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Nanotechnology in Image Sensor to Enhance the Sensing Capability: A Survey

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***Abstract*— In the field of image sensing, nanotechnology can be used to create advanced sensors that can detect smaller objects and more details in an image. For example, nanostructures such as nanowires and nanotubes can be used to create sensors that are more sensitive to light. Additionally, nanomaterials can be used to create more sensitive and efficient sensors that can detect a wider range of wavelengths. This can enable image sensing devices to detect and process more information, allowing for improved image quality. Therefore, in this article we have explored the details of nanotechnology in image sensing.**

***Keywords*—nanotechnology, sensing material, image sensor**

I. Introduction

NANOTECHNOLOGY is the manipulation of the matter at atomic and molecular level. Nanotechnology based devices are of few nanometers size, with a wide range of utility in electronics, medicine, energy, food, cosmetics, textiles and other areas of science and technology. These devices can be fabricated by two approaches, top down and bottom-up approach. Top-down approach, starts from the bulk of the materials and by several nano-fabrication steps for removal of the undesired material from the bulk material, develops the desired nano-pattern on the bulk material. Bottom-up approach, starting from controlled deposition of atoms by different sophisticated deposition and etching techniques, develops the required cluster of atoms or molecules in predefined arrangements for the development of high-performance nanomaterial products. As we scale down the device size, all material characteristics and device parameters do not simply scale down in the same proportion. Researchers observe a number of interesting material characteristics that arise while miniaturizing the bulk material.

Nanotechnology opens the path for completely new device technology and mechanism based upon Van Der Waals force, polar arrangement of the electron density, or the covalent bond for atoms, molecules, or assembly of atoms and molecules. Therefore, nanotechnology deals with the study and control of matter on a subatomic scale. It focuses on the development of materials, devices, and systems that operate on a nanoscale. Examples of nanotechnology applications include nanoparticles and nanocomposites development for targeted drug delivery, nanoelectronics, nano-sensors, and nanorobotics.

An image is a representation of a person, object, or scene created, captured, or rendered digitally. Images can be still or moving, and can be two-dimensional, such as a photograph, screen display, and as well as three-dimensional, such as a statue or hologram [1].

Various image sensors are available to capture an image which includes: Charge Coupled Device (CCD), Active Pixel Sensor (APS), Infrared Image Sensor, Complementary Metal-Oxide Semiconductor (CMOS), Electron Multiplying Charge Coupled Device (EMCCD), Photodiode Array, Photomultiplier Tube (PMT), X-Ray Image Sensor, Position-Sensitive Detector (PSD), Image Intensifier. Most image sensors use an array of pixels (or photodiodes) to capture light and convert it into an electrical signal [2]. Each pixel is sensitive to a specific wavelength of light and converts incoming light of that wavelength into a voltage or current, depending on the sensor type. When all the pixels are combined, they form an image. During the sensing process, the image sensor reads the light coming in from each pixel and converts it into a digital signal. This signal is then processed by a computer to create a digital image.

The term "image formation" refers to the process by which an image is created from a given set of data [1]. This process typically involves the use of specialized software and hardware to capture, process, and store the data in a format suitable for visual representation.

Some of the steps involved in image formation include the following:

1. Acquisition: Capturing the data that will form the image. This can be done through photography, scanning, or other methods depending on the type of image being created.
2. Pre-processing: Manipulating the captured data to enhance the quality of the final image. This can include noise reduction, sharpening, contrast adjustment, and other techniques.
3. Rendering: Converting the manipulated data into a visual representation. This can involve a variety of techniques depending on the type of image being created, such as vector

graphics, pixel art, or 3D models.

4. Output: Saving the image in a desired format and resolution. This can involve saving the image as a JPEG, PNG, TIFF, or other file type.

Therefore, image sensing is the process of capturing, detecting, and analyzing data from an image. In general, it involves the use visible and thermal sensors, to capture, detect, and analyze an image. This data can then be used to help identify objects and people in a scene, detect motion, and recognize patterns. Image sensing can be used in a variety of applications, such as machine vision, robotics, surveillance, and medical imaging.

An image represents the real-world scene in a 2D plane. A camera captures the light energy reflected from objects on the camera's view. The world we reside in is 3D, but the camera focuses the rays falling on the screen to a 2D image plane. Mathematically, an image can be represented as a two-dimensional function $I(x, y)$, where (x, y) denotes the spatial coordinates, and I indicates the intensity value at that point (x, y), generally termed as pixel. A graphical illustration of the visible image formation model is shown in Fig. 1.

