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A review on photonics and its applications

Kirubel Amsalu, Sivaprakasam Palani *

Department of Mechanical Engineering, College of Electrical and Mechanical Engineering, Addis Ababa Science and Technology University, Addis Ababa, Ethiopia

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ABSTRACT

Photonics technology plays a vital role in various fields, such as manufacturing, biomedical, alternate energy sector, aerospace, telecommunications, etc. It generates and controls light in the form of radiant energy as photon. The light can be manipulated or molded using band gaps in photonic crystals. There are many materials that can be integrated to further the application of photonics. The common material is Graphene, which is a single atom carbon. Application areas of the technology include LEDs, photo detectors, photovoltaic devices, etc. This article presents the review of state of the art of photonics and its application.

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1. Introduction

The term photonics was obtained from the word photon, denoted by tiniest entity of light. Photonics involves generation, detection and manipulation of the signal [8]. It is a technology for generating and control of light as well as radiant energy in the form of quantum unit as photon.

Semiconductor technology has vital role in technology development for miniaturization and high speed performance of integrated circuits. Unfortunately, miniaturization of components / parts in circuits needs high level of power dissipation, resistance, and higher speeds. This could be directed to a greater sensitivity to signal synchronization. In an effort to further the progress of high-density integration and system performance, scientists are now returning to light instead of electrons as the information carrier [9,10]). Refs. [9,10] highlighted the advantages of light over electrons; it has the ability to move faster in dielectric materials compared to electrons moves in metallic wire, which leads to transmit the information at large amounts per second. The dielectric materials have higher bandwidth compared to metals. The bandwidth of fiber-optic communication systems is about one terahertz, however electronic systems such as telephones are only few hundreds kilohertz. In addition, photons are not as interacting as electrons, which help reduce energy losses. Ref. [19], mentioned that the field of photonics is at its young stage, stated that the term "photonics" itself was coined in analogy to electronics. The main difference in this two terms was discussed as electronics involves the control of electric-charge flow (in vacuum or in matter) while Photonics involves the control of photons (in free space or in matter) [23]. This description clearly shows that there exists an overlap between the disciplines. This could be electron controls the flow of photons and vice versa. It also reflects the importance of the photon nature of light for relating the many optical devices' operation [19]. The photonic technologies having great potential for economic impact for next decades and the predicted growth rate of 25% approximately by various industrial organizations. It has 650 ($CDN) billion global industry according to a study by CPIC [22] and projected to have market value of more than €600 billion in 2020.

Photonics technology was widely used for different applications such as laser, optics, fiber-optics, opto-electrical devices, alternative energy, healthcare, telecommunication, aerospace and many more. The crucial parameter in the application of nanophotonic devices is the source of power. Ref. [23], suggested that solar based source power has promising devices for cheaper and large scale energy conversion in solar cells. It is also possible to incorporate the miniaturized version into nanophotonic systems as integrated power sources to form a self-powered system. The nano scale photonic devices can effectively focus the optical field into a nanometer-sized volume have many application requires the tight confinement of optical fields including information and communication technologies, sensors, and enhanced solar cells and lighting [21]. The photonics technologies lead to discovery of new optoelectronics devices, which is energy efficient, better performances and low cost. This could be achieving by manipulation of photons in semiconductor and bulk crystals in LED and Lasers. Now a day's

* Corresponding author.
E-mail address: shiva_au@rediffmail.com (S. Palani).

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optical computers, computers use the crystals and meta-materials. The control of pulse and light could at sub micrometer volumes achieved by nano wire photonics. The graphene photonics devices are more efficient in transparent conductors than semiconducting materials due to low sheet resistance and high transparency. Another application of photonics in medical imaging, Optical Coherence Tomography (OCT) techniques has high resolution of three dimensional images with non-invasive treatment for brain tumors. Photonic sensors and systems are used for intelligence, surveillance, and reconnaissance. The photonic communication was used for transporting terabits of information. Most of industrial machine application especially computer numerical control machine could equipped with online monitoring and inspection and measurement. This paper was addressed much industrial application of photonics. Hence comprehensive of review needed for application of photonics in various fields such as manufacturing, biomedical, alternate energy sector, aerospace, telecommunications. This paper focused on comprehensive review of photonics, advancement in photonics and its application.

