxide doping. These ceramics held promise for applications in tuned circuits.
The composite of oil palm empty fruit bunch fiber (OPEFB) which is the waste product of oil palm industry, environmentally friendly polycaprolactone (PCL) and nickel oxide (NiO). The three were fabricated by compounding all materials in the Thermo Hake blending machine by Ahmad *et al*. (2015). The dielectric properties of the substrates were measured using open ended coaxial method for microwave frequency range between 0.2 MHz and 20 GHz. The results reveal that the permittivity values of the composite can be tuned by changing the ratio of OPEFB/PCL/NiO prior to

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compounding and blending. These composites may offer alternatives to Teflon, which is made primarily from petroleum, for applications in radio and communications, especially in the fabrication of antennas, transmission and other microwave components.

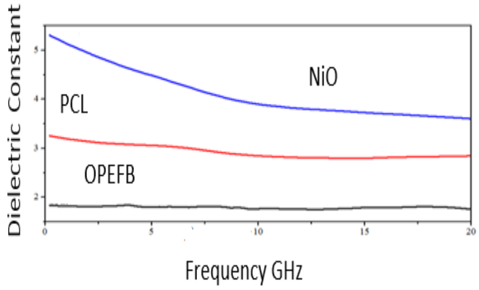

Fig. 3.1: Dielectric constant for pure OPEFB, PCL and NiO

Fig. 3.1 and 3.2 show the variation in dielectric properties of pure OPEFB, PCL and NiO. It can be observed that NiO exhibit the highest dielectric constant and loss factor while OPEFB exhibit the lowest dielectric constant and loss factor (Ahmad *et al.*, 2015).

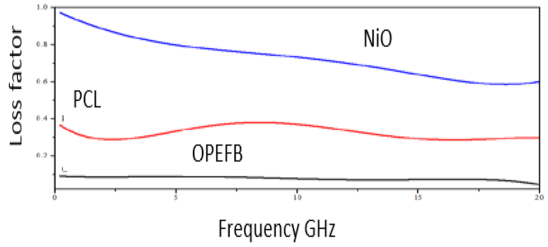

Fig. 3.2: Loss factor for pure OPEFB, PCL and NiO

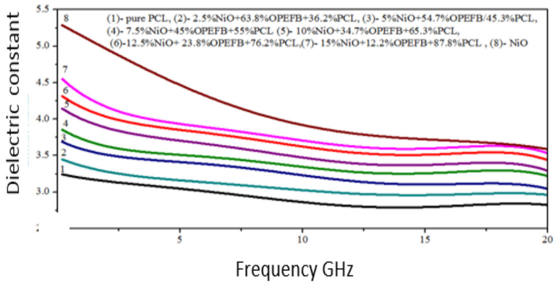

Fig. 3.3: Dielectric constant for OPEFB/PCL/NiO substrate (Ahmad *et al.*, 2015).

In Fig. 3.3, it can be clearly observed that the dielectric constant of all composites decreases as frequency increases. Likewise in figure 3.4, it can be observed that the loss factor decreases with increasing frequency (Ahmad *et al.*, 2015).

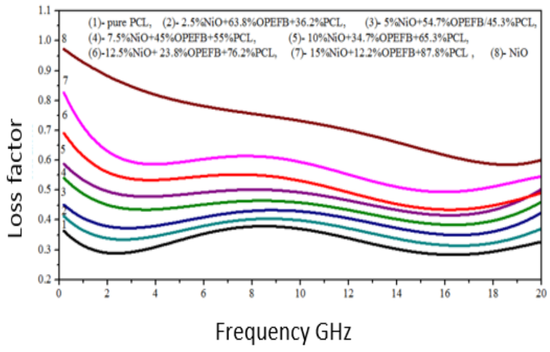

Fig. 3.4: Loss factor for OPEFB/PCL/NiO substrate (Ahmad *et al.*, 2015).