The images formation model has three main components: light source, camera, and target object. The source generates a ray of photons if it is in the visible spectrum. Sun is the natural source of light, and it acts as a source of illumination for the natural photography. The light from the source incident on the target and reflected light is allowed to fall on the lens of a camera based on the reflectance coefficients of the object. The light rays fall on the lens and projected to the imaging sensor generates an image on the imaging plane. Sampling and quantization strategies are applied to represent the image in the digital domain. In the digital image, the intensity value of each pixel is represented by b bits binary digits. Generally, for an 8 bits system, the pixel intensity values range from 0 to 255. Mathematically, an image can be represented as:

$$I(x, y) = l(x, y)\, r(x, y) \tag{1}$$

Where $I(x, y)$ represent the image, $l(x, y)$ denotes the illumination component, and $r(x, y)$ indicate the reflectance component.

Thermal imaging is an approach of converting thermal radiation information into visual information representing the spatial distribution of temperature variation in a scene captured by a thermal camera [3, 4]. The infrared (IR) sensor captures the heat emitted by the objects, and the infrared lens focuses the radiation information on the focal plane array. The IR-sensitive detector coincides with the focal plane array using the photoelectric effects to generate the electrical signal and is processed by the image processor to generate the image. Here, the intensity level of the image is proportional to the object's temperature. The image formation model by the thermal sensor is presented in Fig. 2.

Also, images from other modalities can be represented as follows [5]:

1. Magnetic Resonance Imaging (MRI): Generates detailed pictures of the body's organs and tissues.
2. Computed Tomography (CT): Combines X-ray with computer technology to generate detailed 3D images.
3. Ultrasound: Uses sound waves to produce images of organs and structures within the body.
4. Positron Emission Tomography (PET): Uses radioactive material to create detailed 3D images.
5. X-ray: Uses electromagnetic radiation to create black-and-white images.
6. Fluoroscopy: Uses a continuous X-ray beam to produce real-time images of internal organs or structures.
7. Angiography: Uses X-rays and an injection of contrast dye to produce images of blood vessels.
8. Single-photon emission computed tomography (SPECT): Uses a radioactive substance and a rotating gamma camera to create three-dimensional images of organs and tissues.

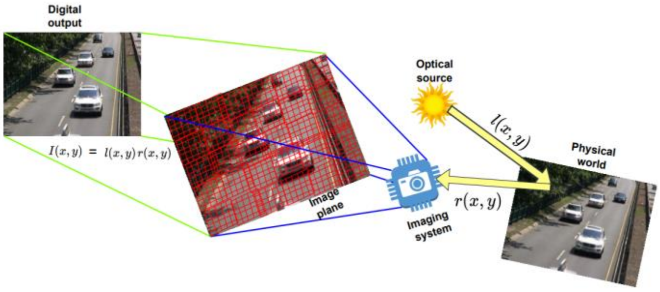

Fig. 1. Visible image formation model.

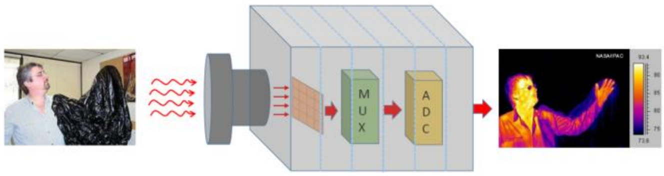

Fig. 2. Thermal image formation model.

The most commonly used sensor material for visible cameras is a type of silicon called a Complementary Metal-Oxide-Semiconductor (CMOS). CMOS sensors are used in most digital cameras, including consumer and professional models, and are preferred for their low power consumption and image quality. Other materials that may be used in digital cameras include CCD (Charge Coupled Device) and CID (Contact Image Sensor). Thermal imaging sensors typically use a material called amorphous silicon, which is sensitive to infrared radiation. Amorphous silicon can detect infrared radiation in the range of 8-15 micrometers. Fig. 3 represent the image acquisition methodology using single sensor, line sensor and array sensors.

Disadvantages of conventional sensor materials are: A limited sensitivity, poor resolution, in disturbed weather condition, larger size, etc. [6].

Therefore, in this article we have explored the use of nanotechnology to enhance the performance of the image sensor in adverse weather condition as follows:

1. Increased Sensitivity: Nanotechnology can increase the sensitivity of image sensors and allow them to capture more detailed images in a shorter amount of time.

2. Smaller Size: Nanotechnology has allowed image sensors to be made much smaller than before, which is beneficial for applications that require a small form factor.

