Nano-Cameras: A Key Enabling Technology for the Internet of Multimedia Nano-Things

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ABSTRACT

Nanotechnology is enabling the development of a new generation of devices which are able to sense, process and communicate, while being in the scale of tens to hundreds of cubic nanometers. Such small, imperceptible devices enhance not only current applications but enable entirely new paradigms. This paper introduces the concept of nano-cameras, which are built upon nanoscale photodetectors, lenses and electronic circuitry. The state-of-the-art in nanoscale photodetectors and lenses is presented and the expected performance of nano-cameras is numerically evaluated through simulation studies. Finally, the open challenges towards integrating nano-cameras in practical applications and ultimately building the Internet of Multimedia Nano-Things are discussed.

CCS CONCEPTS

• **Hardware → Emerging optical and photonic technologies**;

KEYWORDS

Nano-cameras, nano-photodetectors, nano-lenses, nanoscale optics, Internet of nano-things

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1 INTRODUCTION

Over the last decades, progress in sensing, embedded processing and networking has leveraged the development of smart cameras and has fostered their ubiquitous deployment [32, 33]. Nowadays, nanotechnology is enabling the miniaturization of electronic devices down to the nanoscale, and nano-sensors with feature sizes below one hundred nanometers have been developed. In the field of light sensing, nanoscale optical devices have been built with technologies such as plasmonic materials, which enable the development of photodetectors and lenses at the nanoscale.

In this paper, we introduce the concept of nano-cameras, which lies at the intersection of smart cameras and nanotechnology. Nanoscale photodetectors and lenses are the core components of the nano-camera. In order to function as a standalone sensing device and in a network of devices, these cameras also include nanoscale processors, memories, batteries, transceivers and antennas.

By assembling multiple nano-photodetectors in different constellations, nano-cameras will provide attractive capabilities such as extreme spatial resolution, high (spectral) sensitivity and high energy-efficiency. Due to their size, scale and flexibility, a multitude of novel applications can be foreseen in fields including bio-medicine, defense and security, environmental and habitat monitoring as well as the Internet of Multimedia Nano-Things (IoMNT) [16].

The rest of the paper is organized as follows. In Section 2, we discuss the state of the art in nanoscale photodetectors and lenses, which are the key components for nano-cameras. We then introduce the nano-camera concept, its components and applications in Section 3. In Section 4, we present our initial performance evaluation studies which highlight the unprecedented applications of nano-cameras. Finally, we discuss future directions and conclude the paper in Section 5.

2 NANOSCALE OPTICS

The realization of nano-cameras requires fundamentally new device technologies, beyond the evolution of traditional CMOS-based technology. For this purpose, nanoscale materials have gained a lot of research interest in recent years. They are confined to the nanoscale, shrinking devices down to be smaller than 100 *nm*. The diffraction limit of traditional optical devices, which is proportional to the wavelength of the observed light, places a lower limit on their smallest possible size. However, metamaterials and plasmonic structures can overcome the diffraction limit, enabling imaging systems with sizes smaller than the optical wavelength [48]. Compressing light into a nanoscale volume also enables to absorb and detect the light with a nanoscale detector. Nano-photodetectors bring a variety of desirable properties such as low noise, high speed, high sensitivity, low voltage and low power, which can be further enhanced by nanoscale lenses. The following two sections introduce the current state-of-the-art in nanoscale photodetectors and lenses.

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2.1 Nano-photodetectors

Photodetectors, the fundamental building block of optical imaging devices, are optoelectronic devices which are able to detect light and convert it into electricity based on the photoelectric effect. The best known example of biological photodetectors are human eyes, which are able to detect light in the visible range (400 nm to 760 nm) of the electromagnetic spectrum. However, with the help of electronic photodetectors, we are also able to see light beyond the visible spectrum such as infrared (IR: 760 nm to 1 mm), ultraviolet (UV: 10 nm to 400 nm) or terahertz (THz: 1 mm to 100 μm) light, which is required by applications for a variety of environments such as industry, medicine, military and agriculture [2].