## IV. ELECTROCHROMIC DEVICES (ECDS)

Electrochromism refers to the persistent and reversible change of optical properties of a material by an applied voltage pulse. Electrochromic (EC) devices have been extensively studied because of their commercial applications in smart windows of green buildings, display devices and thermal control of equipment. Electrochromic (EC) devices are able to control the throughput of visible light and solar radiation into buildings and control energy efficiency by modulating optical transmittance (Busra, 2017). EC devices are also applied in smart windows of green buildings, full-angle information displays, controlled reflectance mirrors and thermal control of satellites. Electrochromism refers to the phenomenon that the optical properties can be switched reversibly and persistently in materials induced upon a small external voltage (Zhou *et al.*, 2017).

A considerable amount of studies has been recently reported on NiO as a counter electrode for NiO/ $WO_3$ electrochromic applications (Patel, *et al.*, 2016). Pilban-Jahromi, *et al.* (2012), reported that NiO is an anodically coloring inorganic material, in oxidized state, the color of NiO turns to dark bronze and colourless in the reduced state.

The most commonly used anodic oxide-based Electrochromic (EC) materials are Ni and Ir oxide. These oxides can both change from a transparent state to a neutral colored one upon extraction of protons or insertion of OH– ions. Ir is limited to use due to its high cost and limited supply. Hence, Ni oxide has been studied extensively because of its high optical modulation, fast switching speed, good cyclic stability, memory effect and low cost. Furthermore, NiO can also be ion storage films in the standard EC device, which have the color overlay or complementary effect. It is widely accepted that the EC performance of NiO is attributed to the injection/extraction of electrons and cations, which strongly depend on the diffusion length of ions and the appropriate surface area (Zhou *et al.*, 2017).

Michelle *et al.* (2016), fabricated two electrochromic NiO materials through a similar electro-deposition technique, apart from different lower depositing potentials, on a conductive ITO substrate. They realised that, the electrochromic capabilities of the two NiO materials are encouraging. The coloration efficiency for deposition

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process 1 and deposition process 2 are 49 and 17 cm$^2$ C$^{-1}$, respectively while the switching time for deposition 1 for coloration and bleaching is 5.7/7.4 seconds.

NiO played a vital role in EC but there are still difficulties in commercial applications of NiO as promising EC materials due to its slow switching speed, low color contrast and poor cycling durability. Hence, it is important to design a material with nanostructure to obtain fast insertion kinetics and enhanced durability.

## V. MICRO-BATTERIES AND NANO-ELECTRONIC DEVICES

Lalithambika *et al.* (2016) constructed NiO nano wire devices with gold and platinum electrodes and studied the effect of the electrodes in the transport properties. Apart from the pristine NiO nano device, Fe and N atoms are substituted in the device and their effects are also studied. From the obtained results, gold electrode devices are having better performance than the platinum electrode devices. The transmission and PDOS spectra of the gold electrode NiO nano devices shows that N doped NiO nano device is performed well than the other two NiO nano devices with gold electrodes. In the case of platinum electrode NiO nano devices, the Fe doped NiO nano device shows better performance than the other two devices.

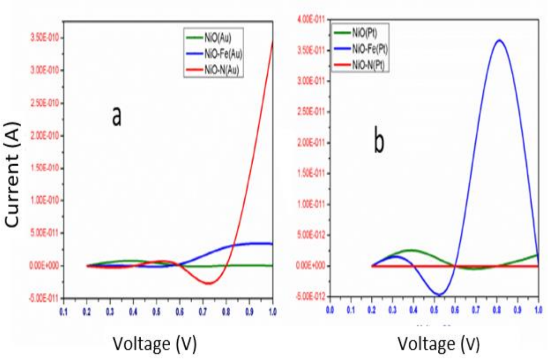

Fig. 5.1: V-I characteristics of (a) NiO nano device with golden electrodes and (b) NiO nano device with platinum electrodes (Lalithambika *et al*., 2016).

The V-I characteristics of the NiO nano devices with gold atoms in Fig. 5.1(a) give the current in the order of 10$^{-10}$ amperes whereas the platinum NiO nano devices show the current in the order of 10$^{-12}$ amperes in Fig. 5.1(b) (Lalithambika *et al*., 2016). The composites can therefore serve as good electrodes and hence useful in manufacturing micro-batteries.

