Bioinspired Infrared Sensing Materials and Systems

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1. Introduction

This review presents an overview of the development of infrared (IR) sensing materials and systems, with the focus on the IR sensing materials and systems that are inspired by the biological systems. IR sensing systems provide information that are most of the time cannot be accessed through visible sensing systems. With the critical roles played by the IR sensing systems in a growing range of applications, the need of portable and high-performance artificial IR sensing systems drives the current technology development. Biological species, naturally, possess many miniaturized and high-performance IR sensing systems. Learning from nature, or taking lessons from these biological IR sensing systems, becomes an attractive approach in the current pursuit of advanced IR sensing materials and systems.

1.1. IR Sensing and Applications

IR light was first discovered by Sir Frederick William Herschel more than 200 years ago.[1] In general, IR spectral region (0.75–1000 µm) can be divided into five bands: near-IR (NIR: 0.75–1.5 µm), short-wavelength IR (SWIR: 1.5–3 µm), middle-wavelength IR (MWIR: 3–8 µm), long-wavelength IR (LWIR: 8–15 µm), and far-IR (FIR: 15–1000 µm) (Figure 1a).[2] Compared to photons of visible light, the photons of IR light have low energy per photon. Any object with temperature above absolute zero emits IR radiation, the wavelength of which depends on the temperature of the object. The emitted IR radiation from the object carries specific information and thus can be used in many different applications, especially in sensing applications. IR sensing technologies were initially developed exclusively for military use (Figure 1b).[3] as such as night vision, surveillance, or target tracking.[11] Due to their technology importance and relevance to many other technologies, the nonmilitary use of IR sensing technologies has been steadily growing.[4–23]

In medical care, IR sensing is widely used in monitoring body temperature (Figure 1c).[4] Compared with conventional thermometers, IR thermography (IRT) process is a fast, noncontact, and noninvasive method to measure and monitor body temperature. Different from the local measurement using the conventional thermometers, IRT can measure temperatures over a large area simultaneously. During one data acquisition process, IRT can map the distribution of body temperature to sort out the areas with abnormal temperatures. At present, IRT has been widely used in medical diagnosis, including fever screening, dermatology, breast cancer, and brain tumor imaging.[5–7]

IR sensing technologies, including IRT, are widely used for noninvasive temperature detection and mapping in many different industrial processes as well.[8–10] Figure 1d[10] as well as Figure 1e[8] shows two typical examples using IR sensing in industrial applications. Figure 1d shows the use of IRT in monitoring the electric power utilities, and Figure 1e shows the use of an IR camera in monitoring the working machineries.

As shown in Figure 1f,[11] IR sensing technologies can also help astronomers study space phenomena.[12–14] In the field of meteorology, IR sensing technologies play critical role too.[15,16] Figure 1g[17] shows an IR image of tropical storm Harvey in 2017 from NASA.

Bioinspired engineering offers a promising alternative approach in accelerating the development of many man-made systems. Next-generation infrared (IR) sensing systems can also benefit from such nature-inspired approach. The inherent compact and uncooled operation of biological IR sensing systems provides ample inspiration for the engineering of portable and high-performance artificial IR sensing systems. This review overviews the current understanding of the biological IR sensing systems, most of which are thermal-based IR sensors that rely on either bolometer-like or photomechanic sensing mechanism. The existing efforts inspired by the biological IR sensing systems and possible future bioinspired approaches in the development of new IR sensing systems are also discussed in the review. Besides these biological IR sensing systems, other biological systems that do not have IR sensing capabilities but can help advance the development of engineered IR sensing systems are also discussed, and the related engineering efforts are overviewed as well. Further efforts in understanding the biological IR sensing systems, the learning from the integration of multifunction in biological systems, and the reduction of barriers to maximize the multidiscipline collaborations are needed to move this research field forward.
In communication, IR-based technologies are primarily used indoor or in short range, either through direct point-to-point communication or diffusive communication (Figure 1h). IR-based communication systems are frequently employed between appliances and their digital assistants. The TV remote control is one typical example of using IR light for the communication between the operator and the TV (Figure 1i).

Besides the applications mentioned above, IR sensing systems are also widely used in the field of chemical and biological detection (Figure 1j,k). Figure 1j shows a typical design of a nondispersive IR (NDIR) gas sensor. This NDIR technology can be used to detect pollutants in air, such as sulfur dioxide (SO₂), carbon monoxide (CO), and nitrogen oxides (NOₓ). IR-based spectroscopy can also be used for biosensing. A recent research reported the use of graphene in improving the interaction between the IR and biomolecules for the enhanced sensing performance (Figure 1k).

### 1.2. Engineered IR Sensing Systems

In general, engineered IR sensing systems can be divided into two categories (Figure 2): photon-based sensing systems, which detect IR photons, and thermal-based sensing systems, which detect the thermal energy converted from the IR radiation.

Photon-based sensing systems detect IR photons by taking advantage of the interaction between IR photons and the electrons in the sensing materials. In the sensing materials, the electrons are either bound to lattice atoms or to dopant atoms or they are in the free form. In the sensing process, the incident IR photons are absorbed through intrinsic absorption by the lattice atoms, extrinsic absorption by the dopant atoms, or by free carrier absorption by the free electrons. Such absorption would change the energy distribution of those electrons and result in the change of the electrical output signals, which generates the sensing response. Typical photon-based sensing systems include the photoconductive detector, photovoltaic detector, photoelectromagnetic detector, and photoemissive detector. Among these sensing systems, photoconductive and photovoltaic IR detectors are the most common ones studied. Compared with photoconductive detectors, photovoltaic detectors have a faster response speed since the strong built-in electric field in the depletion region of the p–n junctions accelerates the movement of the photoexcited carriers.

In general, photon-based IR sensing systems have high signal-to-noise ratio and short response time, but cryogenic cooling is often needed to ensure the proper operation of the systems. Due to the low energy of IR photons, the bandgap of the sensing material should be narrow enough for the generation of the photon-excited carriers. For example, the photon energy of MIR is less than 0.7 eV, which requires the use of a sensing material with a bandgap of less than 0.7 eV. Such small bandgap can easily be overwhelmed by the thermal fluctuations in the surrounding environment, which competes with the targeted IR signal and results in significant thermal noise to the photon-based IR sensors. In order to suppress the thermal noise, cryogenic cooling is needed for the photon-based IR sensing systems, which makes such systems bulky, expensive, and also inconvenient to use. Today photon-based IR sensing systems are mainly limited to the applications in military, space, and research labs due to the above shortcomings.

On the other hand, thermal-based IR sensing systems are 10–100 times cheaper than photon-based IR sensing systems, and they are increasingly used for civil applications. The operation mechanism of thermal-based IR sensing systems is based on the temperature-induced change of material physical properties when the sensing materials are heated by IR radiation. As shown in Figure 2, thermal-based IR sensors usually consist of IR absorbers and thermosensitive materials. The IR absorbers can absorb and convert the photonic energy of IR photons into thermal energy to heat up the thermosensitive materials. The thermosensitive materials can respond with the change of their physical parameters as their temperatures change. Thermal-based sensors can respond to a broad...
spectral range and they can be operated at room temperature without the need of cryogenic cooling. Many thermal-based IR sensing systems, such as thermocouples, bolometers, pyroelectric sensors, and photomechanic sensors, have been demonstrated.\textsuperscript{[25–28]} Figure 2 shows the basic working principles of several typical thermal-based IR sensors. Thermocouples are based on Seebeck effect and they represent the early form of thermal-based IR sensors.\textsuperscript{[24]} In order to detect IR more effectively using thermocouples, a layer of IR absorptive material at the junction is always needed. Bolometers are another type of thermal-based IR sensors and currently they are the most used thermal-based IR sensors.\textsuperscript{[1,25,29]} The bolometer normally consists of a layer of IR absorber that absorbs IR photons to generate heat and a material with a high temperature coefficient of resistance (TCR) and small thermal capacity to generate a large change in resistance upon the temperature
increase induced by IR radiation. Different from the thermocouples, an accurately controlled bias current is needed to pass through the bolometers to produce the output voltage signal. As the temperature change induces the change of the resistance of the bolometers, the output voltage signal changes, which can serve as the readout for the IR radiation during the detection. Combined with a layer of IR absorber, pyroelectric materials, which change spontaneous electrical polarization states as the temperature changes, are also used in thermal-based IR sensors. As IR illuminates the pyroelectric sensor, the temperature of the sensor changes, which leads to the change of the spontaneous polarization and results in the change of the output voltage signal. Photomechanic sensors are also frequently used for the IR sensing applications. The schematic at the bottom right of Figure 2 shows the working principle of bimorph sensors, which represent one type of photomechanic sensors. The bimorph sensors typically consist of an IR absorption layer and a layer that has a coefficient of thermal expansion (CTE) different from that of the IR absorption layer. As the IR radiation is absorbed and the two layers are heated up, these two layers will experience different thermal expansion due to the mismatch in CTE, and such difference in expansion leads to the mechanical bending of the two layers and therefore generates the sensor readout, which most of the time is the change of the optical readout through the deflection of the visible detection beam due to the bending of the layers.

1.3. IR Sensing Materials and Systems Inspired by Biological Systems

Despite considerable achievements in both photon- and thermal-based IR sensing systems, the major research efforts in this field are still focusing on the development of systems that can provide outstanding sensing performance with small sizes, easy operation, and at reasonable cost. Among various efforts, bioinspired engineering of IR sensing materials and systems emerges as one of the promising alternative approaches to achieve portable and high-performance IR sensing systems. Bioinspired engineering of IR sensing is still at its early development stage, and the effort in this direction includes the study of structure–property relationship in biological species, and the use of the learning from such study in designing new materials and systems for high-performance IR sensing.