To define the performance of a photodetector, several measures are used to characterize them [2]:

- Responsivity is the ratio of the generated output photocurrent to a certain incident light power
- Quantum efficiency is the efficiency of a photodetector in converting incident photons to electronic charge for a certain wavelength
- Dark current is the current through the photodetector in the absence of light, which must be accounted for the calibration
- Response time is the duration of the current generated by an absorbed photon
- Noise equivalent power (NEP) is the minimum required input optical power to produce an output photocurrent

In recent years, nanoscale materials have gained a lot of interest as building blocks for photodetectors covering ranges from the UV to the THz region [34]. By definition, nanoscale materials have at least one dimension between 1 nm and 100 nm and can be classified into three major categories, namely two-dimensional (2D), one-dimensional (1D) and zero-dimensional (0D) materials. The following subsections explain the three different categories of nanoscale materials along with photodetectors built upon them.

2D nano-photodetectors. 2D materials, also referred to as single-layer materials, include nano-sheets, monolayers and ultrathin films and have only one spatial dimension confined within the nanoscale, namely their thickness [2]. Compared to usual semiconductor films, the fabrication of 2D materials is typically much easier and cheaper.

At this time, more than 140 2D materials are known, many of them being semiconductors [7]. The four key members of 2D materials are metallic graphene, transition metal dichalcogenides (TMDCs) layered semiconductors, semiconducting black phosphorous and insulating boron nitride. The major advantage of 2D layered materials is, that all of them provide a wide selection of light detection including UV, visible, IR and THz [43].

The material most commonly associated with nano-photodetectors based on 2D materials at this time is graphene, which is a flat monolayer of carbon atoms tightly packed into a two-dimensional honeycomb lattice [49]. Figure 1 shows a 2D graphene lattice, which can be used to fabricate all dimensions of nano-photodetectors, namley 0D nano-particles (a), 1D nano-tubes (b) or 2D nano-sheets (c).

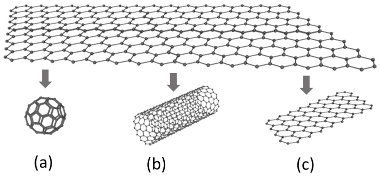


Figure 1: 2D Graphene lattice which can be fabricated into a 0D nano-particle (a), a 1D nano-tube (b) or a 2D nano-sheet (c).

Graphene has a high response speed, high quantum efficiency and a broad spectral detection width, covering wavelengths from microwave to ultraviolet, however it has a low responsivity [6]. Thus, much research was dedicated in recent years to develop graphene-based photodetectors with higher responsivity [4, 12].

TMDCs are an alternative to overcome disadvantages in graphene-based detection systems and have thus also earned a lot of attention in recent years [2, 28]. Compared to graphene, TMDCs are atomically thin semiconductors consisting of metal atoms placed between two layers of chalcogen atoms [35]. Various TMDC-based photodetectors have been presented over the last years [44, 46].

Phosphorene, being a single layer of black phosphorus, attracted great attention for the fabrication of nano-photodetectors due to its high anisotropy and carrier mobility. Thus, various nano-photodetectors based on phosphorene have been fabricated recently, showing high responsivity in the near infrared range [38, 40]. When integrated with waveguides, phosphorene-based nano-photodetectors feature significant advantages over those based on graphene, since they have a very low dark current.

However, like graphene, also other 2D materials suffer from certain disadvantages, which leads to the exploration of heterogeneous forms by combining different 2D materials to get the best out of each. Various heterogeneous structures have thus been introduced in the last years [31, 45].

1D nano-photodetectors. 1D materials comprise nano-wires, nano-rods, nano-tubes, nano-belts and nano-ribbons, whose diameter is restricted to be smaller than 100 nm [2, 6]. Thus, 1D materials have two spatial dimensions confined within the nanoscale.

A well-known example is the carbon nano-tube (CNT) discovered in 1991 by Iijima [13]. CNTs have a cylindrical shape with diameters of only $1-3$ nm and can be fabricated by rolling carbon sheets such as graphene into a tube (see Figure 1 (b)). Nano-tubes are typically based on a hexagonal honeycomb carbon lattice, however, the different orientations of the structures lead to different material properties, enabling them to operate as transistors, light emitters or light detectors. Further, various 1D plasmonic nano-photodetectors have been developed in recent years [9, 27].

Besides CNTs, other materials have been investigated in order to fabricate nano-photodetectors based on nano-wires [10], nano-belts [36], nano-rods [41] and nano-ribbons [22]. Like in 2D materials, also heterogeneous structures are investigated to improve the photo detection performance further [18, 26].