Jason *et al.* (2007), synthesized high-definition metal–oxide–metal (MOM) heterojunction nanowires in the Au–NiO–Au system using a template-based method. These nanowires are 70 nm in diameter and 7µm in total length, with a 100 to 300 nm wide NiO segment sandwiched between the Au nanowires axially. These Au–NiO–Au nanowires have been incorporated into high-quality single-nanowire devices, fabricated using a direct-write method. The current–voltage (I–V) responses of individual Au–NiO–Au nanowires have been measured as a function of temperature in the range 298 to 573 K. From figure 5.2, the I– V response at room temperature has been found to be nonlinear, it becomes more linear and less resistive with increasing temperature. These types of MOM nanowires are likely to offer certain advantages over all-oxide nanowires in fundamental size-effect studies, and they could be potentially useful as nanoscale building blocks for multifunctional nanoelectronics of the future.

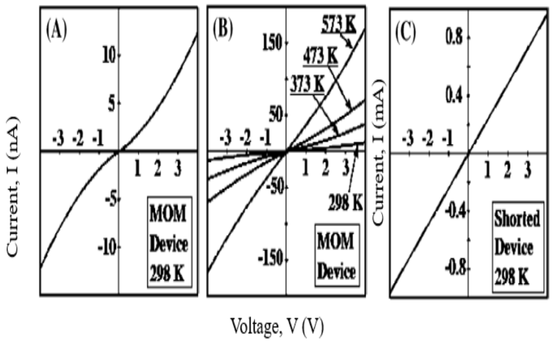

Fig. 5.2: I–V responses from the device pictured in Fig. 5 at: (A) 298 K and (B) at 298 K, 373 K, 473 K, and 573 K. (C) I–V response from the shorted device at 298 K. Note the vastly different ordinate (I) scales in the top [(A) and (B)] and the bottom (C) plots (Jason *et al*., 2007).

## VI. GAS SENSORS

Irudaya *et al.* (2016), prepared pure and Li doped NiO nanoparticles by a cost-effective sol-gel method. All the samples exhibit cubic structure. Photoluminescent emission spectra reveal the blue shift exhibited by the synthesized nanoparticles. Hence these Li doped NiO nanoparticles can be used for catalytic and gas sensor applications.

Nanocomposite NiO:Au thin films, formed by gold nanoparticles embedded in a nickel oxide matrix, have been grown by reactive pulsed laser deposition (R-PLD). The NiO:Au nanocomposites have been tested as hydrogen sensors. Embedding Au nanoparticles into the NiO film matrix reduced the sensors operating temperature and improved their performance by orders of magnitude as shown in figure 6.2 (Fasaki *et al*., 2018).

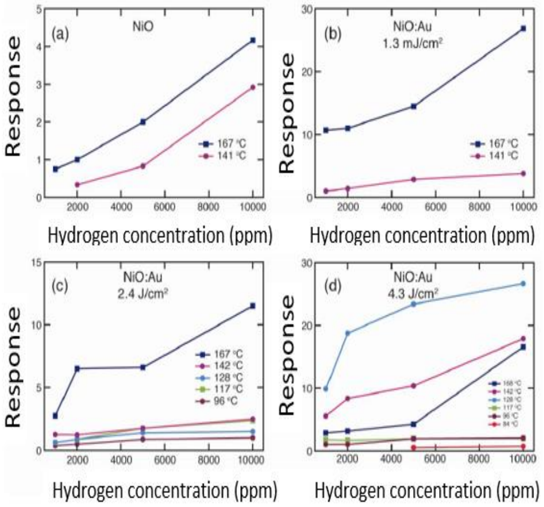

Fig. 6.2: Summary of sensing results for all temperatures and hydrogen concentrations in air, obtained (a) with the reference NiO sample, (b) with NiO:Au nanocomposite with 15.6wt% Au concentration (1.3 J/cm$^2$ laser fluence), (c) with NiO:Au nanocomposite with 23.5wt% Au concentration (2.4 J/cm$^2$ laser fluence), and (d) with NiO:Au nanocomposite with 44.4wt% Au concentration (4.3 J/cm$^2$ laser fluence) (Fasaki *et al*., 2018).