3. Lower Costs: Because of the smaller size and increased sensitivity, nanotechnology can lead to lower costs for image sensors.

4. Higher Resolution: By using nanotechnology, image sensors can have a much higher resolution than before, leading to better image quality.

5. Higher Durability: Nanotechnology has also allowed image sensors to be more durable, which is beneficial for applications that require long-term use.

6. Increased Battery Life: Nanotechnology can also help increase the battery life of image sensors, which is beneficial for applications that require a long battery life.

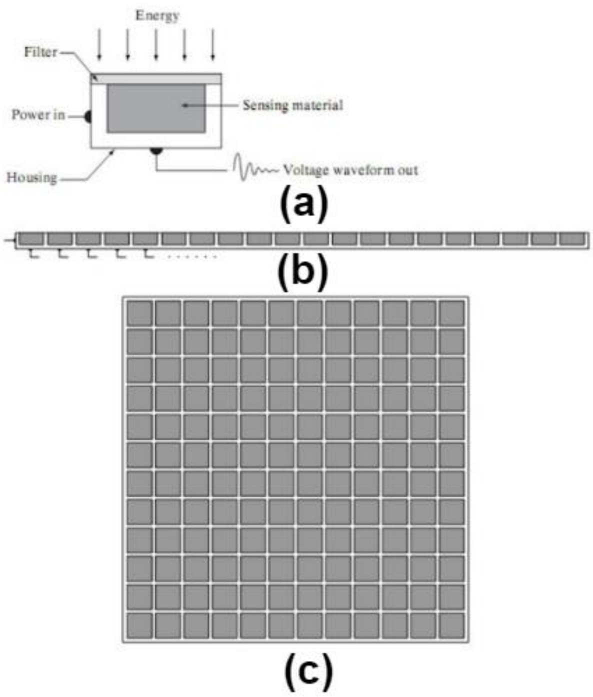

Fig. 3. Image acquisition using (a) Single Sensor (b) Line Sensor and (c) Array sensor.

II. NANOTECHONOLOGY IN IMAGE SENSOR

Sensitivity of CMOS, CCD and CID based image sensors are limited by the conductivity of the light sensitive materials. Nanomaterials have been used in the fabrication of image sensors to improve their performance [7, 8]. Nanomaterials can be used for increasing the sensitivity of the image sensor. By incorporating nanomaterials into the pixel design, the photosensitive area of the sensor can be increased, resulting in higher sensitivity and improved signal-to-noise ratio. Nanomaterials can also be used to create a more efficient light-harvesting system, which can lead to improved dynamic range and higher speed. Additionally, nanomaterials have been used to create more efficient antireflection coatings, allowing for a greater amount of light to be captured by the sensor.

Also, the use of nanomaterials in image sensors can enable them to detect a wide range of light intensities, from the brightest of light to the faintest of light. Additionally, nanomaterials can be used to create sensors that can detect a wide range of wavelengths, from the near-infrared to the visible spectrum. Examples of nanomaterials that can be used in image sensors include carbon nanotubes, graphene, nanoparticles, nanowires and quantum dots. The array of sensors illustrated in Fig. 3 can be replaced by nanomaterials as follows:

Carbon nanotubes (CNT) are cylindrical tubes made of carbon atoms. The array of single wall carbon nanotube is shown in Fig. 4. They are typically around the diameter of a nanometer, which is one billionth of a meter, and can be many micrometers in length. Electronic and optical properties of CNTs are linked with the chiral vector of the CNTs [7, 8]. Controlling the chirality of CNTs during the fabrication steps leads to different types of CNTs [7]. They are extremely strong and are often used in a variety of materials and products, such as batteries, fuel cells, semiconductors, and even materials for biomedical applications [8]. They can also be used to create strong, lightweight materials that are ideal for use in engineering applications [8].

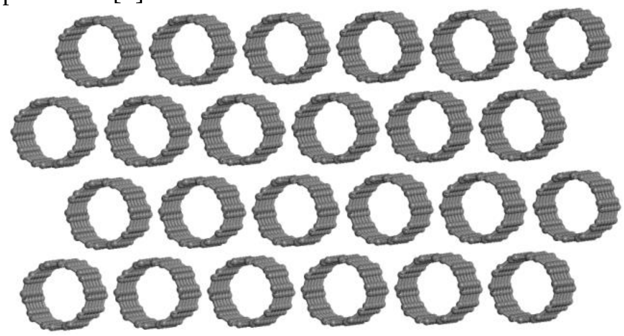

Fig. 4. Array of carbon nanotube.