A major recent research direction focuses on the development of simple fabrication procedures to assemble 1D nano-structures into networks [37] or oriented arrays [25]. These assemblies will improve the performance including sensitivity and stability and will enable 1D nano-photodetectors for practical applications [2].

0D nano-photodetectors. In 0D materials, all three spatial dimensions of the material are restricted to the nanoscale [2]. Therefore, they are also referred to as nano-particles. The best known 0D materials for building nano-photodetectors are quantum-dot (QD) based materials [2, 6]. Graphene quantum dots (GQDs) have especially gained interest in recent years. GQDs are small graphene particles (see Figure 1 (a)), which enable a broadband detection and an especially high detectivity for certain regions of the spectrum.

In order to improve the performance, hybrid forms are investigated. Those do typically not apply QDs as main component of the photodetector but exploit hybrid forms with 2D materials such as graphene, black phosphorus and TMDCs. This nano-photodetector family is known as 2D-QD devices [21, 42]. In 2D-QD devices, the additional QD layer enables a higher light absorption which leads to a higher quantum efficiency and gain of the photodetector as compared to detectors solely based on 2D materials [2, 20].

2.2 Nano-lenses

For the construction of a camera, not only a sensor is required but also a lens which controls the light. Optical lenses, typically constructed from glass or plastic, focus a light beam by means of refraction in order to form an image. As mentioned above, the diffraction limit places a fundamental limit to the resolution of conventional optical lenses. However, research conducted within in the last decade showed that this fundamental limit can be circumvented by the use of plasmonic materials, which introduced a new era for imaging systems. Light, which is emitted from objects, does not only include the propagating waves but also evanescent waves. The latter carry the sub-wavelength detail of the object and can be significantly amplified by a plasmonic lens, which enables imaging below the diffraction limit [47].

The best known earliest approaches of lenses which can overcome the diffraction limit include super- and hyperlenses [14, 47]. The first superlens was able to image 60 *nm* features (corresponds to $\frac{1}{6}$ of the observed wavelength). Later improvements enabled a resolution of $\frac{1}{20}$ of the wavelength. The first hyperlens was constructed using nano-wires of 35 *nm* width and was capable of capturing images of objects smaller than 150 *nm*. Nowadays, the hyperlens can be realized by fabricating existing planar nanoscale material into a cylindrical geometry.

In recent years, ultrathin flat lenses have attracted great attention as essential components in nano-optics and photonic systems. They are usually constructed from 2D materials and are able to focus light with minimal aberration. One of the thinnest lenses is based on graphene and has a thickness of 0.34 *nm* [19]. With a radius of 49 μm and a focal length of 120 μm, it enables to observe wavelengths around 850 *nm*. A general improvement to fixed focus lenses are variable focus lenses. One example is a graphene-based lens, whose focal length can be tuned from 7.3 μm to 15.2 μm [23]. This lens is with 3.5 $\mu m \times 13$ μm also very small in size.

Additionally, various ultrathin TMDC-based lenses were developed and found to provide advantageous characteristics. One example is the TMDC-based visible light lens with a thickness of 6.3 *nm* and a diameter of 20 μm, being able to bserve wavelengths of 532 *nm* [39]. It is a concave lens and has thus a negative focal length, which was calculated to be -248 μm. The thinnest TMDC-lens has a thickness of 0.7 *nm*, which corresponds to the physical limit of TMDC material thickness [24]. It is fabricated as monolayer and can achieve 3D focusing with almost diffraction-limited resolution. One very important aspect is, that monolayer TMDCs can be transferred to arbitrary substrates making the lens ready to be integrated with diverse electronic or photonic devices.

In general, the graphene lenses were found to be thinner and easier to fabricate compared to the other 2D material lenses, having the potential to enable easy development of nanoscale optical systems [29]. 2D materials other than graphene offer a better performance for some specific properties, applications and frequency ranges. A single-layer TMDC-based lens provides for example an extremely high optical path length, which is about one order of magnitude larger than in single-layer graphene.

Besides graphene and TMDCs, also other nano-materials are exploited to build nano-lenses. One example is the titanium dioxide lens for visible light, with a diameter of 240 μm and a focal length of 90 μm [17]. Another example is the broadband achromatic lens for imaging in visible ranges, which was introduced very recently [3]. The authors showed, that a metalens with tailored dispersion can transform low-cost spherical lenses into diffraction-limited achromatic lenses, enabling various applications such as in lithography, microscopy, endoscopy and virtual and augmented reality.