2. Photonic crystals

Photonics utilize the advantages of photonic energy. Photon energy defined as the energy carried by a single photon. This energy can be calculated using Eq. (1). The higher energy of photons depends on photons frequency whereas lower energy can be with longer photons wavelength.

$$E = hc/\lambda \tag{1}$$

where h is the Planck constant, c is the speed of light in vacuum and λ is the photons wavelength. Therefore, after realizing the concept of light energy it is a must to know how light energy is manipulated and controlled. Photonic crystals are the solutions. In simple terms, the idea of photonic crystal is to design materials so that they can affect the properties of photons, which has similar affect in ordinary semiconductor crystals for electron properties [9,10]. The orthodox way of manipulating optical photons has relied on the mechanism of total internal reflection. Ref. [24] stated that when light come across an interface in lower index of refraction, the light gets refracted to some extent due to the angle of incidence and beyond a certain critical angle. This helps in total internal reflection (TIR). Light pipes, optical waveguides and fiber optics depends on this phenomenon could efficiently transport light with minimal loss.

Ref. [9,10] stated that light propagating through high-dielectric material can be reflected at the boundary with a low-dielectric material. This could limit miniaturization of optical components. Miniaturization of optical components must have smooth interface regarding to wave length of the light. Photonic crystals use the concept of bandgap to defeat this problem. Similarity on the analogy between electronic bandgap of semiconductors and photonic bandgap can be driven.

In a semiconductor, the atomic lattice represents a periodic potential to an electron propagating through the electronic crystal. In photonic crystals, the periodic "potential" is due to a lattice of macroscopic dielectric media instead of atoms [9,10]. In addition to that photonic crystals are materials patterned through dielectric constant, which can make a range of banned frequencies called a photonic bandgap the optical analogue of electronic bandgap in semiconductors.

The photons cannot propagate the medium due to bandgap. A defect could lead to localized photonic states in the gap. Based on the nature of defect the photonic shapes and its properties can be determined. Using any dielectric constant the defect in photonic crystal can be achieved in any shape, size. Thus, photonics defect states in band gap could change to any frequency and spatial extent of design interest [9,10]. Micro cavity, wave guide and perfect mirror can be obtained by point defect, line defect and line defect respectively. Photonic defects can provide the chance to shape and mold the flow of light for photonic information technology. Intricate structures of photonic crystals could be fabricated by lithography techniques such as electron beam lithography and X-ray lithography [9,10].

2.1. Photonic bandgap

In theoretical perspective, the explanation of light must involve the solution of Maxwell's equation, Eq. (2), in a periodic dielectric medium. Normally photons do not interact with each other hence; the equation will be a standard single particle problem. This inferred that the theoretical computations can give very precise predictions and descriptions of photons. Morales [14] discussed that Maxwell's equation, in the absence of external currents and sources, can be cast in a form which is reminiscent of the Schrodinger equation that is

$$\left\{\nabla \times \frac{1}{\in(\mathrm{r})}\nabla\times\right\}\mathrm{H(r)} = \frac{\omega^2}{\mathrm{c}^2}\mathrm{H(r)} \tag{2}$$

where H(r) is the magnetic field of the photon, ∇ is the photon's frequency, c is the speed of light and $\in(r)$ is the macroscopic dielectric function. For constructing a periodic array of macroscopic dielectric atoms, the photons in this crystal can be expressed in terms of a band structure [9,10].

2.2. Photonic cavity

As discussed above, it is possible to trap light at a point within the crystal. One of the methods involves changing the dielectric medium in some local region of the crystal. For instance, a change can be made to a single 'dielectric atom' by modifying its dielectric constant, by modifying its size or simply removing it from the crystal. Fig. 1 shows the consequence of creating a vacancy; where a vacancy is a defect with radius of $r = 0$. Hence, by removing a rod from the lattice, a cavity was created which is enclosed by reflecting walls.

If the defect involves the removal of dielectric (an 'air defect' as in the case of the vacancy) as shown in Fig. 1, then the cavity mode progress from the dielectric band leads to sweep across the gap by changing the amount of dielectric removed. Similarly, if the defect gets the addition of extra dielectric material (a 'dielectric defect') then the cavity mode drops from the air band. Apart from tuning the frequency, it is also possible to control localized photonic state at symmetry level. For instance, Fig. 2 shows the symmetries of the localized photon mode for three different values of defect radius.