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## VII. MICROWAVE ABSORBERS

The use of materials for microwave absorption is a topics of interest to various scientific communities. Among those interested in special materials are accelerator builders, microwave tube experts, fusion device builders and materials scientists from various areas of technology.

In their effort to determine the microwave absorbing properties of NiO and $Co_{0.2}Ni_{0.4}Zn_{0.4}Fe_2O_4$ Ferrite Composites, Pei-Jiang *et al*. (2018), prepared hierarchical spherical NiO particles by using a hydrothermal method, and synthesized CNZF ferrites by using a sol–gel auto-ignition method. Electromagnetic and microwave absorption properties of these samples were systematically studied. Due to the high impedance matching characteristic, large attenuation capability, and well-coupled layer, the double-layer absorbers, with the CNZF composite as the absorption layer and NiO composite as the matching layer, showed promising reflection loss (RL) values, wider absorbing bandwidths, and smaller thicknesses, as compared with the individual single-layer absorbers. With the optimal total thickness of 3.2 mm, the absorber exhibited a maximum RL value of –67.0 dB at 9.2 GHz. It is believed that these new double-layer absorbers could be promising candidates as advanced microwave materials for various practical applications.

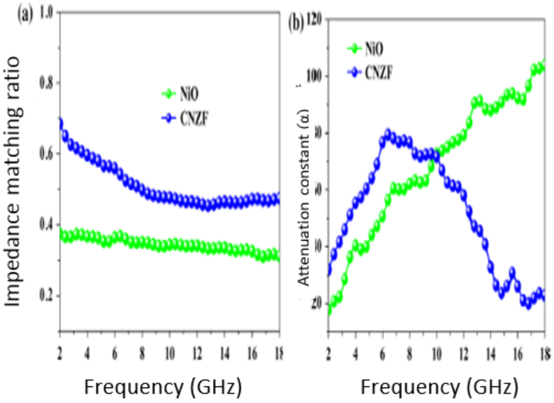

Fig. 7.1: (a) Impedance matching ratio, (b) attenuation constant (α) of the NiO and CNZF composites (Pei-Jiang *et al*, 2018).

Fig. 7.1(a) illustrates the impedance matching ratios of the NiO and CNZF composites. As observed, CNZF has a more suitable impedance matching ratio over the whole frequency region (2–18 GHz), as compared with the NiO sample. In fact, the impedance matching ratios of both the NiO and CNZF samples are higher than 0.3. As shown in Fig. 7.1(b), the attenuation constant (α) indicates an integral loss effect including dielectric loss and magnetic loss, which is given in equation (1) (Pei-Jiang *et al*, 2018).

$$\alpha = \frac{\sqrt{2\pi f}}{c} \mathrm{X} \sqrt{(\mu''\varepsilon'' - \mu'\varepsilon') + \sqrt{(\mu''\varepsilon'' - \mu'\varepsilon')^2 + (\mu'\varepsilon'' - \mu''\varepsilon')^2}} \qquad (1)$$

Ravindra *et al*., (2017) synthesized $Ni_{0.}2Co_{0.3}Zn_{0.5}Fe_2O_4$ ferrite nanoparticle and PANI/ $Ni_{0.}2Co_{0.3}Zn_{0.5}Fe_2O_4$ ferrite nanocomposite by sol-gel auto combustion method and in situ polymerization method. They studied the electromagnetic properties of the composite and reported that, the composite exhibits excellent absorption performance over a broad band range in the radar band with good electromagnetic properties. PANI/ $Ni_{0.}2Co_{0.3}Zn_{0.5}Fe_2O_4$ nanocomposite improves electromagnetic properties compared with PANI or ferrite.