3 THE NANO-CAMERA CONCEPT

3.1 Components of a Nano-camera

Nano-cameras are nano-devices able to detect, (pre-)process and transfer "images". Nano-photodetectors and nano-lenses, as discussed in Section 2, are the fundamental building blocks of nano-cameras and can be assembled in different constellations. Additional components including memory, processor, transceiver, antenna and battery are also required to realize a nano-camera. In summary, the main components of a nano-camera are as follows [16]:

- **Nano-photodetectors**, as described in Section 2.1, represent the pixels of the camera. The total number of photodetectors corresponds with the resolution of the nano-camera.
- **Nano-lenses**, as discussed in Section 2.2, control and focus the light. Lenses can be used for individual or multiple nano-photodetectors.
- **Nano-memories** store sensed or received information. Current technology enables single-atom nano-memories [30], whose dimensions define the amount of stored information.
- **Nano-processors** process sensed or received information. Nano-fabrication already enables to create electronic components such as transistors or logic gates from nano-materials, enabling the development of nano-processors [11].
- **Nano-transceivers and -antennas** establish data communication (e.g., Terahertz-band communication [1]) between nano-cameras and enable the transfer of image data and eventually the deployment of a nano-camera network.
- **Nano-batteries** [15] in combination with nanoscale energy harvesting systems [8] provide the power-supply for nano-cameras. The device size imposes limits for the amount of the energy harvested and stored.

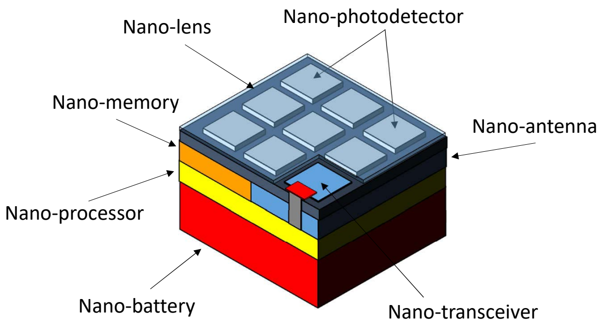


Figure 2: Planar constellation of a nano-camera based on a 3D vertically stacked architecture where all components are assembled in a layered structure.

Naturally, the size and arrangement of the individual components directly influence the capabilities and properties of the nano-camera including processing power, memory capacity, energy capacity and communication abilities. Further, the area of the nano-camera determines the total number of nano-photodetectors which affects the multimedia capabilities.

3.2 Constellations of a Nano-camera

In light of these properties, we present and sketch two constellations of the nano-camera's components: a planar and spherical pixel allocation. Figure 2 depicts a planar constellation exploiting a 3D-integrated vertical stack of components, resulting in a sensing plane similar to traditional imagers, while significantly reducing the size. However, the area of the sensing plane is bound to current electronic circuitry and lens diameters, which are on the order of a few μm. The stack includes the nano-battery as lowest layer, the nano-processor, -memory and -transceiver on top of it and the nano-photodetectors with the nano-lens at the top level.

Compared to traditional, already existing camera systems, nano-cameras provide several advantages. First of all, nano-photodetectors give an order of magnitude higher sensitivity and do not require active illumination, which means that they provide much better low-light condition imaging. This enables for example intra-body medical applications, where nano-cameras are injected or swallowed. Further advantages include the capability of taking images at an order of magnitude faster with significantly lower power than traditional cameras.

The major difference in nano-cameras compared to traditional cameras however, is their potential in enabling a new generation of applications with their unique characteristics. Specifically, nano-cameras can be build to observe various frequencies at the same time by simply assembling different nano-photodetectors such as IR, UV, THz and visible light detectors into one device.

Figure 3 depicts a non-conventional pixel allocation of a nano-camera. In this example the nano-photodetectors are arranged in a sphere resulting in a fully omni-directional image sensor. In a spherical constellation, all components must fit within the confined space of the photodetector sphere. However, this constellation enables a direct sensing of the light field at the position of the nano-camera, as our simulation studies in the next section will show.

