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Learning from Solar Energy Conversion: Biointerfaces for Artificial Photosynthesis and Biological Modulation

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Abstract

Three seemingly distinct directions of nanomaterials research, photovoltaics, biofuel production, and biological modulation, have been sequentially developed over the past several decades. In this Mini Review, we discuss how the insights gleaned from nanomaterials-based solar energy conversion can be adapted to biointerface designs. Because of their size- and shape-dependent optical properties and excellent synthetic control, nanomaterials have shown unique technological advantages as the light absorbers or energy transducers. Biocompatible nanomaterials have also been incorporated into biological systems including biomolecules, bacteria, and eukaryotic cells for a large collection of fundamental studies and applications. For the photocatalytic biofuel production, either isolated bacterial enzymes or the entire bacteria have been hybridized with the nanomaterials, where functions from both parts are synergistically integrated. Likewise, interfacing nanomaterials with eukaryotic systems, whether in individual cells or tissues, has enabled optical modulation of cellular behavior and the construction of active cellular materials. Here we survey different approaches in which nanomaterials are used to elicit electrical or mechanical changes in single cells or cellular assemblies via photoelectrochemical or photothermal processes. We end this Mini Review with the discussion of future nongenetic modulation at the intracellular level.

Graphical Abstract

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Keywords

Biological modulation; solar energy conversion; nanomaterials; optical stimulation

The ability to synthesize nanomaterials in a controlled, precise manner has dramatically expanded the device possibilities for solar energy conversion. These advancements have driven decades of intense research, yielding both new basic science insights and immediately applicable breakthroughs. Researchers have exploited the unique features of nanomaterials, such as their high surface-to-volume ratio, ability to support surface plasmons, and synthetic tunability, in order to improve the performance of solar energy conversion. The applications in this area can be broadly grouped into three categories: solar-to-electricity, solar-to-thermal, and solar-to-chemical. Understanding photon conversion in these processes at the nanoscale has provided researchers in other fields with new approaches to target diverse research problems, which are largely beyond solar energy conversion. In this Mini Review, we will highlight how the general principles from energy science can be applied for biointerface studies, and in particular, how nanomaterials serve as light transducers in biological modulation.

Nanomaterials in Solar Energy Science

Photovoltaic and Photoelectrochemical Processes

Broadly, solar energy science concerns, first, the absorption and conversion of solar energy and, second, the extraction or storage of this new converted form of energy (i.e., electricity, heat, or fuel). While many lessons can be gleaned from nature's way of storing energy (e.g., photosynthesis), a key to optimizing light-matter interaction resides in artificially synthesized nanostructures. For example, employing nanowire structures, in contrast with bulk materials, can increase the efficiency of photoinduced charge carrier collection because the carriers have shorter distances to travel (Figure 1A). First generation solar cells required high quality crystalline silicon wafers as the minority carrier that would otherwise be trapped by defects before reaching the surface for successful charge extraction.¹ Such high purities are not required for silicon nanowire or microwire arrays, as the photon absorption length and the charge collection distance can be decoupled; the minority charge carriers can travel radially to reach the surface while photons can be absorbed along the long axis of the nanowires or microwires.² While bulk measurements on many nanowires or microwires can provide important insights that relate the material geometry (e.g., spacing, diameter, length,

and so forth) to its photovoltaic efficiency,^{3–5} optical and electric characterization down to single nanostructures can elucidate the fundamental limits and potentials of using nanostructures in solar-driven applications.⁶ For example, Lieber and coworkers used the metal-catalyzed vapor–liquid–solid method to synthesize p-type/intrinsic/n-type (p-i-n) coaxial silicon nanowires (SiNWs) and studied their photovoltaic characteristics and potential applications as the power source for nanoelectronics.⁷ Similar to the carrier separation and collection in microwire arrays, the holes can travel to the p-type core and the electrons can travel to the n-type shell. The nanowire length, intrinsic-shell thickness, and shell crystallinity can be controlled to vary the open-circuit voltage, short-circuit current, and energy conversion efficiency of the single nanostructures.^{7,8}