Shown in Fig. 7.2(A) and 7.2(B), the minimum value of reflection loss was -14.40dB at the 18GHz frequency for $Ni_{0.2}Co_{0.3}Zn_{0.5}Fe_2O_4$ nanoparticles of thickness 3.0mm and -22.58dB at 18GHz frequency for PANI/$Ni_{0.2}Co_{0.3}Zn_{0.5}Fe_2O_4$ nanocomposite of thickness 3.0mm. So microwave absorption is increased with PANI (Ravindra *et al.*, (2017).

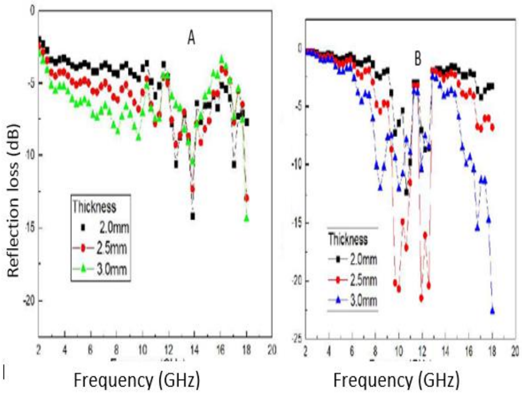

Fig. 7.2: Absorption characteristics of (A) $Ni_{0.}2Co_{0.3}Zn_{0.5}Fe_2O_4$ ferrite nanoparticles and (B) PANI/ $Ni_{0.}2Co_{0.3}Zn_{0.5}Fe_2O_4$ ferrite nanocomposite

## VIII. SOLAR CELLS

There is need for affordable, clean, efficient, and sustainable solar cells. Photovoltaic (PV) cells employ the semiconducting materials to covert the light into electricity when exposed to light (Jeon, *et al*., 2015). Kingsley *et al.* (2018), fabricated Metal oxide $TiO_2$/NiO heterojunction solar cells using the spray pyrolysis technique. The optoelectronic properties of the heterojunction were determined. The fabricated solar cells exhibit a short-circuit current of 16.8 mA, open-circuit voltage of 350 mV, fill factor of 0.39, and conversion efficiency of 2.30% under

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100mW/cm$^2$ illumination. Therefore, their study will help advance the course for the development of low-cost, environmentally friendly, and sustainable solar cell materials from metal oxides. Fig. 8.1 depicts generation of electricity by a solar cell using a P-N junction.

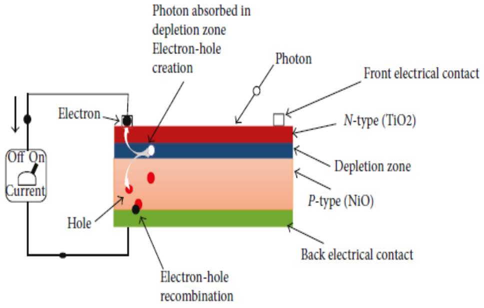

Fig. 8.1: Solar cell generation of electricity using a P-N junction (Kingsley *et al.*, 2018)

## IX. THIN FILM TRANSISTORS (TFTS)

Thin film transistors (TFTs) take place commercially in today's technology, such as flat panel displays, smart phones and computers (Kasap and Rowlands, 2000). These devices facilitate the advancing of video system technology by enabling the large dimension displays (Liao *et al*., 2005). They are most commonly utilized as the pixel switching components in flat panel displays (Kuo and Nominanda, 2006). Additionally, this technology finds several applications apart from the display technologies, such as X-Ray detection, microelectronic devices (memories), chemical sensors and bio-chemical sensors (Estrela and Migliorato, 2007).

TFTs are kind of field effect transistors principally containing three terminals (source, gate and drain) and including semiconducting, conducting and dielectric layers. The semiconducting material is located between source and drain terminals; whereas, the dielectric one is placed between the semiconducting material and the gate (Li *et al*., 2016).

NiO is a promising material to fabricate low cost p-type oxide TFTs. Solution-based processing techniques are rather attractive than vacuum-based processes due to their simplicity, low cost and high quality films. Solution-processed NiO based p-type TFTs have been reported many times (Liu *et al*., 2016). The schematic representation of cross sectional solution-processed NiO based p-type TFT structure is provided in Fig. 9.1.