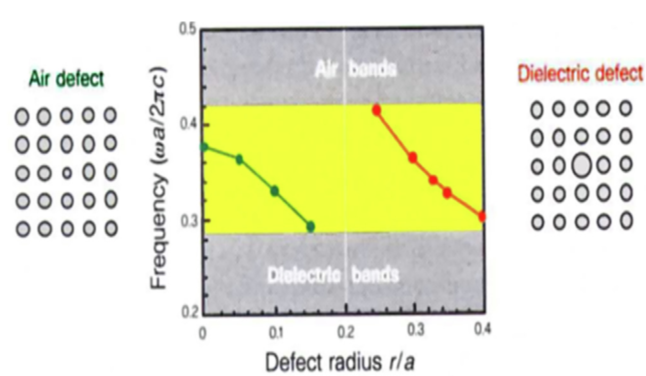

Fig. 1. Air defect and Dielectric defect. Figure reproduced with permission from: ref. [3], © 2019 Springer Nature.

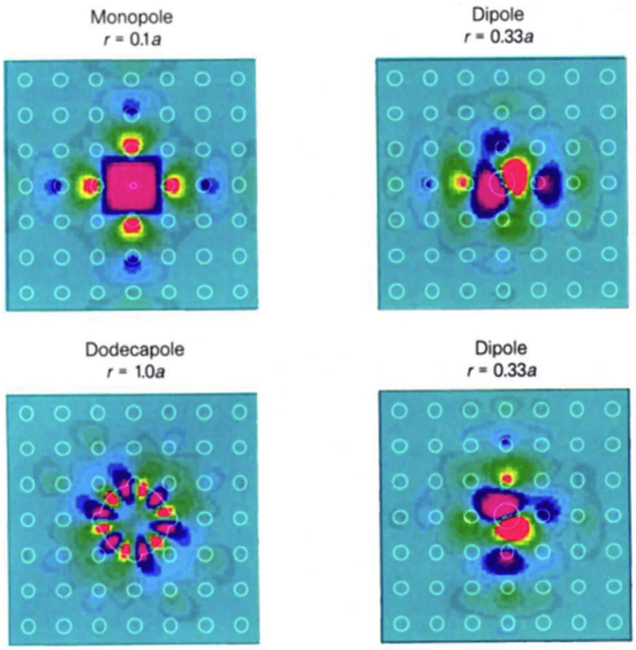

Fig. 2. Localized states in the gap for a defect formed by varying the radius *r* of a single rod. Figure reproduced with permission from: ref. [3], © 2019 Springer Nature.

3. Nanowire photonics-application

Yan [23], explained the development of semiconductor nanostructures which is known as nanowire. Another well-known semiconductor microstructure, with tunable optical properties, is quantum dots. When the quantum dot size decreases, quantum confinement leads to increased band gap. This could help blue shifted light emission which is emission of light with shorter wave length or increased energy. However, the development of nanostructures with cross sections of 2–200 nm allowed confinement to 2D, therefore, electron and photons can freely propagate along the third dimension (Fig. 3).

Nanowire semiconductor microstructures are prepared by bottom up approach and this process may require highly controlled synthesis of 1D structure, single-crystalline, high-optical-quality materials. Vapors–liquid–solid (VLS), process promotes the seeding and growth by introduced catalytic liquid alloy phase could adsorb a vapor to super saturation levels. The large quantity of various nanowires for semiconductor can be produced by VLS. Furthermore, Morales and Lieber [14] discussed recent advances in both physical (laser ablation and thermal evaporation) and chemical deposition techniques (chemical vapor transport and deposition, and metal-catalyzed molecular beam epitaxy). These techniques could be effectively used for production of wide range of inorganic nanowire compositions such as Si, Ge, ZnO, CdS, GaN, GaAs and InP. When developing optical computers, computers which utilize crystals and meta-materials to control light and manipulate pluses within sub micrometer volumes are more important [23]. In addition, nanowires represent an important class of photonic building blocks. They can be processed either by chemically synthesizing or using latest lithography techniques. Although nanowires fabricated using lithography techniques have their own features, chemically grown nanowires possess unique advantages of being single crystalline, relatively defect free, having atomically smooth surfaces and being able to accommodate large atomic mismatches.