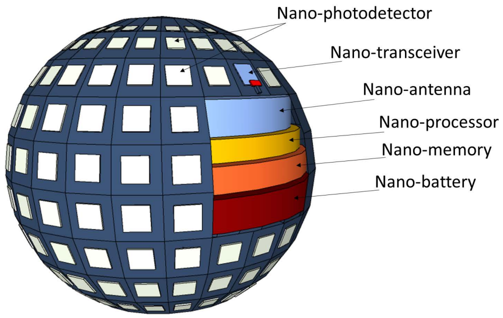


Figure 3: Spherical constellation of a nano-camera resulting in a fully omni-directional sensor. The electrical components including nano-battery, -processor, -memory and -transceiver are placed within the sphere.

4 PERFORMANCE METRICS AND EVALUATION

In this section, we utilize finite-element methods to evaluate the preliminary performance of nano-pixels and nano-cameras.

4.1 Responsivity of Nano-pixels

The image quality of a nano-camera ultimately depends on the response of each individual nano-pixel. The responsivity of a nano-photodetector is the ratio of generated photocurrent I_{ph} and incident optical power P_{inc} (see Section 2.1). In the most general case, we define the responsivity $\mathcal{R}$ as [5]:

$$\mathcal{R} = \left(\frac{e\lambda}{hc}\right)(1-R)\eta\left(1-e^{-\alpha}\right)\Gamma_G, \qquad (1)$$

where e stands for the electron charge, h is the Planck's constant, c is the speed of light, λ is the wavelength of operation, R is the reflectance of the pixel, η stands for the internal quantum efficiency, α is the absorbance of the pixel, and Γ_G captures any gain.

As discussed in Section 2.1, different 0D, 1D and 2D technologies with different quantum efficiency η, reflectance R, and absorbance α are being developed. Nevertheless, it is important to note that as the pixel becomes smaller, the number of photons intercepted by the pixel is also reduced, as $P_{inc} = \int_A \mathcal{P} dA$, where $\mathcal{P} = \frac{E \times B}{\mu_0}$ is the Poynting vector and E and B are the electric and magnetic fields. The resulting photocurrent I_{ph} is what determines the final response of the pixel.

In Figure 4, we illustrate the photocurrent as a function of the pixel size, for different pixel technologies, namely, carbon nano-tube thin films/single-layer graphene Schottky junction [43], graphene on silicon and graphene coupled with silicon quantum dots [42], and, as a reference, standard CMOS technology (in all cases, incident power density equal to 1 W/m^2). As shown in the figure, the benefits of looking in 0D, 1D and 2D-based nano-pixels are twofold. On the one hand, the utilization of novel technologies enables the manufacturing of smaller pixels, which are imperceptible and can be integrated in higher densities (with CMOS, the smallest pixel

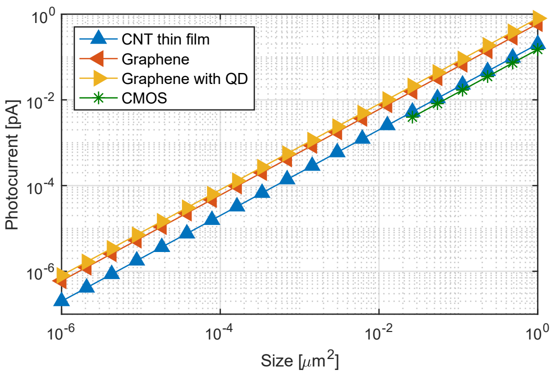


Figure 4: Photocurrent for different pixel technologies as function of the pixel size.

technology is approximately 0.5 μm, while nanometric pixels are possible with 0D, 1D and 2D technologies). On the other hand, the quantum efficiency is also higher in the QD-based, CNT or graphene technologies. All these allow denser integration of nano-pixels in planar nano-cameras (Figure 2) and their deployment in non-conventional constellations, as we show next.