During billions of years of evolution, biological species have developed many sophisticated structures and superior functionalities in order to adapt to the environment and survive. The ultratoughness of seashells, the hybrid wetting property of the desert beetle wing structure, the quick adaptive capability of chameleons to the surroundings, and the outstanding thermal insulation property of polar bear furs are only few examples of the superior functionalities from biological systems. Bioinspired engineering, which takes learning from the biological systems in engineering man-made systems, becomes an attractive research area in solving practical problems.
through nature inspired approaches. As to the IR sensing, biological IR sensing from many biological species is not new to us. Rattlesnake,[48] fire beetles,[49] vampire bats,[50] etc., all have distinct IR sensing capability with their specific IR detection organs. For example, IR pit organ in rattlesnake is used to trace its prey by detecting IR radiation emitted from the prey. The IR sensing organs of fire beetles are used to locate the forest fires in order to lay their eggs in freshly burnt woods. The IR sensing organ of vampire bats enables them to pinpoint the blood-rich spots on their homoeothermic prey. Figure 3a shows the schematic of pit organ structures of rattlesnake,[48] which consists of similar structural design as in the engineered bolometers. Other biological systems, including bats, and some species of fire beetles (for example, Merimna atrata),[51] also have the bolometer-like IR sensing organs. Figure 3b[51] shows some other species of fire beetles (for example, Melanophila acuminata), whose IR sensing organs rely on the similar mechanism that is used by the engineered photomechanic IR sensors.[49] The detailed sensor structural features of both types of biological species will be discussed in the later part of this review.

Besides the biological species that have IR sensing capability, the biological species with thermal sensing capability can also inspire the developments of advanced IR sensors. Biological IR sensors sense IR radiation or sense the heat induced by IR radiation. Biological thermal sensors, on the other hand, can sense heat, no matter if the heat is induced by IR radiation or not. Many biological systems have developed their thermal sensing capabilities to detect the change of temperature because the temperature change can profoundly affect their biological functions. For example, many vertebrates have the thermogated ion channels, such as transient receptor potential cation channel subfamily V, member 1 (TRPV1) and subfamily A, and member 1 (TRPA1), to function as thermal sensors by converting thermal signals into bioelectrical signals (Figure 3c).[52] Due to the structural liability of nucleic acids and proteins in response to temperature change, these biomolecules are frequently utilized for thermal sensing in the biological systems as well. Inspired by the thermal sensors in biological systems, some man-made thermal sensors have been developed.[53–57] Certainly, if appropriate IR absorbers are integrated into these thermal sensors, they can be converted into IR sensors.

The development of advanced IR sensors is also inspired from some biologic systems with photonic structures even though they do not possess either IR or thermal sensing capability. For example, most butterflies do not have the function for the IR or thermal detection, but the elegant photonic structural designs of their wings also enable the development of high-performance IR sensors.[37,58] Figure 3d shows a typical

**Inspiration for thermal-based IR sensing**

![Figure 3. Four categories of biological systems for bioinspired IR sensing. a) Biological systems with bolometer-like IR sensing organs, including rattlesnakes (Reproduced with permission.[44] Copyright 2010, Macmillan Publishers Limited), vampire bat (Reproduced with permission.[45] Copyright 2011, Macmillan Publishers Limited), and some species of fire beetles (M. atrata) (Reproduced with permission.[51] Copyright 2004, Springer-Verlag). The schematic of IR organ of rattlesnakes (Reproduced with permission.[44] Copyright 2010, Macmillan Publishers Limited) is shown in (a). b) Biological systems with photomechanic IR sensing organs, including some species of fire beetles (M. acuminata) (Reproduced with permission.[51] Copyright 2004, Springer-Verlag). c) Biological systems with no IR sensing capability, but with thermal sensing capabilities. Vertebrates, such as mouse, with temperature receptors (thermal ion channel) are representative examples. The schematic of a mouse: Reproduced with permission.[53] Copyright 2015, Elsevier. The schematic of thermal ion channel: Reproduced with permission.[53] Copyright 2017, Wiley-VCH. d) Biological systems with photonic structures: butterfly wings represent this type of biological systems in inspiring the development of high-performance IR sensors.](image-url)
example of Morpho butterfly wing that inspires the development of IR sensors. The Morpho butterfly wings are well known for their brilliant structured color due to the interaction between light and nanostructures of the wings. Many sensors or sensory designs, including chemical\cite{99,60} biological,\cite{61} as well as temperature and IR sensors,\cite{37,58} have been developed using Morpho butterfly wings due to the sensitive visible output from the wing structure.\cite{37,58–60,62}

Engineered IR sensing includes both photon-based IR sensing and thermal-based IR sensing, and there have been excellent reviews for these IR sensing technologies.\cite{1,2,25–28} For bioinspired IR sensing, most of the current approaches center on thermal-based IR sensing (Figure 3). With the exciting progress of bioinspired engineering approach,\cite{36–40} this review focuses on the development of IR sensing materials and systems that are inspired by biological systems, especially with the focus on the most recent advancement in this area. Specifically, the rest of the review will be organized around the following four areas, all of which rely on the learnings from biological systems:

1. **Inspiration from Biological Bolometer-Like IR Sensing:** Biological species, such as snakes, vampire bats, and some species of fire beetles, have specific organs, which have similar structural design as in the engineered bolometers, to detect IR radiation. In this section, the studies of these typical examples of biological bolometer-like IR sensing organs will be introduced to help understand the structure–property relationship and also the IR sensing mechanism in the corresponding biological systems. The related research inspired by those biological systems for IR sensing is discussed in this section as well.

2. **Inspiration from Biological Photomechanic IR Sensing:** Some species of fire beetles have IR sensing organs that rely on the photomechanic detection mechanism. Such mechanism is also frequently used in engineered photomechanic IR sensors. In this section, the studies of these typical examples of biological photomechanic IR sensing organs are introduced to help understand superior remote IR sensing capability of these fire beetles. This section also discusses the engineering efforts inspired by those biological photomechanic IR sensing systems.

3. **Inspiration from Biological Thermal Sensing:** Some biological molecules, including DNA, RNA, and proteins, can function as thermosensors through changing their conformations in response to the change of temperature. In addition to these biomolecule-based thermosensors, there are also some complex biological temperature sensor systems, including the cell membranes and some ion channels that mostly are embedded within the cell membranes. In this section, the studies of these examples of biological systems with thermal sensing capability are introduced first. The research efforts on thermal or IR sensing based on these biological systems are then reviewed. The possibility of converting the thermal sensors to IR sensors is also discussed in this section.

4. **Inspiration from Biological Photonic Structures:** Besides learning from the biological systems that have IR or thermal sensing capability, some other biological systems with elegant photonic structural designs can also inspire the new development of advanced IR sensors. For example, the iridescent color of Morpho butterfly wings inspired the development of high-performance IR sensors. In the section, we introduce the structural properties of the wings of Morpho butterflies, and then provide overview of the thermal or IR sensing systems that are inspired by the biological photonic structures. We also re-examine some of these bioinspired thermal sensing systems for the potential usage in IR sensing.

## 2. Inspiration from Biological Bolometer-Like IR Sensing

As discussed above, most bolometer-based IR sensors have an IR absorber to convert IR energy into heat and a thermal-sensitive system to directly sense the temperature change induced by the heat. Through natural selection, some biological systems have also developed bolometer-like IR sensing organs. Some species of snakes, vampire bats, and some species of fire beetles are typical examples of these biological systems with bolometer-like IR sensing organs due to the configuration of their IR sensing organs. For example, in the families of boas (Boidae), pythons (Pythonidae), and the subfamily Crotalinae of the family of Viperidae, they have both an IR absorber to convert IR energy into heat and a thermal-sensitive system to directly sense the temperature change in the IR sensing organs. Vampire bats have also developed bolometer-like IR sensing organs that have basic components for IR absorption and temperature sensing to capture their endothermic prey. Except these IR sensing vertebrates, some species of insect beetles, such as in Acanthocnemus and Merimna, have also displayed the bolometer-like IR sensing organs, which include the IR absorbing area and the temperature sensory complex that is below the IR absorbing area to sense temperature change induced by the absorbed IR energy. Before mimicking the IR sensing capability of biological species, the underline structural or molecular mechanisms that enable such function should be understood. In this section, we first present the research findings on these typical examples of biological systems with bolometer-like IR sensing capability, and then discuss the efforts in generating man-made systems that are closely related to these biological systems.

### 2.1. Inspiration from Snakes with Bolometer-Like IR Sensing

Most snakes have a pair of eyes that can see, more or less, the same wavebands of light as human eyes. The families of boas (Boidae), pythons (Pythonidae), and the subfamily Crotalinae of the family of Viperidae have additional “eyes” that can “see” the light in the IR range.\cite{35} These “eyes” are termed as “pit organs” or “pits.” Almost all pythons and Crotalinae studied so far have pit organs while some members of boas only have IR receptors. The function of pit organs is to detect the IR radiation from the prey and provide additional information for efficient prey targeting.