4. Graphene photonics and optoelectronics

Graphene is two dimensional, thinnest and strongest materials in the universe [4,5]. In addition, its charge carriers show giant inherent mobility, optical transparent, zero effective mass, and can travel for micrometers without scattering at room temperature. It has high electrical current, intrinsic property, lower resistivity than any other material known at room temperature. It is also stronger than diamond with a weight of less than a paper. It represents a theoretically new class of materials that are only one atom thick [5]. Due to these fascinating properties, graphene has earned the title "Wonder Material". True potential of graphene can utilize in photonics and optoelectronics application and mainly combination of its optical and electronic properties can fully be exploited [1]. All optical circuits yet to be commercialized at large scale due to abundant advantages of photons. Some hybrid optoelectronic circuits have produced with significant improvement in performance of electronic circuits. The main difficulty for designing a multipurpose optical component analogous has limited development of all optical systems [9,10]. Localization properties of defects creates the photonics crystal very attractive medium for design of novel type filter couplers, lasers and light - emitting diodes. In the case of laser or LED cavities, photonic crystals provide a particularly unique capability- the control of spontaneous emission [9,10]. Spontaneous emission, as in Fig. 4, is the natural tendency for an excited atom to "fall" to a state of lower energy while releasing its energy in the form of emitted radiation [9,10]. It is also an emission where an excited atom or molecule decays to the ground state and emits a photon. This process is found in every light emitting device used in the optoelectronic industry.

LEDs, for example, emit light from the radiative recombination of electrons and holes in a forward-biased p-n junction. Moreover, by increasing the applied voltage, the number of electron-hole pairs in the junction region can become sufficiently large for

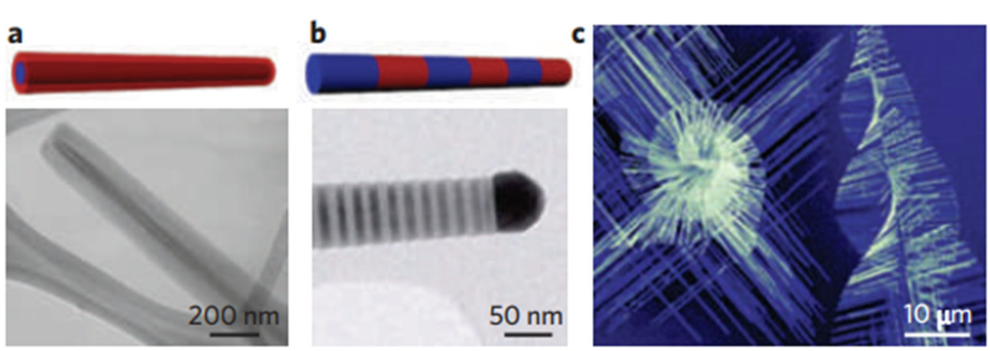

Fig. 3. (a) TEMimage of a GaN/AlGaN core– sheath nanowire. (b) TEM image of an InP super-lattice nanowire. (c) SEM image of highly branched PbS nanowires. Figure reproduced with permission from: ref. [5], © 2019 Springer Nature.

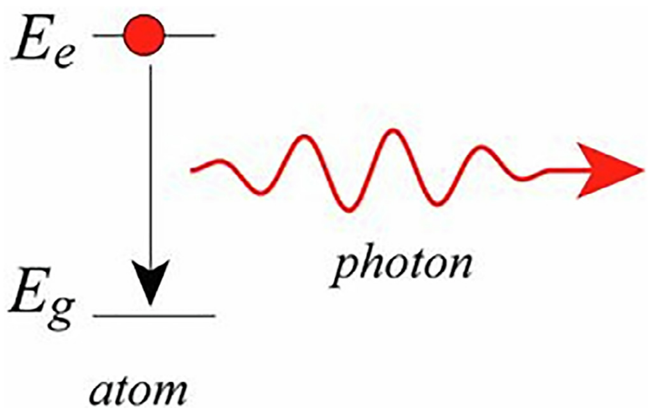

Fig. 4. Decay of an atom while releasing a photon of energy.

stimulated emission i.e. emission stimulated by other photons [9,10]. The rate of spontaneous emission of a given initial state is proportional to the density of the final states available at the transition frequency, and to the square of a matrix [9,10]. In other ways it is affected by changing the density of allowed states [8], which is shown in Fig. 5. The free-photon Density of States (DoS) per unit volume, Df, can be expressed as Eq. (3). Where ωthe frequency of the transition and λ is is the wavelength of light.

$$D_{f\approx\frac{1}{\omega}\frac{1}{\lambda^{3}}} \tag{3}$$

4.1. Transparent conductors

Most optoelectronic devices such as display touch screens, light emitting diodes (LEDs) and solar cells require materials with low sheet resistance and high transparency. Graphene is compared with doped semiconductors on parameters such as low sheet resistance and high transparency relative to thickness and wavelength show in Fig. 6.