4.2 Imaging with Non-conventional Constellations

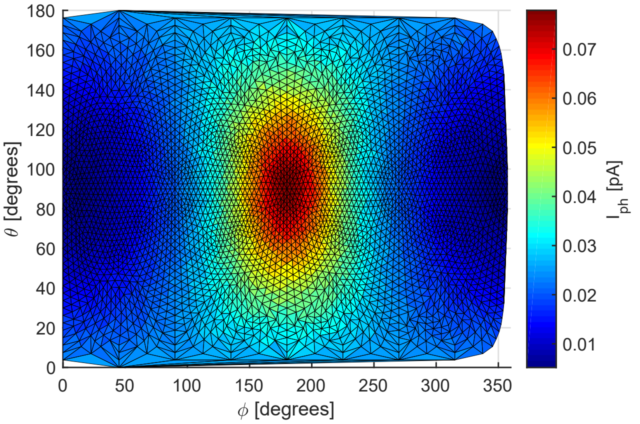
As mentioned in Section 3.2, one of the major opportunities introduced by nano-cameras is the possibility to arrange the pixels in geometries beyond the traditional planar structure. For example, as shown in Figure 3, a spherical distribution of the pixels around the nano-camera could be envisioned for seamless full-dimensional imaging.

In Figure 5, we illustrate the generated photocurrent per pixel in a spherical 1 μm^3 nano-camera at the origin of coordinates, when illuminated by a light source in $\theta = 90^\circ$ and $\phi = 180^\circ$ and in $\theta = 135^\circ$ and $\phi = 225^\circ$. It is clear from the simulations that only those pixels which are fully blocked by the camera will not be able to detect a single photon from the light source. The possibility to capture images in all directions at the same time enables applications including real-time 3D imaging, fully-immersive video experience or seamless localization, among others.

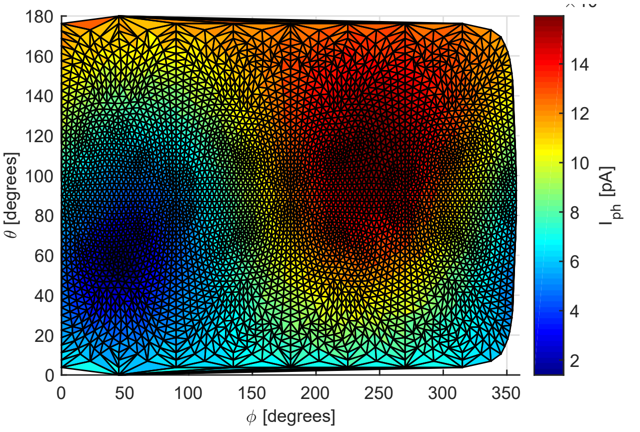
5 CONCLUSION AND FUTURE DIRECTIONS

In this paper, we have introduced the concept of a nano-camera, which is built upon nanoscale photodetectors, lenses and electronic circuitry including memory, processor, transceiver and battery. We discussed the current state-of-the-art in nano-photodetectors and nano-lenses and numerically evaluated the performance of a nano-camera in terms of responsivity and novel constellation.

With their attractive characteristics such as high flexibility and sensitivity, low power and low cost, nano-cameras will enable a new era of multimedia applications. These include intra-body imaging (e.g., for the gastrointestinal tract, vascular system, or even the brain), nano-structure monitoring (e.g., nano-defects in sensitive infrastructures, aerospace industry), fluids monitoring or animal habitat monitoring (e.g., equip insects with nano-cameras).



(a) $\theta = 90^\circ$, $\phi = 180^\circ$



(b) $\theta = 135^\circ$, $\phi = 225^\circ$

Figure 5: Unfolded (2D) photocurrent map for the spherical camera, when illuminated from a) the side, and b) at an angle.

However, there are various open challenges towards the realization of these novel applications. First, the size mismatch between the photonic elements and the electronic circuitry is a major issue in nano-cameras. Thus, new techniques to overcome this problem are essential to realize the whole photodetection system at the nanoscale. Second, the size limitations also impose limitations on storage, processing and communication capabilities. With the help of empirical studies, a good balance between on-camera processing and remote processing needs to be defined in order to avoid communication overhead. However, significant progress has been made in electromagnetic nano-communication networks already. Third, determining the camera pose and sensing time is highly relevant for analyzing the sensed data from nano-cameras, but nanotechnology currently provides rather limited support for it. Finally, energy supply and energy harvesting represent another challenge for realizing a truly self-powered nano-camera. However, first self-powered nano-photodetectors have been introduced recently [34].

As nanotechnology advances at a fast pace, we expect to see a dramatic change in several fields of camera technology in the near future. Similarly, major contributions from the signal processing and communications communities will be needed to make the most out of nano-camera technology and, ultimately, the Internet of Multimedia Nano-Things.

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