Scientists first discovered the pit organs in the rattlesnake ≈330 years ago, but not till the year of 1937 the pit organs were
confirmed with detection function for IR radiation.\textsuperscript{[63]} The work from Bullock and Dieke reported in 1956 on the successful recording of the action potentials from single neurons established the basis for the further research on the pit organs.\textsuperscript{[64]}

The detailed microstructures of the snake IR pit receptors were studied using both scanning electron microscopy (SEM) and transmission electron microscopy (TEM) techniques.\textsuperscript{[63,65]}

Furthermore, the studies by Christensen and co-workers confirmed the temperature-sensing function of the pit organ.\textsuperscript{[66]}

The surrounding tissues of the pits are responsible to convert IR radiation into thermal energy due to their strong IR absorption properties.

In 2010, the molecular basis for IR sensing of snakes was further elucidated by Hollopeter and co-workers.\textsuperscript{[48]}

Through an unbiased transcriptional profiling approach, the TRPA1 channels were identified to be the IR receptors on the sensory nerve fibers of the pit organ. This work demonstrated that the IR sensing by the snake pit organs was through the thermo-sensing process of TRP channels, and not through the photochemical transduction process.

Although the pit organs are developed for the purpose of IR detection, their morphologies, numbers, as well as the locations are different among different species of snakes. The pythons and boas belong to categories of ancient snakes and their pit organs are relatively simple. Figure 4 shows the structures of the pit organs for both species. The location of the IR pit organs on pythons (\textit{Python molurus}, Figure 4\textsuperscript{a,b,c}) is presented in Figure 4\textsuperscript{b} (side view) and Figure 4\textsuperscript{c} (front view)\textsuperscript{[67]}. As schematically shown in Figure 4\textsuperscript{d}, the pit organ of pythons contains an open cavity structure with the IR receptors located at the bottom of the cavity.\textsuperscript{[63]} The bottom of the cavity is known as the “pit fundus” and it also functions as a retina. The atomic force microscopy (AFM) image of the living surface tissue (Figure 4\textsuperscript{e}) shows the receptor areas of the pythons, which display terracelike microstructure with nanopit arrays dispersed at the surface.\textsuperscript{[68]}

The average spacing between the nanopits was $\approx$520 nm, and such spacing helps efficiently filter out both the UV and visible signals for the sensitive IR detection.

The IR receptors in the boas are located around scales and they have different morphology from that of pythons (Figure 4\textsuperscript{f–h}).\textsuperscript{[63]} For the boa without pits, the IR receptors are found on the edges of their scales (Figure 4\textsuperscript{g}). For the boa with pits, the deep pockets between the scales form the pits, and the IR receptors are at the same locations as those of boa without pits. Unlike pythons, no IR receptors are presented in the bottom of the pits of boas.

Compared to boas and pythons, pit vipers (Figure 5\textsuperscript{a}) represent a modern type of snakes and their pit organs show more complex morphology and structure than those of boas and pythons.\textsuperscript{[63]} The pit organ of pit viper consists of three parts (Figure 5\textsuperscript{b}): an outer chamber, an inner chamber, and a pit membrane that separates these two chambers.\textsuperscript{[63]}

The terminal nerve masses (TNMs) embedded in the pit membrane serve as thermal receptors to sense the temperature change of the pit membrane.\textsuperscript{[66]}

The IR receptors in pit membrane are suspended and such arrangement helps decrease the heat capacity of the detection components and improve the IR detection sensitivity.

Similar configurations can be revealed when comparing the IR sensing organ of a pit viper and also a typical structure of engineered bolometer (Figure 5\textsuperscript{b,c}). The IR absorbing components in both systems, pit membrane in pit viper and IR absorber in bolometer, are suspended. The readout components of the temperatures of the IR absorbing components are

![Figure 4](https://example.com/figure4.png)

**Figure 4.** IR sensing systems in pythons and boas. a) An optical image of \textit{P. molurus} (Pythonidae). The head of \textit{P. molurus} from side view b) and front view c). The arrows point out the location of the pit organs. d) Schematic illustration of the cross-sectional morphology of a single pit organ of a pythonid (e.g., \textit{P. molurus}). The pit fundus with IR receptors at its surface acts as a retina in sensing IR radiation. e) AFM image of the surface within the pit organ of \textit{Burmeister python}. f) An optical image of \textit{C. caninus} (Boidae). g) Schematic illustration of the IR receptor structure of a boa without pits (e.g., \textit{Boa constrictor}). The IR receptors are located at the edges of the scales. h) Schematic illustration of the IR receptor organ of a boa with pits (e.g., \textit{C. caninus}). The location of IR receptors is the same as boa without pits, but deeper invaginations separate the scales with IR receptors to form pits. a,d,f,g,h) Reproduced with permission.\textsuperscript{[61]} Copyright 2011, Society for the Study of Amphibians and Reptiles. b,c) Reproduced with permission.\textsuperscript{[67]} Copyright 2001, Elsevier. e) Reproduced with permission.\textsuperscript{[68]} Copyright 2001, American Chemical Society.
slightly different: in pit vipers, the temperature is sensed by the TNM embedded in the pit membrane through temperature-sensitive ion channels; in bolometer, the temperature is measured through the change of the electrical resistance within the thermal-sensing layer.

More detailed structural features of the pit organ are revealed under the electron microscope. As displayed in Figure 5d–f, the top surface of the pit membrane contains a large number of micropits with 0.25–0.5 µm in depth and the density of these micropits is \( \approx 3.66 \mu \text{m}^{-2} \).\(^6\) Such unique structure is considered to be favorable for filtering off the visible light with wavelength centered around 500 nm.\(^6\) The back wall of the pit facing the inner chamber is covered with many dome-like structures, which are also covered with many small depressions at their surfaces (Figure 5f). These dome-like structures act as light traps and are useful to prevent the back scattering of IR radiation that transmit through the pit membrane.\(^6\) The roughness on the surface of domes can help scatter the visible light that penetrates through the membrane. The special structural design of the pit organ of the pit vipers is useful to filter out the light with unnecessary wavelengths and enables maximum sensitivity to the IR photons in the wavelength range of 8–12 µm.

The structural features of IR sensing organs in pit vipers enable their unique functions, including wavelength-selective design that can filter out visible light for the sensing of the light in the IR region. As shown in Figure 6a, the pit membrane works as an optical grating due to its unique microstructure.\(^6\) Most of the incident IR radiations (red lines) are absorbed by the pit membrane while most of the incident visible lights (green lines) are reflected by the pit membrane. The visible lights that penetrate through the pit membrane will be scattered between the micropits on the surfaces of back wall of the pit and micropits on the inner surface of the pit membrane. The IR lights that penetrate through the pit membrane will be absorbed in

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**Figure 5.** The architecture of the pit organ of a pit viper, *Gloydius blomhoffii*. a) The optical image of *G. blomhoffii* (Crotalinae). The arrow indicates the location of the pit organ. b) Schematic illustration of the cross-sectional morphology of the IR pit organ of a crotaline (e.g., *G. blomhoffii*). a,b) Reproduced with permission.\(^6\) Copyright 2011, Society for the Study of Amphibians and Reptiles. c) The schematic of the engineered bolometer. d) The optical image of a cross-section through the pit organ. The scale bar is 10 µm. e) The SEM image of the outer surface of the pit membrane. The scale bar is 5 µm. f) The SEM image of the surface of the back wall of the pit membrane. The scale bar is 2.5 µm. d–f) Reproduced with permission.\(^6\) Copyright 2011, Society for the Study of Amphibians and Reptiles.
Figure 6. IR pit organs and man-made IR sensors. a) The schematic illustration of how the surface architecture of the pit organ shown in Figure 5 enables the wavelength selectivity for IR sensing. The black points in the pit membrane are TNMs that work as heat receptors. Reproduced with permission.[63] Copyright 2011, Society for the Study of Amphibians and Reptiles. b) The schematic of spectrally selective thermal IR detectors. c) The schematic of the plasmonic piezoelectric nanomechanical resonant IR sensor. An aluminum nitride piezoelectric film is sandwiched between a top nanoplasmonic metasurface and a bottom metallic electrode. The nanoplasmonic IR absorber selectively absorbs the IR radiation to heat the resonator. The resonator, the resonance frequency of which is dependent on the temperature, shifts its resonance frequency from $f_0$ to $f'$. d) The measured absorption spectra of the piezoelectric plasmonic resonant structure demonstrated in (c) with different Au patch sizes. Through changing the unit cell size, the absorption spectra can be adjusted. The unit cell sizes of different designs are as follows: design A: $a = 1780$ nm, $b = 128$ nm; design B: $a = 680$ nm, $b = 253$ nm; design C: $a = 640$ nm, $b = 313$ nm; design D: $a = 1620$ nm, $b = 331$ nm. c,d) Reproduced (Adapted) under the terms of CC BY 4.0.[70] Copyright 2016, Nature Publishing Group. e) The schematic of a hybrid PA-PIRs. The dashed rectangle is the simulation domain. The geometrical parameters include $p$ (periodicity), $d$ (the diameter of Au hole), and $t$ (the thickness of pyroelectric ZnO). f) Simulated absorption spectra of PA-PIRs demonstrated in (e) with varied $d$ (1.4, 1.8, 2.4, and 2.7 µm). The periodicity and the thickness of ZnO are 3.0 and 0.68 µm, respectively, for all four samples. e,f) Reproduced with permission.[71] Copyright 2016, American Chemical Society. g) The schematic of a thermopile with Au-based 2D plasmonic crystals as an IR absorber. h) The calculated absorption of the plasmonic IR absorber demonstrated in (g) with the changing of period. g, h) Reproduced with permission.[72] Copyright 2012, AIP Publishing LLC.
the light traps that are formed by the clustered large and small domes on the back wall of the pit, which will prevent the back-scattering of IR lights and improve the quality of IR images.