CNTs can be used as electron emitters. By incorporating CNTs into image sensors, it is possible to create devices that have a high electron emission rate, which can increase their sensitivity to light. CNTs also have a high surface area available for light absorption, which makes them an ideal material for use in photoactive layers of image sensors [7]. CNTs have a very fast response time and very high sensitivity to light in the near-infrared region i.e., the spectrum used for night vision. CNTs can be used as photoactive layers in night vision cameras to capture high quality images in low light conditions, especially for military and security applications [8, 9]. CNTs can be used as thermal sensors also, as it shows high thermal conductivity up to 3000 W/mK, which is higher than other commonly available metals [8]. In addition to high conductivity, CNTs show thermoelectric effect, which allows CNTs to generate electric potential in response to temperature gradients [8, 10].

Graphene is a two-dimensional form of carbon. It is a single layer of carbon atoms arranged in a hexagonal honeycomb monolayer lattice structure as shown in Fig. 5. Graphene is the strongest, lightest and most conductive material known and it is also the thinnest material in the world. Its unique properties have enabled scientists to explore its potential for numerous applications, such as flexible and transparent electronics, energy storage, photonics, and medical diagnostics and treatments [11].

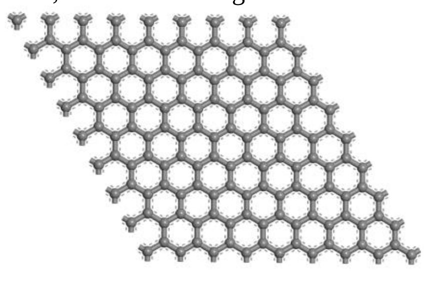

Fig. 5. Hexagonal honeycomb structure of monolayer Graphene sheet.

Graphene can be used to improve the electron transport of the image sensor. Graphene's very high electrical conductivity and low resistance makes it an ideal material for use in the electron transport layer, and can improve the efficiency of charge transport and reduce noise in the signal [11]. These can lead to an increase in the overall sensitivity of the image sensor. One of the key advantages of graphene as a thermal image sensor is its high thermal conductivity. Graphene has a thermal conductivity of up to 5000 W/mK, which is several orders of magnitude higher than other materials commonly used in thermal imaging applications [11]. This high thermal conductivity enables graphene to rapidly conduct and dissipate heat, making it useful for thermal management applications as well. In addition to high thermal conductivity, graphene has low heat capacity, which quickly responds to the change in temperature.

Nanoparticles are particles that measure between 1 and 100 nanometers in diameter. They are typically composed of materials such as metals, polymers, or ceramics. Nanoparticles have a variety of applications, such as in medicine, electronics, energy storage, and cosmetics. They can also be used to create nanomaterials, which can be used as coatings or as structural components in nanomaterial-based products.

Gold, silver, platinum, copper, zinc and other metal nanoparticles exhibit a surface plasmon response (SPR) that strongly absorbs and scatters the particular wavelength of light. It shows the resonance effect due to the interaction of conduction electrons with incident photons. The SPR properties of these nanoparticles can be tuned by changing their size, shape, and the surrounding environment, making them attractive for use as imaging sensors [12, 13]. Schematics of gold nanoparticles is shown in Fig. 6. Gold nanoparticles have potential applications in the development of high-resolution imaging systems. Gold nanoparticles arrays can be developed to create photodetectors with extremely high pixel densities enabling the high resolution [13]. The strong SPR properties of silver nanoparticles make them attractive contrast agents, as they can increase the contrast between different tissues and structures in the body. Silver nanoparticles as shown in Fig. 7 can also be used in the development of contrast agents for medical imaging, such as magnetic resonance imaging (MRI) or X-ray imaging [14].

Platinum nanoparticles can be used for contrast agent for computer tomography (CT) images due to their high atomic number [15]. Copper nanoparticles can be used as contrast agents for photoacoustic imaging due to their ability to efficiently convert light into heat and generate acoustic waves, which can be detected and used to form images [12]. Zinc nanoparticles have potential to be used in fluorescence imaging, where they can be conjugated with fluorescent dyes to enable imaging of specific bio-molecules or cells [12, 13].

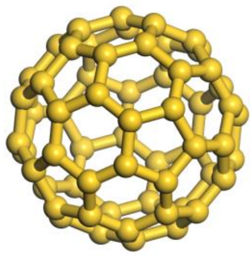

Fig. 6. Schematics of gold nanoparticle.