Compared to the photon-to-electricity conversion in photovoltaics, solar fuel production requires additional charge transfer steps to drive redox reactions at the semiconductor–electrolyte interface.⁹ These steps require a fine-tuning of the materials' surface properties as well as an increase in the lifetime of the charge-separated state. Nanomaterials provide unique advantages since their increased surface-to-volume ratio, as compared to planar devices, (1) provides more surfaces for the reactions to take place and (2) reduces activation overpotentials that arise from the kinetic inefficiencies associated with low surface area materials.¹⁰ In addition, the size, composition, and morphological control in the syntheses of colloidal nanocrystals or other nanostructures have opened additional avenues for photoelectrochemical processes. For example, Alivisatos and co-workers have designed a multicomponent heterostructure, Pt-tipped CdS nanorod with an CdSe seed for photocatalytic hydrogen production.^{11,12} The photoexcited electron migrates from CdS to the Pt tip to be used in the H^+ reduction, while the hole moves to the CdSe seed (Figure 1B). Spectroscopic studies on the electron¹³ and hole¹⁴ transfer dynamics in nanomaterial photosynthetic systems have yielded important insights on how to improve efficiencies.^{15,16} Studies on catalysts coverage and photoabsorber architecture have also identified the optimal photocathode design to minimize the trade-off between optical absorption and catalytic activity of opaque catalyst.¹⁷ Furthermore, several techniques have been developed for fabricating multifunctional or integrated devices. For example, Yang et al. synthesized a high-performing watersplitting photocatalytic device by coating the silicon photoanode with $Co_3O_4/Co(OH)_2$ biphasic thin-films via plasmon-enhanced atomic layer deposition.¹⁸ In these multifunctional thin-films, the Co_3O_4 nanocrystalline spinel protects the Si substrate and provides durable catalyst/substrate interface while $Co(OH)_2$ promotes catalytic activities. As another example of integrated devices, Segev et al. combined photoelectrochemical and photovoltaic cells, such that the surplus photogenerated charge carriers (not consumed in fuel production) are collected to produce electrical power.¹⁹

In later sections, we will discuss how nanostructured light absorbers and advanced fabrication techniques can be coupled with efficient enzymatic catalysis systems found in nature to create more efficient photocatalytic fuel generation.

Photothermal Process

The photothermal effect refers to the process by which light energy is absorbed and converted to heat, typically within metals or small bandgap semiconductors that display

more efficient electron–phonon coupling^{20,21} While industrial photothermal solar energy plants focus on improving macroscopic processes (e.g., concentrating light, insulating, and transferring the heat),²⁰ new areas of research utilize the plasmonic effect: the phenomenon in which mobile charges within metals or heavily doped semiconductors oscillate resonantly with incoming photons.²² In addition to enhancing the light absorptivity in photovoltaic and photocatalytic devices,²³ the plasmonic effect seen in nanoparticles can enable localized photothermal processes as the oscillating electrons de-excite and couple their energy to vibrations in the local chemical environment. Spectroscopic studies have been performed to better understand the heat transfer dynamics from the plasmonic particles to their surrounding environment,²⁴ as well as the local heating mechanism through light scattering.²⁵ Applications of photothermal processes in the bioelectric and biomechanical modulations will be discussed in Photothermal-Bioelectric Stimulation and Photothermal-Biomechanical Stimulation, respectively.

Nano-bio Interface for Solar Fuel Science

Incorporating highly efficient photoabsorbing synthetic nanomaterials into biological systems can complement certain inefficient metabolic pathways and the low photoabsorptivity of natural photosynthetic systems.²⁶ Semiartificial photosynthetic systems can utilize nature's intricate catalytic machinery to produce chemical fuels, whose reactions are too complex for purely artificial photosynthetic systems to execute.²⁷ In this section, we review various ways in which inorganic nanomaterials are incorporated into biological systems: either freely floating in the same solution, bound to the microbial membrane, or internalized within the microbe.

Initial efforts using purely artificial photosynthetic systems have focused on single electron reactions such as proton reduction to evolve hydrogen. By incorporating hydrogenase purified from *C. acetobutylicum* to light-absorbing nano-particles, Dukovic, King, and co-workers observed the photocatalytic production of hydrogen, where the rates were limited by the photoluminescence quantum efficiency of CdTe nanocrystals²⁸ or CdS nanorods²⁹ (Figure 2A). Similarly, more kinetically complex reactions such as the reduction of N₂ to NH₃ were carried out by using CdS nanocrystals as photosensitizers that are interfaced with a nitrogenase molybdenum–iron protein.³⁰ In natural systems, chemical energy is provided from the hydrolysis of ATP. In the biosynthetic hybrid systems, the photogenerated electrons from semiconductor nanocrystals can provide the energy normally supplied by ATP. The energy conversion efficiencies involved in these biomimetic approaches were usually limited by the electron transfer from the inorganic light absorbers to the enzymatic active sites. This highlights the importance of forming strong electronic coupling at the nanobio interface and of having engineered energetics to prolong the excited states.