In recent years, there is a trend to develop wavelength-selective IR sensors that only respond to a small spectral region of IR radiations.\cite{70-73} To achieve the wavelength selectivity, the conventional IR sensors usually were modified by a selective absorber (Figure 6b), for example, a plasmonic absorber. Since the plasmonic absorbers only absorb IR radiation at specific wavelength, the IR sensors with special designed plasmonic absorbers could provide wavelength selectivity. Several recent researches in this area are shown in Figure 6c–h. Rinaldi and co-workers demonstrated a plasmonic piezoelectric nanomechanical resonant IR sensor by combining a nanoplasmonic metasurface with the piezoelectric mechanical resonator (Figure 6c).\cite{70} The nanoplasmonic metasurface-based IR absorber can selectively absorb the IR radiation to heat the resonator to generate output signal, and the whole system therefore has spectral selectivity in IR detection. As shown in Figure 6d, the absorption spectra could be tuned through changing the size of the unit cell of the IR absorber. Nagao and co-workers exploited a hybrid plasmonic–pyroelectric IR detector (PA-PIR) with narrowband spectral selectivity (Figure 6e).\cite{71} The IR detector was made of an Au-based plasmonic absorber and a pyroelectric ZnO layer. The plasmonic absorber selectively absorbed the IR radiation at the plasmonic resonances to generate heat and subsequently affected the electrical polarization states of the pyroelectric ZnO layer. By adjusting the structural parameters of the plasmonic IR absorber, the detectable wavelength of IR radiation to the system could be modulated (Figure 6f). Kimata and co-workers developed a wavelength-selective IR sensor by modifying the IR absorber layer of thermopile (Figure 6g).\cite{72} In the device, the Au-based 2D plasmonic crystals only absorbed IR radiation at specific wavelength to generate heat that could be detected by the thermocouple. The absorption wavelength of the IR absorber layer could be adjusted by changing the structural parameters as well (Figure 6h).

As shown in Figure 6, the configurations of these plasmonic absorbers are actually very similar to that of microdepressions at the surface of pit membranes of pit vipers. Further optimizing the design of these absorbers by leveraging the learning from the structure of pit organs of pit vipers may provide unique opportunities in enhancing the performance of those man-made wavelength-selective IR sensing systems.

Inspired by the microstructure of the biological pit organ, Tsukruk and co-workers proposed a possible design of photothermal IR sensor.\cite{74} In their design, hollow microsphere lattice were used as the thermal barrier to mimic the low thermal conductivity of the IR receptor in Ball python, and a gradient photonic lattice was used to scatter the non-IR light to mimic the function of pit membrane of pit vipers. Using such design, the absorbed IR radiation by gradient photonic lattice could be converted into thermal energy, which led to the variation of the lattice spacing due to thermal expansion. Through characterization of the photonic lattice using laser reflection, the IR radiation could be detected. The proposed design well imitated the working function of the IR pit organs of the snakes and might open up the possibility in engineering of man-made “snake-like” IR sensing systems.

Among all the creatures that have IR sensing capability, snakes might be the only one that not only can detect IR radiation, but also can form the IR image of the subjects. As shown in Figures 4 and 5, the pit openings of pythons and pit vipers are smaller than the receptor area and they function like the aperture of a pinhole camera. When an object in the snake visual field moves or the snake moves, different part of the receptor area will be illuminated due to this configuration of the pit organs, and a series of action potentials can thus be created. The mapping of action potential can be interpreted as IR patterns or images by the central nervous system. Such mapping function enables snakes to locate the prey targets accurately even in the complete darkness, which the engineering IR detectors can learn from for further improvement of the IR detection function.

2.2. Inspiration from Bats with Bolometer-Like IR Sensing

To detect the IR radiation from the endothermic prey, vampire bats also develop sensing organs that have basic components for IR absorption and temperature sensing, which are similar to those of bolometers. They are the only mammal known to have such IR organs.\cite{75} As shown in Figure 7a, three “leaf pits” are located between nasal pads and the noseleaf of the bat.\cite{76} Vampire bats modify a heat-sensitive TRPV1 ion channel by alternative splicing of TRPV1 transcripts to produce a channel with a truncated carboxy-terminal cytoplasmic domain to lower its thermal activation threshold from close to 40 °C to close to 30 °C.\cite{77} Figure 7b shows the protein sequences of this short TRPV1 (TRPV1-S) and long (TRPV1-L) isoforms. HEK293 cells expressing vampire bat TRPV1-S or TRPV1-L showed different temperature response (Figure 7c). TRPV1-S was activated at a substantially lower threshold (30.5 ± 0.7 °C) than TRPV1-L (39.6 ± 0.4 °C). Currently, research reports of engineered IR sensing systems that are inspired by the design of the IR sensing systems in bat are still lacking. With further growth of the research in this area, there will be efforts in taking advantages of the IR sensing ability of the vampire bats, in combination with their unique ultrasonic detection capability for the development of multifunctional IR detection systems.

2.3. Inspiration from Fire Beetles with Bolometer-Like IR Sensing

Among all the species that possess IR receptors in nature, fire beetles received probably the most attention in the studies of IR sensing that are related to biological systems. The larvae of fire beetles need to live on the freshly burnt woods to avoid the defense reaction from the living trees. Since forest fire happens not so frequently, fire beetles need to quickly find the freshly burnt woods to allow their offspring to hatch and grow safely.\cite{19,77,78} Such survival manner of the fire beetles is enabled by their sensitive IR receptors. Some species of fire beetles have photomechanic IR sensing organs, which is discussed in the next section. Some species of fire beetles, such as Acanthocnemus and Merimna, have bolometer-like IR sensing organs (Figure 8). The IR organs of M. atrata are located on
lateral sides of the second and third abdominal sections, and consist of external cuticle and internal sensory complex. The shallow dint of the cuticle is an area that absorbs the IR radiation. The diameter of the nearly circular absorbing area is \( \approx 300–400 \) \( \mu \)m, and the surface of this area has honeycomb-like microstructures (Figure 8b). The sensory complex is just below the absorbing area and contains multipolar neuron. The multipolar neuron has a special dendritic region called terminal dendritic mass (TDM), which innervates the IR absorbing area. The TEM image and schematic of multipolar neuron structure are shown in Figure 8c,d. When the cuticular area absorbs the IR radiation, the neuron can sense the temperature change by changing its spike frequency. Even though the structure of IR sensing organ in Figure 8 is different from that of pit viper, the major sensing components, including the IR absorbing component and the temperature-sensing component, are both similar to that of a bolometer. Such structural design provides another alternative in designing engineered bolometer.

### 3. Inspiration from Biological Photomechanic IR Sensing

For the photomechanic IR sensing mechanism, the sensing system absorbs the IR radiation and converts it into mechanical signal for the readout device. There are different forms of man-made photomechanic IR sensors, including bimorph IR sensors discussed in the introduction (Figure 2). In nature, the IR sensing organs of some fire beetles, such as *Melanophila acuminata* and *Aradus*, represent the most well-known photomechanic IR sensors.
Figure 9 provides the structural details of IR sensilla of *M. acuminata* (Figure 9a).[85] As can be seen, in each of the pit organ there are ≈70 dome-shaped sensilla with diameter of ≈15 µm (Figure 9b).[39] Electron microscopy studies revealed more detailed structural features of the beetle pit organ.[39,86]

As shown in Figure 9c,d, a single sensillum consists of four components: the outer layer is a hard exocuticular shell while the inner core is a soft spongy cavity filled with water. Between the core and the outer shell, there is an onion-like multilayer zone that is composed of chitin fibers. These three components form the IR absorber of a sensillum, while the dendrite, the forth component, functions as the IR receptor to transfer the IR stimuli to the neuron. As commonly agreed, these fire beetles, such as *Melanophila* and *Aradus*, sense the IR radiations through a photomechanic process.[78,84,87] It has been reported that the protein and chitin, as well as the water inside the sensilla can absorb the IR radiation around 3.0 µm due to the vibration mode of specific chemical groups, such as C–H and O–H. The emission maximum of IR radiation from a forest fire also centers around such wavelength region.[78,86,88] The experimental setup and the data are shown in Figure 10.

The pit organ was exposed to IR light with different radiation energy and wavelength. The decreasing of radiation energy increased interspike time between spikes and decreased the spike number.[90] From their calculation, *Melanophila* can detect a 10-hectare forest fire even 12 km away from the fire. Recently, this group suggested that the sensitivity of fire beetle may even reach to a few nW cm⁻² by in-depth analysis of a historic oil tank fire, and the beetle was found to be able to detect the fire from a distance of 130 km.[91]

Based on the studies of the microstructures as well as the understanding of the mechanism of the IR sensing in fire beetles, various research groups have explored different ways to generate artificial IR sensing systems that mimic the IR sensing systems in beetles. As early as 1947, Golay invented a pneumatic IR sensor (Golay sensor).[92] As illustrated in Figure 11a, a Golay sensor contains a transparent window, a gas-filled cell, a detecting membrane and an optical system serving as the readout system.[87] When the system is heated by the IR radiation, the pressure in the gas-filled cell increases, which leads to
the deflection of the deformable membrane. The deformation of the membrane can be monitored by the optical readout system so the IR radiation can therefore be detected. Although Golay did not realize at the time when he invented Golay sensor, the similarity of the sensing mechanism between Golay sensor and the IR pit organs of the beetles was evident. Fifty years later, Schmitz and co-workers designed a Golay cell that was even closer to the design of the IR sensilla of the beetles by replacing the gas in the cavity with a liquid due to the higher absorption coefficient of the liquid than the gas.[39] The schematic diagram of liquid-filled IR sensor inspired by beetle is shown in Figure 11b.[87] To optimize the sensitivity in the IR sensing, different types of liquid were also tested under the IR radiation with the same illumination power density.[39] With proper combination of both the IR absorption and thermal expansion of the liquid, optimized IR sensing performance can be achieved.