4.2. Photovoltaic (PV) devices

Chapin [3] described photovoltaic (PV) cell converts light into electricity. The fraction of absorbed photons converted to current defines the internal photocurrent efficiency (IPCE). While current PV technology is dominated by Si cells, Fig. 7a, Green et al. [6], stated the efficiency to be up to 25%. Different types of photovoltaic devices shown in Fig. 7(a–e). Hoppe and Sariciftci [7], highlighted Organic Photovoltaic cells (OPVs), Fig. 7b, which have lower efficiency than Si cells, rely on polymers for light absorption and charge transport. And Krebs [12] discussed the manufacturing technique using roll-to-roll process. Fig. 7c represents Dye-synthesized solar cells (DSSC). According to Oregan [15]. DSSCs use a liquid electrolyte as a charge transport medium. In addition, it consists of a high porosity nano-crystalline photo anode, comprising TiO2, and dye molecules deposited on a transparent conductors (TC). When illuminated, the dye molecules capture the incident photon generating electron/holes pairs. The electrons are injected into the conduction band of the TiO2 and transported to the counter electrode, the cathode. Regeneration of dye molecules is accomplished by capturing electrons from a liquid electrolyte.

4.3. Light-emitting devices

Organic light-emitting diodes (OLEDs) Fig. 7d consists of an electroluminescent layer between the charge injecting electrodes and one electrode should be transparent. OLEDs used for ultrathin television, display screen because of image quality, ultrathin device structure and lower power consumption [2].

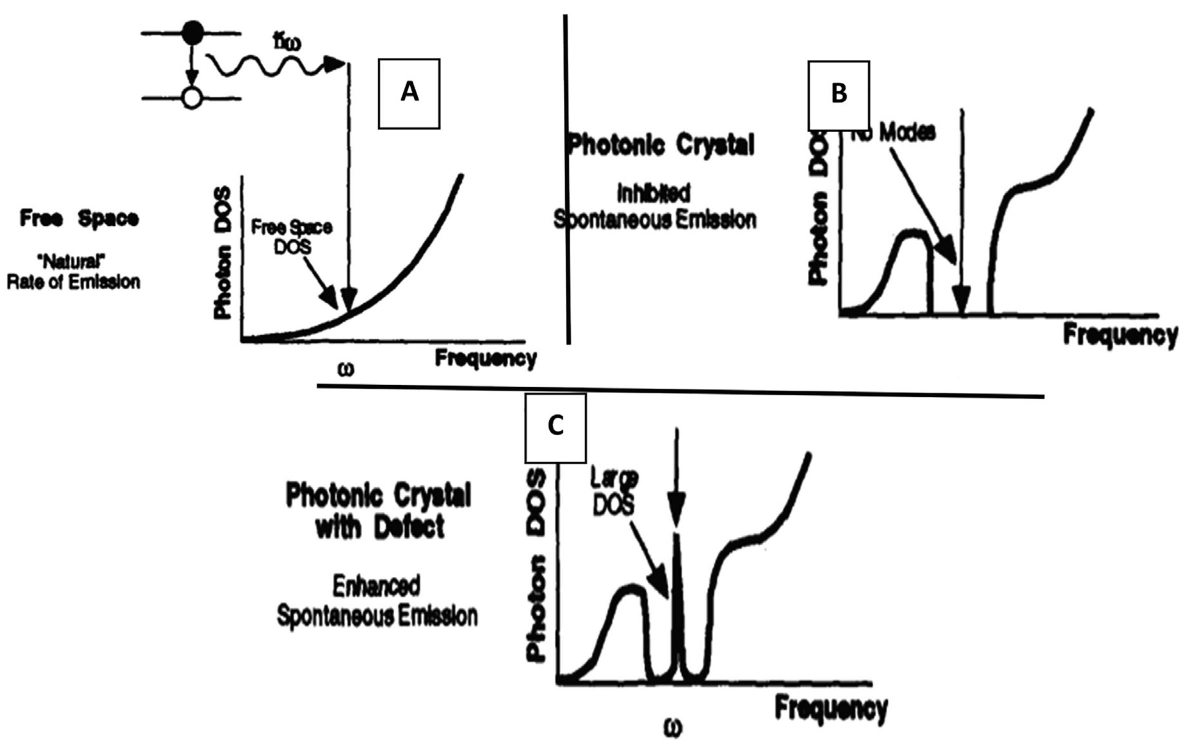

Fig. 5. Density of states (A) free space (B) a photonic crystal (C) a photonic crystal with a local defect Figure reproduced with permission from: ref. [9], © 2019, Solid State Communications.