Another way to form a bio-inorganic interface is to incorporate an inorganic material in a complete cellular system. The inorganic component can be used in an analogous manner to the engineered nucleic acids and proteins in traditional synthetic biology. Nocera and co-workers have driven the CO₂ fixation process by interfacing a bacterium (*Ralstonia eutropha*) with a water splitting CoP alloy.³¹ These bacteria consumed the H₂ produced from the inorganic catalysts and synthesized the biofuels. When the bioinorganic hybrid system

was further coupled with a photovoltaic system, the reduction of CO₂ was carried out with an order of magnitude higher efficiency than what is seen in natural photosynthesis. Similarly, by simply replacing the type of bacterium, the Nocera group also demonstrated NH₃ synthesis from N₂ and water (Figure 2B).³² The advantages and drawbacks of using purified enzymes, that is, oxidoreductases, versus the entire living electroactive bacteria are discussed in a review by Lapinsohn et al.³³

Tight bio-inorganic interfaces can be formed by exploiting certain bacteria's unique ability to mineralize metal ions as a way to reduce metal toxicity in their environment.³⁴ By introducing molecular precursors for Cd and S, Yang and coworkers induced precipitation of CdS NPs on CO₂-reducing bacterium.³⁵ The membrane-bound CdS NPs photosensitized the synthesis of acetic acid. By interfacing inorganic materials, this nonphotosynthetic bacterium was able to execute a photosynthetic CO₂ fixation process leveraging both the high photoabsorptivity of the CdS nanoparticle and the energetically efficient biosynthetic route of the bacteria. To further improve the electron transfer process, the researchers internalized photosensitizers, Au nanocrystals in this case, in the same bacterium in order to bypass the slow mass transport of electrons across the cell membrane (Figure 2C).³⁶ They engineered the Au nanocrystal surface using ligands with the goal of prolonging the lifetime of the photogenerated electrons so that they could transfer to the electron transfer system within the cytoplasm.

Future research in this area can benefit from the advanced tools that can better characterize the nanomaterials. For example, by visualizing the grain boundaries and current carrying domains of nanoparticle aggregates, Grätzel and coworkers have identified a type of nanomaterial that may have a photon-to-current converting efficiency approaching the theoretical limit.³⁷ Sambur et al. used a super-resolution imaging technique to identify the most efficient way to modify photoanodes with oxygen evolution catalysts, suggesting an activity-based material engineering strategy for enhanced photoelectrochemical conversion.³⁸ By leveraging the advances in the study of inorganic nanomaterials (e.g., the bandgap energy, carrier diffusion length, and band-edge positions relative to desired half-reactions³⁹) and that of syntheticbiological interfacing techniques, one can facilitate true synergies of combining the two components.⁴⁰ These ideas can eventually link the inorganic phototransducing nanomaterials to more advanced biosystems, namely eukaryotes, for the advancement of both fundamental biophysical research and potential clinical applications.

Nano-bio Interface for Cellular Modulation

In this section, various recent works will be introduced to elucidate how nanomaterials can be used to optically modulate cells and tissues for potential treatment of neural degenerative diseases or cardiac conduction disorders. Excitable cells, such as neurons and muscle cells, fire action potentials for intercellular communication. Studies have shown that different cues, whether chemical, electrical, thermal,⁴¹ or mechanical,⁴² can instigate the firing of action potentials. Optical stimulations of excitable cells typically involve photoelectrochemical⁴³ or photothermal⁴⁴ processes. These processes can either redistribute ions near the nano-bio interfaces or alter the biophysical properties of membranes.

Photoelectrochemical Stimulation

Optically modulating cellular behaviors with semiconductors can directly incorporate material designs from solar energy conversion research. Parameswaran et al. interfaced p-i-n SiNWs (discussed in the previous section) with primary dorsal root ganglion (DRG) neurons in order to optically elicit action potentials.⁴⁵ The presence of diffused atomic Au on the NW surface was an integral part of photoelectrochemical current generation, as the Au species can catalyze the photocathodic reaction in a freestanding material configuration (Figure 3A,B). By controlling the laser power, duration, and frequency, trains of action potential can be generated (Figure 3C), obeying up to the intrinsic limit of the neurons. This freestanding semiconductor nanomaterial-based optical modulation offers the prospect for target-specific cellular control at the single-cell level (Figure 3D).