Another effort inspired by the fire beetles was reported by Steltenkamp and co-workers, who created a µ-biomimetic IR sensor that was inspired by the photomechanic mechanism of IR receptors of M. acuminate using micro-electromechanical

![Diagram](image_url)

**Figure 10.** a) Experimental setup for electrophysiological recordings of Melanophila beetle. The inset shows the emission spectrum of the ORIEL IR element at a power of 9 W. The response of pit organ exposed to b) unfiltered IR stimulus, c) 1.65 µm longpass filter inserted into the camera shutter, d) and 2.4 µm longpass filter inserted into the camera shutter. a–d) Reproduced with permission.[85] Copyright 1998, Springer-Verlag.

![Diagram](image_url)

**Figure 11.** a) Schematic of the Golay IR sensor filled with gas. b) Comparison of the fire beetle sensillum with the man-made IR sensor inspired by fire beetles. a,b) Reproduced under the terms of CC BY 2.0.[87] Copyright 2011, Beilstein-Institut. c) The schematic model of the sensillum with nanocanals. d) The schematic model of IR sensor with cavity and reservoir that are linked by canal of the compensation leak: \(V_C\) (volume of cavity), \(P_C\) (pressure of cavity), \(V_R\) (volume of reservoir), and \(P_R\) (volume of reservoir). c,d) Reproduced under the terms of CC BY 4.0.[39] Copyright 2015, MDPI AG.
system technology.[84] Such IR detection system exhibits almost
the same design as that of the sensillum of the fire beetles.
The µ-biomimetic design was fabricated on silicon wafer with a
polydimethylsiloxane (PDMS) cover on top and a glass sub-
strate at the bottom. The device includes two components:
the reception unit and the compensation unit. In the recep-
tion unit, a Si$_3$N$_4$ membrane coated with gold was used as the
deflection component, which also served as the lower electrode
of the plate capacitor. IR detection could be realized by moni-
toring the capacitance change when the heated water expanded
and subsequently deflected the Si$_3$N$_4$ membrane. The compen-
sation unit of the device is linked with the pressure chamber
through a thin channel (Figure 11d) to minimize the distur-
bance from the ambient, similar to the function of nanocanals
in the beetle sensillum (Figure 11c). In their later work, the
relationships between temperature and amplitudes of capaci-
tance change under different modulation frequencies were
established by using a simplified sensor.[83]

Besides the direct mimicking of IR sensilla of beetle
M. acuminata discussed above, some other IR sensing approaches
that do not directly mimic the structure but are inspired by
the IR sensing principles of fire beetles were also investig-
gated. Recently, Luo et al. reported the use of thermorespon-
sive hydrogel nanoparticles (NPs), poly(N-isopropylacrylamide)
(PNIPAM) NPs, for the IR sensing application (Figure 12). [93]
Similar to the volume change of the fluid in sensilla induced by
IR radiation, the synthesized PNIPAM NPs also changed their
volume under the IR radiation. Instead of expansion, however,
the NPs showed the opposite volume change and shrunk to the
collapsed state at temperature above the lower critical solubility
temperature (LCST). Consequently, the volume change of the
NPs led to the change of their refractive index and therefore
provided an effective readout by building up the relationship
between optical transmission and temperature. Based on the
study on the NPs with a series of sizes and concentrations, the
sample of NPs (∼120 nm in diameter) with 0.09 wt% displayed
the highest temperature sensitivity of 29 mK, which is compara-
tble to the temperature sensitivity of many other man-made
IR sensing systems. Using PNIPAM NPs in solution as the
IR absorber and the transmittance of the NP solution as
the optical read out provides a sensitive bioinspired system for
the uncooled IR detection.

Hirata et al. explored the thermal response of ultrathin
PNIPAM layer by using the surface plasmon resonance
(SPR) technique.[94] As a sensitive detection tool, the SPR
technique has been broadly used for different sensing
applications such as chemical and biological sensing.[95–99]
In their work, PNIPAM layers with different thickness
were spin coated on a layer of gold followed by drying at
elevated temperature. Due to the high sensitivity of SPR
to the change of surface refractive index, the temperature-
induced refractive index change of PNIPAM film can easily
be detected using SPR.

Besides the PNIPAM film on Au system reported by
Hirata et al., there are also reports of other configurations
of the PNIPAM-Au systems with temperature-sensing capa-
bility. For example, Lee et al. reported a hybrid SPR coupling
sensor with the configuration of Au-film–PNIPAM–AuNP,
in which the Au NPs and Au film are separated by a layer of
PNIPAM (Figure 13a).[100] Due to the plasmonic coupling
between the Au NPs and Au film, the sensitivity of Au-film–
PNIPAM–AuNP system to temperature was enhanced greatly
compared to the system of Au-film–PNIPAM without the
coupling effect. The temperature sensitivity of the Au-film–
PNIPAM–AuNP system was also observed to be influenced by
the densities of AuNPs on the surface (Figure 13c,d). Similar
Au-film–PNIPAM–AuNP plasmonic coupling system was also
reported by Ding et al.[101] In their study, a dynamic, ultrafast
color switching performance upon temperature stimuli was
obtained (Figure 13e,f). Such plasmonic coupling system with
enhanced temperature sensitivity provides an opportunity
to use the PNIPAM–SPR system for the high-performance
uncooled IR sensing.

Rather than using PNIPAM film, Luo et al. further con-
structed an uncooled plasmonic IR sensing system based on
the PNIPAM NP–Au film.[102] The IR sensing principle using
such system is schematically illustrated in Figure 14a. In the
study, a layer of poly(NIPAM-co-AAc) NPs was immobilized
on the Au film through crosslink reaction using cysteamine
hydrochloride. Under the IR illumination, the temperature
of the hydrogel NPs increased. Such increase in tempera-
ture resulted in the collapse of the NPs, which in turn shifted
the SPR angles to provide the sensing signal. Figure 14b shows
the setup used in the performance characterization.[103]

Figure 14c,d shows the temperature-dependent SPR curve
shift and angle shift. The diameter of PNIPAM NPs used
was ∼360 nm. With the increase of the temperature, the SPR
angle increased with the maximum sensitivity reached to
28 mK in the temperature range of 37–38 °C. Further tuning
the size of PNIPAM NPs should optimize the sensitivity of
the system. Due to the individual response of the particles,
such system also provides the potential in high-resolution
IR imaging.
4. Inspiration from Biological Thermal Sensing

There are only limited numbers of biological systems that have IR sensing organs, and most of these systems fall into the two major categories of IR sensing mechanism (bolometer or photomechanic) as discussed above. There are many other biological systems that do not have IR sensing capability, but have thermal sensing capability, which can also inspire the development of engineered IR sensing technologies. In this section, we first discuss the thermal sensing of biological molecules, including DNA, RNA, and proteins. These biomolecules respond to the change of temperature through the adjustment of their conformation. More complex biological temperature sensor systems, including the cell membrane and some ion channels that are embedded within the cell membranes, are also discussed in this section. The physical state of the membrane, such as the membrane fluidity, can be affected by the change of temperature, which can then change the transmembrane protein–lipid interactions and induce the cell signaling. As temperature changes, the conformation of thermosensitive transient receptor potential channels (thermoTRPs) changes. Such conformation change results in the opening or closing of the channels, affects ion permeation, and generates action potential signals. At the later part of this section, the engineered IR or thermal sensing technologies that are inspired by the above systems are discussed.

Temperature is an essential parameter that affects the behavior of organisms. Living organisms can detect the
temperature change through different thermosensing mechanisms, transduce such change into physiological signals, and subsequently adapt to the temperature change in their environment. At the molecular level, biological molecules, including DNA, RNA, and proteins, can function as thermosensors.[104–109] They change their conformations in response to the change in temperature and subsequently initiate signaling cascades.[106,107] For example, temperature change would affect the topology of DNA and impact the cellular gene expression.[108,109] The 3D structure of mRNA is sensitive to the change of temperature that enables the modulation of the signal translation.[108,109] Protein-based thermosensors include chemosensory proteins, transcriptional regulation proteins, chaperones, and also proteases. The tertiary and quaternary structures, sometimes even the secondary structure of the proteins, are very sensitive to the temperature change.[108,109] The conformation and the assembly of the proteins thus show temperature dependence, which in turn affects the functions of the proteins.