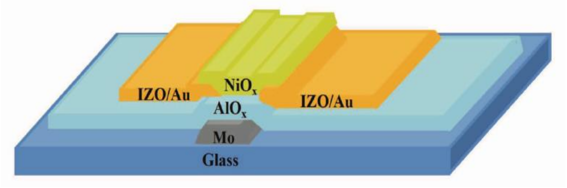

Fig. 9.1: Schematic cross-section of solution-processed NiO based TFT with a bottom-gate bottom-contact structure. NiOx based active layers and the AlOx gate insulator are deposited by spin coating (Li *et al*., 2016).

## X. INDUCTORS

Inductor is one of the basic electronic components having a wide variety of applications in various electronic circuits like oscillators, filters, transmitters etc (Richard and Travis, 2011). Raju and Murthy (2012), using the mechanical milling process have successfully synthesized a series of nano-composites of nickel–zinc ferrite paraformaldehyde. They reported that, with the increase in the volume of polymer, the permittivity, permeability, and dielectric and magnetic loss of all the composites decreases. The permittivity and permeability of all the composites have shown good frequency stability and low dielectric and magnetic losses within the measurement range. Such magnetic composites are candidates for capacitor–inductor integrating devices such as electromagnetic interference filters in RF communications.

Figure 10.1 shows the magnetic hysteresis curves of the composites under applied magnetic field at room temperature. The magnetization of PFD + NiZn ferrite nanocomposites exhibited a clear hysteretic behavior, and the area within the hysteresis loops was increased with increase in the ferrite content.

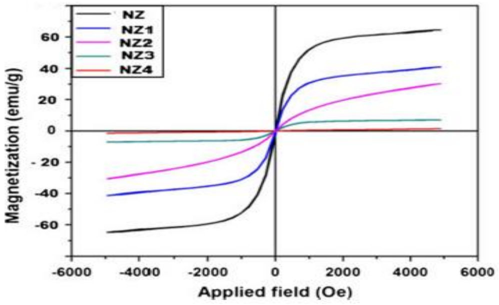

Fig. 10.1: VSM loops of x PZF + (1 - x) NZF (0 ≤ x ≥ 1) nanocomposites

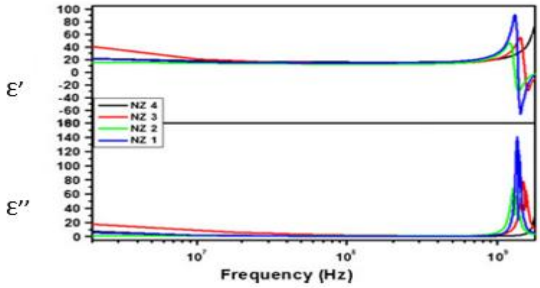

Fig. 10.2: Frequency dependence of real and imaginary parts of permittivity of x PZF + (1 - x) NZF (0 ≤ x ≥ 1) nanocomposites

Fig. 10.2 shows the variation of the real (Ɛ') and imaginary (Ɛ'') parts of permittivity with frequency at room temperature for all composites. It can be observed that the values of Ɛ' and Ɛ'', increase with increasing ferrite content in composites, but are lower than those of the pure ferrite (NZ 1) (Raju and Murthy, 2012).

## XI. CONCLUSION

In recent years, nanostructured materials have received steadily growing attention as a result of their peculiar and fascinating properties and applications. In our contemporary

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era, sophisticated electronic devices rely on components that are made from what are called semiconducting materials. The good electrical, optical, magnetic, thermal and mechanical properties of NiO paved way to its applications in semiconductors, nickel cermet for the anode layer, batteries and solar cells, electrochromic devices, plastics and textiles, nanowires and nanofibers, antiferromagnetic layers, light weight structural components in aerospace, active optical filters, gas or temperature sensors, transparent heat mirrors, thermistors and varistors, glasses and glazes, optoelectronic devices, capacitors and supercapaciotrs, inductors, electromagnetic interference filters, antennas, tuned circuits, accelerators and radar absorbing materials.

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