In contrast to freestanding single nanowires, multiple nanoscale semiconductor components can be assembled/ fabricated into macroscopic devices for larger scale tissue or organ-level stimulation. Parameswaran and Koehler et al. have used a fibronectin-coated SU-8/p-i-n SiNW mesh to optically stimulate and train rat heart ex vivo to beat at the frequency of applied optical pulse.⁴⁶ In an earlier pioneering example, Palanker and co-workers implanted silicon photodiode microarrays into the subretinal region of a rat's eye to restore the vision of rat, where the devices replace the damaged photoreceptors.⁴⁷ In practical applications, a video camera can capture the original images, followed by image processing in a mini-computer, signal transduction into a goggle, and projection of NIR pulses onto an eye. In a related study, Tang et al. interfaced a gold nanoparticle (AuNP) decorated titania nanowire (TiO₂ NW) array with the retina to restore vision in blind mice.⁴⁸ Because pure TiO₂ NW absorbs primarily in the UV region, having AuNPs is necessary to enhance the photoabsorption efficiency in the visible region (the absorption of ~10 nm AuNPs peaks around 550 nm). Along with the excellent biocompatibility and stability of this nanomaterial, the orientation of highly anisotropic NWs that resemble the architecture of a photoreceptor is advantageous as it imparts efficient light absorption and charge transportation (Figure 3E,F). The similarity in architecture among the photoreceptors, the AuNP-TiO₂ array, and the aforementioned Si nanowire array suggests how the geometries of nanostructures can be leveraged for light-triggered biological processes.

Photothermal-Bioelectric Stimulation

Analogous to using photoelectrochemical effect to restore vision, researchers explored the photothermal process to restore hearing. Stoddart and co-workers used plasmonic heating of AuNRs to modulate auditory neurons.⁴⁹ Traditional infrared neural stimulation results in a limited photothermal effect as water is the primary source of heating.⁵⁰ By adding the AuNRs, biologically transparent near-infrared lasers (with a 780 nm wavelength) can be utilized and deeper tissues can be reached. Recent studies have suggested two mechanisms for photothermal neuromodulation: (1) production of capacitive current across cell membranes⁵¹ and (2) activation of thermosensitive ion channels.⁵² Benzanilla and co-workers used the photothermal effect of AuNPs to elicit action potentials in DRG neurons through the change of membrane electrical capacitance.⁵³ It was experimentally revealed that the rapid change in local temperature induces a capacitive current due to the change in membrane capacitance,^{51,54} which depolarizes the cells and elicits action potentials.

Additionally, the ligation of AuNPs' surface with antibody-conjugates provides ways to target specific cell phenotypes.⁵³ Besides using plasmonic heating, Jiang et al. have used the photothermal effect of amorphous Si mesostructures to trigger action potentials of DRG neurons,⁴⁴ where the multiscale structural heterogeneities softened the materials and enhanced the light adsorption.

Photothermal-Biomechanical Stimulation

Hybridizing the plasmonic nanomaterials with temperature sensitive polymers can open up a plethora of new applications by leveraging the polymers' mechanical responses.⁵⁵ Poly(Nisopropylacrylamide) (PNIPAm) is particularly suitable because of its high thermal responsiveness with a sharp phase transition.⁵⁶ Sutton et al. incorporated Au nanorods into a PNIPAm hydrogel to mechanically modulate cell morphology through light triggering (Figure 3G).⁵⁷ The hydrogel containing the plasmonic particles sit on a microstructure, to which cells were attached. Irradiating the structure with a NIR laser causes the hydrogel to contract due to the heating from AuNRs. Subsequently, the contraction bent the microstructures and deformed the cells, elongating the cells to 140% of their unperturbed length. Given the facts that (1) cells attach to various microstructures,⁵⁸ and (2) plasmonic nanostructures have shape- and size-dependent resonance absorption peaks,⁵⁷ this photothermal mechanomodulation platform can potentially produce a large variety of cellular responses with light.