Besides the biomolecule-based thermosensing, some complex biological temperature sensor systems involve the response of collective molecules. The change of the membrane properties upon temperature variation is a typical example.[109,110] Serving as the boundary between the internal cellular components and the external environment, the membrane can directly sense the stimuli from the extracellular and transfer such signal into the cell to initiate cellular response. The function of the membrane closely depends on the physical state of the membrane. It is discovered that the temperature change would affect the membrane fluidity and causes the changes in the membrane thickness.[109,111] Such change in the physical property of the membrane would alter the transmembrane protein–lipid interactions and induce the cell signaling. Besides thermal sensing by membrane itself, some ion channels, which mostly are protein complex embedded within the cell membranes, also have the function of thermal sensing.[110,112–113] These ion channels include the thermoTRPs, the anoctamin chloride channel family, and also the TREK-1 potassium channel. Among those ion channels, the thermal sensing property of TRP channels has been studied the most.[110,114–118] Both heat-activated TRP channels and cold-activated TRP channels belong to thermoTRPs and different ion channels sense temperature in different ranges.[110,118] It is believed that the temperature change would induce the conformation change of the thermoTRP channels and result in the opening or closing of the channels. The structural change of the TRP channels would trigger the membrane depolarization that in turn can regulate the ion permeation, leading to formation and propagation of action potentials to send signals to the brain. As shown in Figure 15a, TRP channels in sensory neurons can sense multiple stimulations, including thermal, pH/chemicals or mechanical stimulations.[118] In thermal sensing, different thermoTRPs work in different temperature ranging from noxious heat to noxious cold (Figure 15b).[117] TRP cation channel subfamily V, member 1 (TRPV1), member 3 (TRPV3), and member 4 (TRPV4) respond to warm temperatures, and member 2 (TRPV2) is activated by noxious heat; TRP cation channel subfamily M, member 8 (TRPM8), plays a key role in sensing cold environment, and TRPA1 is only active in cold hyperalgesia. Figure 15c shows TRPV1 and TRPV2 in nerve fibers that sense heat. The opening of TRPV1 and TRPV2 that is induced by the heat causes cell depolarization, which triggers the opening of voltage-gated Na⁺ and Ca²⁺ channels, and then the action potentials are generated to send the heat signals to the brain.
brain. The thermoTRPs are the principal heat receptors in the peripheral nervous system of many vertebrates, and they show the ability to detect a wide range of temperature (Figure 16).[52] These biological temperature-sensing mechanism certainly provide unique inspiration for the engineering of advanced thermo-based IR sensing systems.

Inspired by the thermosensing properties of the biological systems, Naik et al. investigated a protein-based temperature sensor based on TlpA protein.[54] The TlpA protein is an \(\alpha\)-helical protein that exists in the form of an elongated coiled-coil homodimer at low temperature. The conformation of the protein dimer is highly sensitive to temperature, and the increase of the temperature would induce the unfolding of the dimer to random coil. Such unfolding process is also rapid and reversible. Combining the high sensitivity of TlpA protein to temperature change with the incorporation of the green fluorescent protein (GFP) as the fluorescence indicator, Kiyonaka et al. further demonstrated that such system showed great potential as the temperature sensor, especially for the visualization of subcellular thermoregulation in living cells (Figure 17a–c).[55]

Using protein cytochrome c (cyt c) in IR sensing also attracts considerable attention.[119–122] Cyt c is a type of globular protein

| Vertebrates | Zebrafish | African clawed frog | Mouse |
|-------------|-----------|---------------------|-------|
| Heat receptors | TRPV1, >32 °C | TRPV1, >40 °C TRPA1, >38 °C | TRPV1, >42 °C |

| Vertebrates | Chicken | Pit viper | Vampire bat |
|-------------|---------|-----------|-------------|
| Heat receptors | TRPV1, >46 °C TRPA1, >40 °C | TRPV1, >40 °C TRPA1, >37 °C | TRPV1-long, >46 °C (body) TRPV1-short, >29 °C (pits) |

Figure 15. Thermosensitive transient receptor potential ion channels (thermoTRPs). a) Multiple TRP channels are expressed by sensory neurons. b) The schematic of thermoTRPs that work in different temperature ranging from noxious cold to noxious heat. a,b) Reproduced under the terms of CC BY 3.0.[118] Copyright 2012, MDPI AG. c) The schematic of the detection of heat by TRPV1 and TRPV2 in nerve fibers. Reproduced with permission.[117] Copyright 2008, Elsevier.

Figure 16. Heat receptors of some vertebrates. Temperatures in this figure represent the apparent activation threshold for the indicated ion channels in different biological systems. Reproduced with permission.[52] Copyright 2015, Elsevier.
contains a covalently bound heme active center (Figure 17d). Deb et al. found that the thin films of cyt c exhibited a surprisingly high temperature coefficient of resistance, which reached ≈35% in the temperature range between 25 and 60 °C. The achieved TCR is much higher than that of the traditional IR sensing materials used for the microbolometer (≈4% K\(^{-1}\) for VO\(_x\) and ≈3% K\(^{-1}\) for α-Si). Such high TCR value might be due to the temperature-dependent conformation change of cyt c and the unique electric property of the bounded heme group. Su et al. further deposited the cyt c thin film onto the surface of a photoresist of SU-8 for the long-wavelength IR sensing. Due to the high TCR value of cyt c and low thermal conductance of SU-8, such system showed great potential for microbolometer based uncooled IR sensing (Figure 17e). More
recently, Wu and co-workers reported the generation of a nano-hybrid material system by wrapping the cyt c molecules around the semiconducting single-walled carbon nanotubes (s-SWNTs) for the application in uncooled IR detection (Figure 17f–h).[40] The heterojunction between the interface of s-SWNT and cyt c can facilitate the dissociation of the electron–hole pairs that are generated in s-SWNT upon IR photon excitation. The electron conducting chain of cyt c and the hole conducting channel of s-SWNT are also favorable for the charge transport in the SWNT network. Due to the high external quantum efficiency value (>90%), the nanohybrid material demonstrated more than two orders of enhancement in the IR-induced sensor response than the SWNT-based IR detector reported previously.[40]

Besides using proteins, there are also some attempts to use other biological materials for the IR sensing as well. For example, biopolymer chitin was used in the uncooled IR detection recently (Figure 18a,b).[36] In the study, chitin was used as the coating material on top of the polysilicon ceramic beams for the construction of bimorph IR sensors. Due to the strong IR absorption of chitin in the wavelength ranges of 3–5 and 8–10 μm, and its high CTE, such chitin–polysilicon bimorph sensor was expected to provide 50 times of the sensitivity improvement over the common metal-ceramic bimorph sensor. These studies provide an interesting bioinspired approach that directly uses biological molecules for the performance improvement of IR sensors at uncooled operation condition.

The biological ion channels that are sensitive to temperature also inspired tremendous studies for the design and fabrication of biomimetic ion channels.[53,56,57,125] These ion channels are sensitive to temperature and can be potentially used for a broad range of applications, including temperature and IR sensors. Figure 19 provides several examples of such man-made ion channels that are responsive to temperature changes. Azzaroni and co-workers first explored a solid-state nanochannel with channel surface modified with thermo-responsive PNIPAM brushes.[56] Change of the temperature would result in the conformational transitions of the PNIPAM brushes between the swollen state and the collapsed state inside the nanochannels (Figure 19a,b). Such artificial stimuli-responsive nanochannels could therefore function as the molecular gates for the modulation of the ion flow. Li and co-workers developed a new strategy by introducing a host–guest system into the inner walls of nanochannels to achieve the thermal response (Figure 19c).[53] The temperature stimuli affects the interaction of the host–guest and changes the surface charge and the wettability of the nanochannel, which in turn switches the ion transporting between cation transport and anion transport (Figure 19d). Han and co-workers demonstrated a new mechanism for thermal-sensing ionic gate nanochannels based on the expansion and contraction of wax–elastic copolymer (polystyrene–(ethylene–butylene)–polystyrene, SEBS) that was confined in the nanochannels (Figure 19e,f).[57] A flexible pad device containing polycarbonate track etched (PCTE)/wax–SEBS thermal sensitive nanochannels was fabricated and showed good sensitivity to temperature change with repeatable performance. In addition, a patchable bandage-type heat-sensing nanochannel was fabricated and the successful detection of the human body heat was also demonstrated (Figure 20).

The bioinspired thermosensitive nanochannels represent various attempts to mimic the biological thermal ion channels. The molecular mechanism for the IR detection capability of snakes and bats are based on the thermo sensitive ion channels, so these artificial nanochannels with temperature-sensing capabilities should have the great potential to be used for high-performance bioinspired IR sensing.

5. Inspiration from Biological Photonic Structures

As biological systems survive through billions of years of natural selection, they have developed amazing capabilities to adapt to the environment. Some of these biological systems do not have IR or temperature-sensing organs, but their elegant structural designs have also inspired the new development of advanced IR sensors. Butterflies, for example, represent one of those biological systems. The wings of butterflies play critical roles in their life cycles, including sexual discrimination,[126,127] predation avoidance,[128,129] and thermal regulation.[130,131] Some butterfly species have developed wings with beautiful colors, which are originated from the photonic nanostructures on the wings.[132–136] Among varieties of such butterfly species, *Morpho* butterflies, the wings of which exhibit vivid iridescent
blue or purple colors, have attracted plenty of attentions in both the study of their optical property and various applications, including the applications that involve IR and thermal sensing\[^{[37,59,60,137]}\].