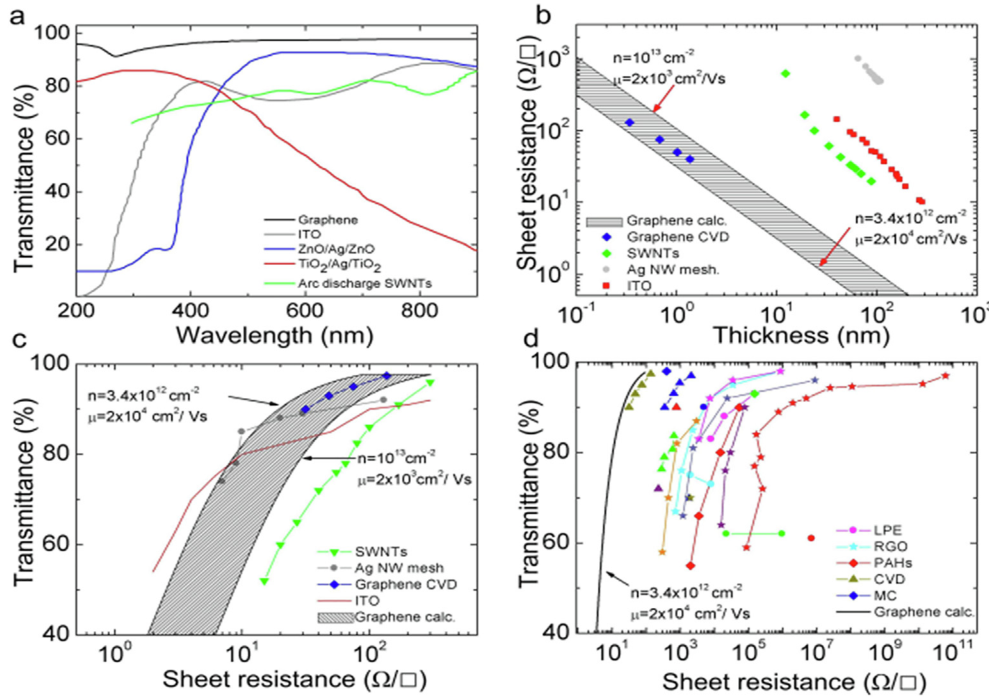

Fig. 6. Transmittance for different conductors. Figure reproduced with permission from: ref. [13], © 2019 Springer Nature.

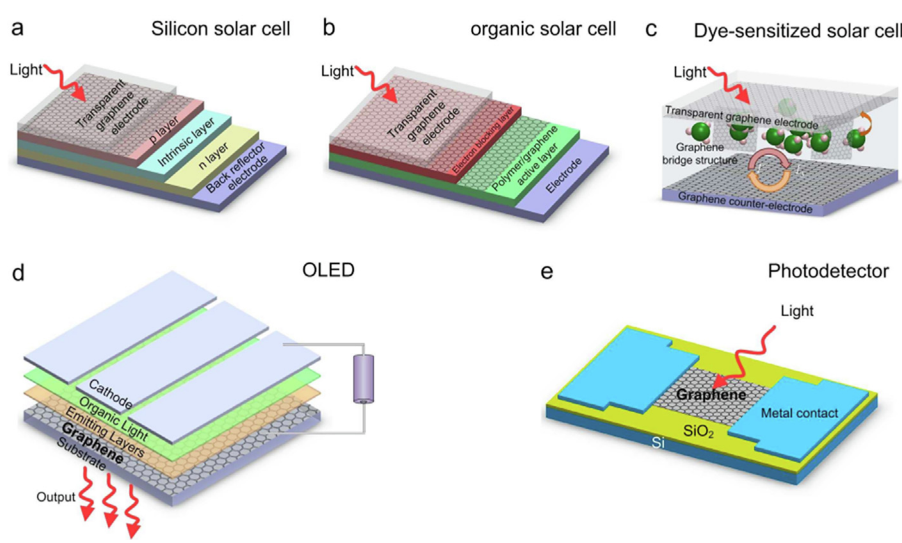

Fig. 7. Schematic representation of different PV devices. Figure reproduced with permission from: ref. [13], © 2019 Springer Nature.