Introducing nanomaterials into cells that can convert light energy into heat can also mechanically perturb the intracellular environment. Jiang et al. introduced a novel intracellular mechanical manipulation tool by optically stimulating a SiNW internalized in an endothelial cell.⁵⁹ Upon illuminating the SiNW, the microtubule that entangled the NW was immediately repelled, forming a void near the NW. The authors suggested that this void was formed by a photoacoustic mechanism. In this process, a shock-wave was generated as a result of local heating, which drove the mechanical depolymerization of the microtubule network around the SiNW. In addition to this cytoskeletal response, it was also hypothesized that the local photothermal effect from SiNWs could transiently perforate organelles, such as the endoplasmic reticulum and mitochondria, thus triggering intracellular calcium ion release.

The examples shown in this section highlight some recent advances in using nanomaterials for nongenetic cellular modulation. Specifically, the highlighted photoelectrochemical or photothermal methods do not induce permanent changes to the cell, as in genetic manipulation. Additionally, some of the interfacing materials such as Si can degrade over time under physiological conditions,⁶⁰ and get cleared out from the biological system. Further discussion on establishing a strong biointerface for cellular modulation⁶¹ and the advantage of using a nongenetic method⁶² can be found in other reviews.

Outlook for Future Intracellular Modulation

The prospect of forming a bio-inorganic interface at subcellular length scales is exciting as localized optical stimulation can serve as bio-orthogonal cues for intracellular modulation. The successful introduction of nanomaterials into a biological system involves several

challenges. First, the nanomaterial has to be internalized for subcellular targeting. Rigorous studies are being done to understand the effect of size, shape, and surface chemistry of the nanoparticles on the internalization process.^{63,64} For example, many studies suggest that passivation of the particle by certain molecules, such as polyethylene glycol (PEG), can help prevent nonspecific surface binding of antibodies and blood serum proteins.^{65,66} Yu and co-workers demonstrated that half-PEGylated and halfligand coated Janus particles were preferentially uptaken by T cells.^{67,68} Additionally, microparticle uptake is nontrivial and the uptake mechanisms are still being studied. Zimmerman et al. showed that SiNW can be internalized into different types of mammalian cells (e.g., endothelial cells and glial cells) through the endogenous phagocytic pathway.⁶⁹ Subsequently, the SiNWs were actively transported to the pronuclear region and later packaged into lysosomes. Lieber and co-workers demonstrated spontaneous internalization of SiNWs by primary neurons (which are nonphagocytic cells) by modifying the SiNW surface with a trans-activating transcriptional activator cell-penetrating peptide.⁷⁰ These studies show the potential for the formation of robust intracellular biointerfaces. Once the nanomaterials enter the cell, they have to first escape endosomal entrapment, then translocate and specifically bind to target organelles. While endosomal escape represents a daunting challenge in the field, many studies have suggested potential solutions for effective release of nanoparticles inside cells.^{71,72} Much progress has been made in subcellular targeting of nanoparticles within the context of drug delivery,⁷³ as well as medical applications—especially for oncology (e.g., thermal ablation of tumor cells).⁷⁴ Efforts include surface modifications, bioconjugate reactions,⁷⁵ and hybridization of different nanocomponents including, but not limited to, liposomes, micelles, mesoporous silica, polymers, viruses, AuNPs, and carbon nanotubes.⁷⁴ Furthermore, the effects of the nanomaterials' other physical properties on the intracellular components, such as the organelle response toward nanomaterial mechanics and geometry, should be further studied for longterm in vitro or in vivo applications.⁷⁶ Lastly, the optical properties of the nanomaterial should be considered. For deep tissue optical modulation, NIR light at wavelengths in the ranges of 650–950 and 1000–1350 nm is the most suitable choice of light source owing to its high tissue transmission. Therefore, for in vivo experiments or deep tissue applications it is imperative to use nanomaterials that can respond to the NIR light. The optical modulation of cellular activities is a rapidly growing area of research, and it promises to serve as a powerful tool for both fundamental biophysical studies and the clinical applications.

The three areas of nanoscience research highlighted in this Mini Review, solar energy conversion, light-driven biofuel production, and optical modulation of cellular activities, have sequentially evolved and will continue to build on each other. The basic science insights gleaned from the earlier work on solar energy have inspired much of the advances in biointerfacing of nanomaterials. Looking forward, scientific discoveries within these three areas of research may be integrated to promote further innovations in hybrid information processing systems, synthetic biology, and precision medicine.