**Figures 21 a–c** show the structure of the wing of *Morpho sulkowskyi* butterfly\[^{[138]}\]. The structures of different *Morpho* butterfly wings are similar to each other with only subtle differences between them\[^{[138–141]}\]. When the wings are observed under optical microscopy, well-arranged scales are found to cover the wing surfaces (Figure 21b). The fine structure of the scales can be further revealed under TEM (Figure 21c). The cross section of the wing scale resembles the structure of Christmas-tree with parallel ridges aligned in ordered arrays. Each ridge consists of 7–9 layers of lamella alternatively arranged on both sides of the ridge. These air-filled structural arrangements generate photonic band gaps that can selectively reflect light of specific wavelengths. The optical properties of the wings are very sensitive to their structures and compositions. Any stimulation that changes either structure or composition of the photonic structure of the wing would induce the change in the optical signal from the wings.

With their unique structural and optical properties and also their strikingly low thermal mass \((2.2 \times 10^{-13} \text{ J K}^{-1})\), *Morpho* butterfly wings provide a novel platform for uncooled IR detection\[^{[37]}\]. Potyrailo and co-workers first demonstrated an interesting IR-sensing design by converting the IR signal into visible readout using *Morpho* butterfly wings (Figure 21d–f). In their work, the butterfly wings were doped with SWNTs to enhance the absorption of IR photons. As the IR radiation was absorbed and converted into heat, the temperature of the wing structure increased. The nanostructures of the wings then expanded, leading to the changes of visible reflectance from the wings, which served as the signal readout (Figure 21f). The combination of the low-thermal-mass of the air-filled wing nanostructures with the good IR absorption by the doped SWNTs enabled this system as a high-speed IR sensor with temperature sensitivity of 62 mK and heat-sink-free response speed of 35–40 Hz. Based on the simulation by the finite-difference time-domain (FDTD)
method, the spacing change between ridges upon thermal expansion under IR radiation played a dominant role in the high sensitivity of the IR response, while the expansion of the lamella and reduction in the refractive index only played minor roles in the IR response from such sensor design.

Besides the structural expansion in butterfly wings during IR stimulation, other geometrical deformations upon IR illumination should also impact the optical property of the wings and provide possible sensor readout for the IR radiation under detection. Zhang et al. recently developed a new butterfly wing-based IR sensing approach, in which they selectively modified the butterfly wing structure to achieve a pseudo 3D bimorph structure (Figure 21g–i).\(^{[58]}\) Through physical vapor deposition, the edge of the lamella was selectively coated with gold (Au). Due to the difference in CTE between the chitin of the wings and the Au coated on top of the wings, the absorption of the IR radiation would cause the temperature increase and result in the bending of the lamella due to the mismatched thermal expansion between the wing lamella formed by chitin and the Au coating. Such bending effect resembles the photo-mechanic deformation of the man-made bimorph structures that were used for the IR detection. Those man-made bimorph structures in general only have one beam at microscale, while in Zhang’s work, the butterfly wing-based bimorph structures were extended into nanoscale with multiple beams ordered in 3D. The structural deformation on each lamellae during the IR absorption generated the optical property change and the collective effect of such change from all the lamella arranged in 3D provided the enhanced sensitivity for IR stimulation. This design, although not optimized in thickness and composition, indeed achieved a temperature sensitivity of 32 mK, which is \(\approx 2\)-fold increase over that of the butterfly wings doped with SWNTs.

The essential mechanism of IR sensing using butterfly wings discussed above is based on IR-heating induced deformation with optical readout in visible range. As mentioned in the introduction, materials or systems with thermoresponsive property also have the potential for the application in IR sensing. Recently, Lu et al. reported a biinspired thermoresponsive photonic structure obtained by attaching thermosensitive PNIPAM to the surface of \textit{Morpho} butterfly wing using glutaraldehyde (Figure 22a).\(^{[141]}\) The PNIPAM-modified butterfly wing exhibited a reversible reflection spectra shift with the change of temperature. Similar work was reported by Xu et al., who also took advantage of the unique optical feature of \textit{Morpho} wings and the temperature-sensitive property of a PNIPAM-based material, poly(N-isopropylacrylamide)-co-acrylic acid (PNIPAm-co-AAc), to achieve the sensitive thermal
detection with optical readout (Figure 22b). The two systems, although similar in composition and design, showed opposite reflectance change with the temperature. The *Morpho* butterfly–PNIPAM hybrid material underwent a redshift in the wavelength when temperature increased. The underlying mechanism was believed to be the refractive index change of the PNIPAM with the temperature (Figure 22a). The *Morpho* butterfly–(PNIPAM-co-AAc) system, on the other hand, showed a blue-shift with the increase of the temperature. In this case, the mechanism is proposed to be the change of the thickness of the PNIPAM-co-AAc coating (Figure 22b).

With their sensitive response to the change of temperatures, such hybrid thermoresponsive structures potentially can also be used for IR sensing application. Most of the present butterfly wing inspired IR sensing approaches are based on the principle of photo–thermal–mechanical conversion. For the two systems presented in Figure 22, they could also be extended into IR sensing using the same principle. Due to the IR absorbance of the PNIPAM-based material as well as butterfly wing itself, the nanostructures on the wings will deform upon IR illumination, which will also lead to the blue or red shift of reflectance spectra for the optical readout. Optimizing the thickness of the PNIPAM on the wing surface and also tuning the response temperature range through chemical modification might further enhance the IR sensing performance of such systems.

Besides using the wings from *Morpho* butterflies, other types of butterfly wings, for example the wings of *Papilio* butterflies, have also been investigated for the thermal sensing purpose. Zhang and co-workers recently proposed a novel thermal sensor based on the photonic structures of the *Papilio* butterfly wings.

As shown in Figure 23a, the surfaces of the *Papilio* wing scales were covered by periodically arranged concavities in the horizontal plane, similar to the swimming lanes. Such nanoarchitecture is different from the Christmas tree-like architecture of *Morpho* wings. The TEM image observed from the cross-section view in Figure 23b revealed that each of the concavities was a multilayer structure. In their work, the dominant sensing principle was not based on the thermal expansion of the butterfly wing structure. They used ethanol in the thermal detection and found that the liquidation and

![Figure 21](image-url)
vaporization of ethanol within the multilayered structures played the major role in the thermal detection (Figure 23c). The liquidation and vaporization of ethanol within the multilayered structures produced detectable color change as temperature varies (Figure 23d) and such color change could even be observed by naked eyes (Figure 23e). Such thermochromic response was also reversible between 26 and 32 °C.

Furthermore, using the same type of the butterfly wing, combined with thermoresponsive PNIPAM material, Zhang and co-workers also explored the response of such system to NIR signal stimulation.\[143\] In order to enhance the IR absorbance, the photothermal convertors, Fe\(\text{3O}_4\) NPs in their work, were integrated between the wing surface and the PNIPAM coating. The added Fe\(\text{3O}_4\) NPs helped convert the incoming NIR laser (808 nm) into heat, and resulted in the fast temperature increase of the sample. When the temperature reached the LCST of PNIPAM, phase transition from hydrophilic state to hydrophobic state happened, which led to volume shrinkage of the sample. The shift of the reflection was subsequently observed (Figure 23f).

Both the thermal-mechanical mechanism and the thermal-optical mechanism inspired by butterfly wings provide fresh thoughts for designing uncooled IR sensing with optical readout. The effort in the fabrication of artificial photonic crystals that mimic butterfly wing structures, either Morpho or Papilio can potential provide an engineering platform to unitize those mechanisms for the IR sensing.\[135,144-146\]

With the possible tuning of structure parameters during the engineering process, the IR sensing performance could be further enhanced. Potyrailo et al. demonstrated the fabrication of Christmas-tree like multilayer structures using e-beam lithography.\[147\] Such man-made butterfly wing structures showed better vapor sensing performance than the original butterfly wings. Combined with IR absorber and thermal responsive materials, such man-made butterfly wing structures could potentially be used in high-performance IR detection.

Besides butterfly wings, there are many other examples of biological systems or natural systems that show structured colors.\[148-151\] Many man-made photonic crystals take inspiration from nature opals and other naturally occurring structured colors.\[152-155\] There have also been some efforts in the development of man-made thermal/IR sensors that are inspired by natural systems with structured colors.\[156-161\] Lotsch et al. reported a thermo-optical sensor based on 1D photonic crystals, the optical transmittance of which can be thermally modulated (Figure 24a-c).\[158\] The thermal sensors were made of alternatively assembled layers of silica (SiO\(_2\)) NPs and titania (TiO\(_2\)) NPs, which were also called Bragg stacks (Figure 24d,e). The thermo-optical effect of such Bragg stacks comes from the temperature-dependent thermo-optic coefficient of the component materials (mainly from TiO\(_2\) in this case). Using such Bragg stacks as the optical filters integrated with the OLED or LED

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**Figure 22.** Schematic of the mechanism of the synthesized thermoresponsive photonic structures upon heating. a) The synthesized photonic structure exhibited from macroscale to nanoscale. The PNIPAM was attached to the butterfly wing scales through the bridge of glutaraldehyde. The refractive index of the structure changed upon heating. Reproduced with permission.\[141\] Copyright 2015, Wiley-VCH. b) The mechanism of the thickness change in PNIPAm-co-AAc under thermal stimulation. The macromolecules attached to the wing surface went from swelling state to deswelling state with the increase of temperature. Reproduced with permission.\[62\] Copyright 2015, American Chemical Society.
as the light source, the authors showed that this 1D photonic crystal had the potential for the application in the IR imaging. Interestingly, the optical response to the temperature of this 1D mesoporous photonic material was found to be greatly enhanced with the increase of the humidity.\[159\] The desorption of the water vapor from the particles’ surface upon temperature increase at high humidity condition was proposed to be the key reason for such enhancement. Besides 1D Bragg stacks, Sailor et al. also demonstrated in their study that mesoporous silica photonic crystals filled with different organic vapors showed the ability to respond to the temperature change, due to the condensation and evaporation of the vapors (Figure 24f).\[160\] Specifically, infusing the sample with 2-propanol vapor generated a thermally tunable optical filter with the temperature response of \(\approx 1\ \text{nm}^\circ\text{C}^{-1}\).[161] Compared with biological photonic systems, the artificial photonic crystals have the advantages of the durability, tunability, and scalability that are needed for large scale applications.