4.4. Photo detectors

Fig. 7(e) shows Photo detector, which measures the optical power by converting the observed photon energy into electrical current. The absorption of photons can produce electric current by the excited carriers from the valence band to the conduction band. Common applications as discussed by Saleh and Teich [20], includes remote controls, TVs, DVD players etc.

5. Photonics in healthcare and medicine applications

Photonics technology plays vital role in healthcare industry focused on low cost diagnosis, drug delivery, treatment and disease prevention. It also involves in elective sight correction minimally invasive surgeries for characterization of the human genome [16]. In addition to that light-based technologies provide the better response to medication. This could help the minimizing side effects, reduction of health care cost and shortened stays in hospital. Medical imaging is also a rapidly developing area, in which understanding the status of a patient and corrective action for guidance and implementation. Real-time images using fluorescent biomarkers that selectively bind to tumor cells provide a clear differentiation between healthy and diseased tissue during surgery [11]. The principal application of photonics in healthcare is the application of Optical Coherence Tomography (OCT) in medical imaging. This process allows the capture of a three dimensional image using light to capture it in high resolution. This has exceptional applications in the diagnosis of solid state tumor's, without the need for invasive surgery. The progression of the disease and treatment effect on the tumors can be monitored by using these techniques. In addition to that monitoring of healing, neurological and ophthalmic conditions diagnosis was easily carried out. Noninvasive property and level of detection are major reason for adopting this technology for essential. Also, the speed in which images can be produced and the obvious reduction on surgery costs, recovery time in hospital and the reduced time before treatment can begin for the patient are advantageous. OCT also play in therapy, recovery stage, monitoring the weakening of the tumors, fast detection of reoccurrence during remission. Due to high regulation image the patients can be treated in a specific way and targeted locations. Non-invasive treatment for brain tumor's with Cyber knife system which works by delivering beams of high dose radiation to tumor's with extreme accuracy.

6. Photonics in defense and national security

The sensor systems will be the next battle ground for intelligence, surveillance, and reconnaissance (ISR) with optical based sensors have significant fraction of ISR systems. This could help getting ubiquitous knowledge across an area and also communication of information at high bandwidths. Optical sensing technology can recognize the chemical, biological, nuclear threats and homeland security [11]. Micro Wave Photonics applied in various field applications in satellites, optical/microwave sensors, new generation radars and deep space exploitation [13,17]. Photonic sensors and systems are used for achieving super awareness across all threat domains. This could allow seeing with better clarity by military and security personals. The help of photonic communication links able to transporting terabits of information around the globe, maintaining an exceptional level of awareness in near real time, day or night. Photonics also play major role in military application especially sophisticated satellite surveillance systems for intelligence gathering. Night vision imagers and laser are used for targeting and finding the range to navigation.

7. Photonics sensing, lighting and energy

Lighting sources and distribution systems have much advantage for reduction of electricity consumption. Innovative optical sensors are enhancing human vision, viewing details and revealing information. The infrared cameras are used in various fields for imaging and sensing purposes especially satellite images of clouds and weather patterns, industrial process control for online monitoring and inspection, industrial emissions measurement, environmental monitoring, night vision and home security [11].

High speed IR cameras were used for CNC milling machine to measure the positional accuracy of the table and thermal expansion of screw. The researches show the suitability of thermal and high-speed cameras to determine the positioning errors of the milling table as a function of temperature of the lead screw. Laser assisted camera utilized for noncontact scanning of object to obtaining 3D data point. This could be helping the collision free realization of manipulation of industrial robot [18].

8. Conclusions

In this paper, compressive review of photonics technology, the advantages of photonics over other technology are discussed. Photonics crystal, band gap and cavity, development of nanostructures with photonics technology and its related issues are highlighted.

Various application of graphene in photonics such as Transparent Conductors, Photovoltaic (PV) Devices, Light-Emitting Devices, Photo detectors are presented.

Photonics is important in the conversion of sunlight to electrical, thermal, and chemical energy. In addition to that it has significant contribution to reduction of energy consumption through more efficient lighting, displays, and communications.

Photonics has significant contribution in healthcare and medicine, defense and national security, sensing, lighting, and energy sectors for monitoring and inspection, industrial emissions measurement, environmental monitoring, night vision etc.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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