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Figure 1.

Using nanostructures can enhance the efficiency of solar-energy conversion processes. (A) Schematic diagram of a Si-based photovoltaic device. Charge carriers are generated at the p–n junction and travel across the entire n-type (electron) or p-type (hole) thickness to reach the surface, achieving charge separation (left). In a nanowire photovoltaic device (right), electrons travel a shorter distance radially to reach the n-type surface, while the entire length of the nanowire can still absorb incident light. (B) Schematic diagram (left) of a multicomponent nanodevice designed for photocatalysis. The CdS nanorod generates charge carriers upon light absorption. The CdSe seed localizes holes that are scavenged by solution species and the Pt catalyst uses the photogenerated electrons to drive the hydrogen production reaction. Energy level diagram (right) of different components showing the movement of the photogenerated charges in this system. Adapted with permission from ref 11. Copyright 2010 American Chemical Society.

Figure 2.

Inorganic nanomaterials can be hybridized with biological components to drive photocatalytic processes. (A) Schematic diagram (left) and energy diagram (right) of the 3-mercaptopropionic acid (MPA) capped CdS nanorod and *Clostridium acetobutylicum* [FeFe]-hydrogenase I (CaI) hybrid structure designed for photocatalysed hydrogen production. Ascorbic acid (AA) quenches the photogenerated holes through oxidation to dehydroascorbate (dHA). CaI uses the photogenerated electrons to produce hydrogen. Abbreviations: band gap energy (E_g), rate constant of electron transfer from CdS to CaI (k_{ET}), rate constant of electron transfer from CaI to CdS (k_{BET}), hole transfer rate constant (k_{HT}), excited state decay rate constant in CdS (k_{CDS}), absorbed photon flux (I_{ABS}), rate constant for photo oxidation of MPA ligands (k_{OX}), normal hydrogen electrode (NHE). Reprinted with permission from ref 25. Copyright 2012 American Chemical Society. (B)

Schematic diagram of an electroaugmented reaction chamber for biofertilizer production. A photovoltaic device (not drawn in the figure) supplies a constant voltage across the Co-P HER and CoP_i OER electrodes. Zoomed in schematic: electrons generated at the HER cathode are fed into H₂ase of the bacteria. N₂ and CO₂ from the reaction chamber are fixed by the bacteria to form biomass. Adapted with permission from ref 30. Copyright 2017 National Academy of Sciences. (C) Schematic diagram of a *M. thermoacetica* with internalized Au nanoclusters. First, Au nanoclusters photogenerate charge carriers. Second, holes are scavenged by cysteine (Cys), which is oxidized to cystine (CySS). Concurrently, electrons are fed to enzymatic mediators, along with CO₂, to produce biomass via the Wood-Ljungdahl pathway. Reprinted with permission from ref 34. Copyright 2018 Springer Nature.

Figure 3.

Nanomaterials can be interfaced with eukaryotic cells to modulate the cells' electrical or mechanical behaviors. (A) Schematic diagram (top) of a p-i-n SiNW sitting near a cell membrane. Photogenerated electrons diffuse to the n-type shell and induce membrane polarization via the cathodic electrochemical effect (blue dotted line). This process is proposed to induce action potentials. Photogenerated holes travel along the p-type core (anodic reaction represented by the orange dotted line). SEM image (bottom left) of a single p-i-n SiNW sitting on a DRG neuron and a zoomed-in image showing the interface. A trace (bottom right) of a DRG neuron membrane potential recorded by a current-clamp patch-clamp technique. The neuron is stimulated first, by a current injection (blue pulse) and then, by a laser pulse (green bar). Reprinted with permission from ref 45. Copyright 2018 The Authors. (B) Architectural similarity observed in biological and artificial photoabsorbers. Schematic diagram of a retina (left), and a Au-TiO₂ NW array interfaced retina (middle). Adapted with permission from ref 32. Copyright 2018 Springer Nature. SEM image (right)

of InGaN NW array used in photovoltaic devices. Reprinted with permission from ref 71. Copyright 2012 American Chemical Society. (C) Schematic diagram of a cell sitting on a microstructure composite containing a photoresponsive hydrogel and Au nanorods (represented as red rods). Upon a light trigger, the hydrogel contracts, bending the microstructure and stretching the portion of a cell adhered to the microstructure tips. Reprinted with permission from ref 57. Copyright 2017 Springer Nature.