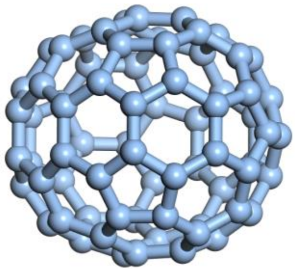

Fig. 7. Schematics of silver nanoparticles.

Nanowires are wires that are extremely small, typically measuring less than 100 nanometers in diameter. They are most often composed of semiconductors, but can also be made of metals, insulators, and other materials. Nanowires are used in a variety of technologies, including nanoelectronics, photonics, and sensors. They are also used in applications such as solar cells, photovoltaics, nanofabrication, and medical devices. Nanowires are particularly advantageous because of their unique properties, including high electrical conductivity, low power consumption, and high surface area-to-volume ratios [16, 17].

Semiconductor nanowires can be used to improve the sensitivity and resolution of the photodiodes in image sensors. Generally, cameras consist of an array of photodiodes that convert incoming light into electrical signals. Semiconductor nanowires can be used to create photodetectors with extremely high pixel densities, enabling the creation of cameras with resolutions that are higher than those currently available using nanowires with high aspect ratios, it is possible to increase the absorption of incoming light, which can improve the signal-to-noise ratio of the image sensor [16, 17]. Nanowires has an extra advantage of being flexible and conformable, which makes it good for the image sensor at curved surfaces.

Nanowires are ultra-thin wires and exhibit very high thermal conductivity, which allows them to efficiently conduct heat over long distances. In addition, nanowires exhibit a high surface-to-volume ratio, which enhances their sensitivity to temperature changes and makes them ideal for sensing applications. IR imaging techniques uses the radiation emitted by the nanowire as a function of temperature to generate an image [16, 18].

Quantum dots (QDs) are nanometer-scale semiconductor structures that confine electrons in all three spatial dimensions. They are typically made from semiconductor materials such as gallium arsenide or indium arsenide and are typically a few nanometers in size. QDs can be used in a variety of applications, such as light emitting diodes, lasers, displays, and photovoltaic cells. They also have potential applications in quantum computing, optical telecommunications, and medical diagnostics [19, 20]. QDs can increase the sensitivity of image sensors by incorporating the use of QDs into the design of image sensors.

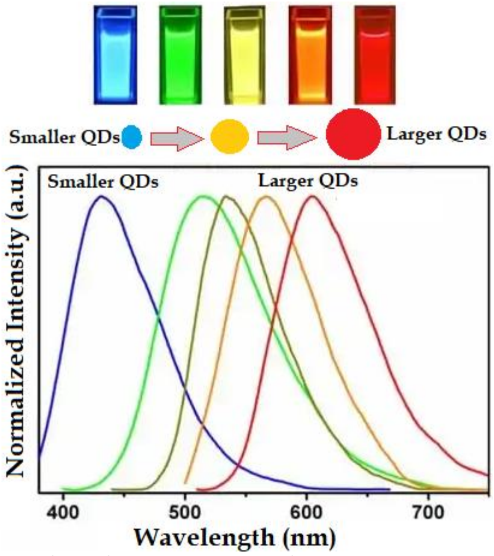

Fig. 8. Shifting of absorption spectra of quantum dot with respect to increase in size. Color change was reported for different size of the QDs [20].

Optical properties of QDs can be tuned by adjusting their size and composition as shown in Fig. 8, and can be used to improve the sensitivity of cameras in low-light condition which is important for night vision. Fig. 8 represents the increase in absorption wavelength with respect to the size of QDs. QDs can be used to enhance the performance of the image sensor by increasing the efficiency of light absorption and improving the color sensitivity of the sensor. In a night vision camera, QDs can be used to enhance the detection of near-infrared light, which is outside the range of visible light. QDs can absorb near-infrared light and convert it into visible light, known as up conversion process, which can then be detected by the camera's image sensor [20].

CONCLUSION

In this article we have explored the use of nanomaterials in the image sensors. It is found that the use of sensor with conventional material degrade the quality of the scene in adversely weather condition. Also, it is observed that if the object size is small, the conventional image sensors provide image with poor resolution. Further, the sensitivity of the existing sensor can be enhanced using nanotechnology. Therefore, in this article we have investigated, the use of nanomaterial in the sensors for perfect acquisition of the image. Overall, the properties of nanomaterials allow researcher to think differently in the image sensing application. Nanomaterials can provide high pixel density, with increase in the surface area, more light absorption will take place and the sensitivity will increase.

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