6. Summary and Outlook

This review provides an overview of both the biological systems that are relevant for IR sensing and also the engineering efforts that are inspired by such biological systems. In nature, some biological systems have developed highly sensitive IR sensing systems primarily for their survival during evolution. Most of these IR sensing systems rely on two detection mechanisms: bolometer-like mechanism and photomechanic mechanism, both of which fall into the category of thermal-based IR sensing systems. The direct learning from those biological systems that have IR sensing capability can not only help further the development of bolometer-based IR sensing systems and photomechanic IR sensing systems, but also help open up the opportunities in developing other types of IR sensing systems. There are, however, only limited numbers of biological systems that have IR sensing capabilities. The biological systems that have no IR sensing capabilities offer a larger pool of inspiring...
candidates than those with IR sensing capabilities for the engineered IR sensing systems. Thermal energy is closely associated with IR radiation, so naturally the biological systems with the capability in thermal energy sensing, or thermal sensing in short, offer another group of inspiring systems for the development of engineered thermal-based IR sensing systems. Besides biological systems with either IR sensing capability or thermal sensing capabilities, other biological systems, which represent an even greater group of candidates, can also help the development of the advanced IR sensing systems. Most recent efforts in this direction, which are also overviewed in this review, focus on the use of butterfly wings for the sensitive optical readout in the IR detection process. Both the biological systems with thermal sensing capability and the biological photonic systems offer the possibility in developing engineered IR sensing systems that are based on operation mechanisms other than bolometers and photomechanic process, two dominant mechanisms in biological systems with IR sensing capabilities.

Certainly, bioinspired IR sensing is still at its early stage. There are many opportunities in pushing forward the development of this exciting research area. Following are several possible directions that this research field needs to focus on in order to accelerate its growth:

1. The critical first element in bioinspired engineering is the understanding of the biological processes that enable the function of biological systems. Same is true for the bioinspired engineering of IR sensing systems, especially for the direct learning from biological systems with IR sensing capabilities. For this aspect, there are still many unknown elements in biological IR sensing. At the molecular level, the working principle for the thermal sensing ion channels still remains as hot debates. The thermal-sensitive ion channels play critical roles in both the bolometer-like IR sensing in biological systems and also in biological systems with thermal sensing capabilities. The understanding of the thermal-sensing
mechanism at the molecular level will in no doubt help the engineering effort in designing better thermal readout components than the current ones, and help improve the performance of the engineered IR sensing systems. At the system level, the detailed studies of both the structures and the functional performance for many biological systems with IR sensing capabilities are still missing. For example, there is lack of such studies for vampire bats, even though they are the only mammal known to have such IR sensing organs. Blood-sucking insects utilize a variety of host-associated signals to find food, and heat released by the host is one important signal for their host-seeking behavior.[162] For example, Mosquitoes, such as *Aedes aegypti*, utilize their sensing system to seeking target with proper temperature.[163] Only thermal stimuli that are close to the target body temperatures can attract mosquitoes, and stimuli at other temperatures will not attract mosquitoes. To remotely sense the heat from the host, there must be an IR sensing mechanism involved in mosquitoes’ hunting for food, but such sensing mechanism still remains to be studied.

2. In most of the biological species, all the functions are integral part of the whole system, and those functions are complementary to each other and form a coherent functional system. For example, in snake, both the visible sensing function and the IR sensing function are important, and the integration of both enables the precise prey targeting. Another example is the integration of the ultrasonic sensing function and IR sensing function in bats, which also enables the prey targeting. With the nature selection, the biological systems probably develop the best integration approaches for those different functions. Such integration approaches provide another rich source of inspiration. In the current engineering approach, most of the time the attention is only paid to single functions. With the increasing demand of the portable and multifunctional systems, the learning from biological systems should also include the study of the integration process, which will help the design and generation of man-made multifunctional systems. One successful example that is inspired from such integration involves the learning from plants.[164] The leaf surfaces of plants help transport the water from the root to the leaf surfaces, and help bring the nutrition to different parts of the plants.[165] In an engineered vapor chamber that serves as the solar thermal energy collector,[166] the evaporator surface was inspired by the leaf surface for the efficient localized interfacial evaporation. The design for the sections between the evaporator and the condenser was inspired by the capillary network within the plants for efficient liquid transport. The successful integration of both functions enabled the system to efficiently convert and transport the solar thermal energy.

3. There are many other optical functions, not necessary biological IR sensing functions, in biological systems that we can take advantage of for the development of high-performance IR sensors. The effort for such approach will expand the concept of inspiration from biological systems that are not associated with IR sensing. All the IR sensing approaches inspired by the biological systems discussed in this review are thermal-based IR sensing approaches. Is it possible to develop photon-based IR sensing systems using inspiration from biological systems? So far there is no evidence of photo-based IR sensing systems in biological systems. There are, however, photon-based sensing systems at other wavelength ranges in biological systems.[167–171] For example, the highly sensitive UV and visible sensing systems in Mantis shrimp could possibly offer some inspiration for the engineering of photon-based IR sensing systems.[172–174] Another example involves the eyes of honeybees (Figure 25).[175] Through the analysis of the compound eye structures and the incident IR light by the FDTD method, it was found that the structure performed well in transmission of light of 2–12 μm, and the incident energy was concentrated in the crystalline cone and the rhabdom, which may guide us to new design for IR sensing.

4. The growth of the field needs to take full advantage of both the advancement in the understanding of the biological systems and the advancement in man-made materials. The improved understanding of the operation mechanism for snakes and fire beetles will help optimize the design to enhance the performance of engineered IR sensing systems, including bolometers and photomechanic IR sensing systems. The detailed learning from the unique IR imaging capability of snake will help the development of engineered IR imaging systems.

![Figure 25. a) Schematic of the model that describes the structures of the honeybee compound eyes. The red lines represent the propagation of incident radiation. b) The simulated transmission and reflection of IR light. a,b) Reproduced with permission.[175] Copyright 2017, IEEE.](image-url)
Biological systems develop their structures and functions based on available biomaterials. In engineered systems, there is freedom to use both the principle learned from the biological system and also the artificial materials recently developed to design and generate IR sensing systems that have better performance than the biological systems. The design, however, should not just be limited to artificial materials. The inclusion of biomaterials in the design of hybrid engineered IR sensing system can also help improve the performance of such sensing systems.

Current IR sensing applications require portable and high-performance systems. Biological sensing systems are naturally portable and exhibit high performance. The learning from biological systems is certainly a promising approach to help the community achieve the application goals. All the engineering approaches that are inspired by the biological systems, including the bioinspired IR sensing, are multidisciplinary. Bioinspired IR sensing involves the dedicated research effort from biologists, chemists, physicists, materials scientists, and other researchers in relevant fields. Currently, the interaction between scientists from different disciplines is still not optimum. Many barriers, including scientific languages in published literatures, still exist and they prevent the maximization of the benefits from the multidisciplinary collaboration. It is thus critical for all relevant researchers to reach out to their counterparts in other disciplines and work together to push forward this exciting research field for the development of portable and high-performance IR sensing systems.

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Conflict of Interest
The authors declare no conflict of interest.

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[1] A. Rogalski, Opto-Electron. Rev. 2012, 20, 279.
[2] F. Zhuge, Z. Zheng, P. Luo, L. Lv, Y. Huang, H. Li, T. Zhai, Adv. Mater. Technol. 2017, 2, 170005.
[3] Ruffles Wiki, http://ruffles.wikia.com/wiki/File:Graphic-infrared-evolution-military-ship.jpg (accessed: February 2018).
[4] I. Fernández-Cuevas, J. C. B. Marins, J. A. Lastras, P. M. G. Carmona, S. P. Cano, M. Á. García-Concepción, M. Sillero-Quintana, Infrared Phys. Technol. 2015, 71, 28.
[5] N. Ludwig, D. Formenti, M. Gargano, G. Alberti, Infrared Phys. Technol. 2014, 62, 1.
[6] O. Faust, U. R. Acharya, E. Y. K. Ng, T. J. Hong, W. Yu, Infrared Phys. Technol. 2014, 66, 160.
[7] B. B. Lahiri, S. Bagavathiappan, T. Jayakumar, J. Philip, Infrared Phys. Technol. 2012, 55, 221.
[8] S. Bagavathiappan, B. B. Lahiri, T. Saravanavan, J. Philip, T. Jayakumar, Infrared Phys. Technol. 2013, 60, 35.
[9] U. Adiyaman, F. Cerutti, O. Ferhanoglu, H. Horun, H. Urey, IEEE J. Sel. Top. Quantum Electron. 2015, 21, 87.
[10] N. Zhang, J. C. Cheng, C. G. Warren, A. P. Pisano, in presented at 2011 IEEE Sens., Limerick, Ireland, October 2011.
