

Mimicking Photosynthesis with Electrode-Supported Lipid Nanoassemblies

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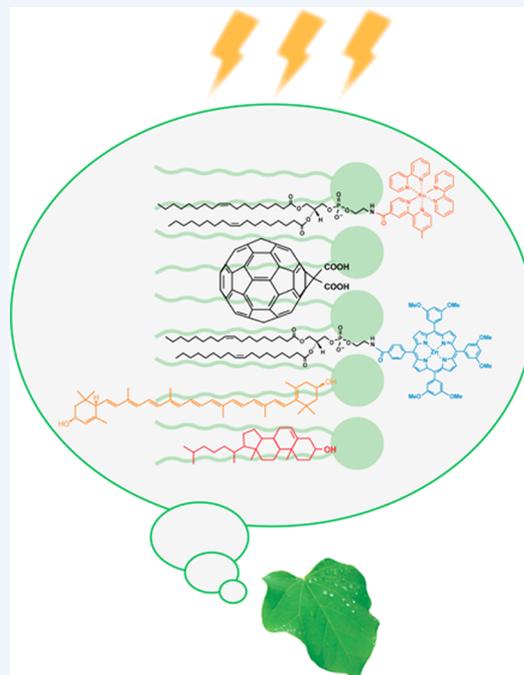
CONSPECTUS: The grand scale, ultimate efficiency, and sustainability of natural photosynthesis have inspired generations of researchers in biomimetic light energy utilization. As an essential and ubiquitous component in all photosynthetic machinery, lipids and their assemblies have long been recognized as powerful molecular scaffolds in building artificial photosynthetic systems. Model lipid bilayers, such as black lipid membranes and liposomes (vesicles), have been extensively used to host natural as well as synthetic photo- and redox-active species, thereby enabling key photosynthetic processes, such as energy transfer and photoinduced electron transfer, to be examined in well-defined, natural-like membrane settings. Despite their long history, these lipid models remain highly relevant and still enjoy wide practice today.

In this Account, we share with the reader our recent effort of introducing electrode-supported lipid nanoassemblies as new lipid models into photosynthesis biomimicking. This line of research builds off several solid-supported lipid bilayer architectures established relatively recently by workers in membrane biophysics and reveals important new features that match and sometimes exceed what earlier lipid models are capable of offering. Here, our eight-year exploration unfolds in three sections:

(1) New photosynthetic mimics based on solid-supported lipid bilayers. This systematic effort has brought three solid-supported bilayers into artificial photosynthesis research: lipid bilayers supported on indium tin oxide electrodes, hybrid bilayers, and tethered lipid bilayers formed on gold. Quantitative on-electrode deposition of various photo- and redox-active agents, including fullerene, $\text{Ru}(\text{bpy})_3^{2+}$, and porphyrin, is realized via liposomal hosts. Vectorial electron transfer across single lipid-bilayer leaflets is achieved between electron donor/acceptor directionally organized therein, taking advantage of multiple incorporation sites offered by these bilayers as well as their sequential formation on electrodes. Supported on electrodes, these bilayers uniformly afford reliable photocurrent generation and modular system design.

(2) Gold-supported hybrid bilayers as a powerful model platform for probing biomembrane-associated photoelectrochemical processes. These hybrid nanostructures consist of one alkanethiol (or substituted alkanethiol) and one lipid monolayer, whose chemical identity and makeup can be separately controlled and modified. Such precise molecular organization and flexible formation, in turn, enable a series of physicochemical parameters key to photosynthetic processes to be explicitly examined and cross-compared. A few such examples, based on donor/acceptor distance and loading, interfacial dipole, and redox level, are included here to illustrate the usefulness and versatility of this system.

(3) Mimicking photosynthesis with supercomplexed lipid nanoassemblies. This research effort was motivated to address the low light absorption suffered by single-bilayer based photosynthetic mimics and has yielded a new lipid-based approach to mimicking Nature's way of organizing multiple photosynthetic subunits. Rhodamine and fullerene assembled within these lipid supercomplexes display robust electronic communication. The remarkable possibility of using lipid matrix to further improve photoconversion efficiency is revealed by cholesterol, whose addition triggers exciton formation that promotes faster energy and electron transfer in these lipid nanoassemblies.



INTRODUCTION

The grand scale, ultimate efficiency, and sustainability of natural photosynthesis have inspired generations of researchers in biomimetic light energy utilization. Decades of research, in molecular organization and photodynamics of numerous natural systems, have brought together a coherent picture of operation filled with spatiotemporal details.¹ Taking the center

stage of this picture are various photosynthetic protein complexes, which organize small pigments and cofactors for coordinated light harvesting, directional charge propagation and separation, and photo- to (electro)chemical quantum con-

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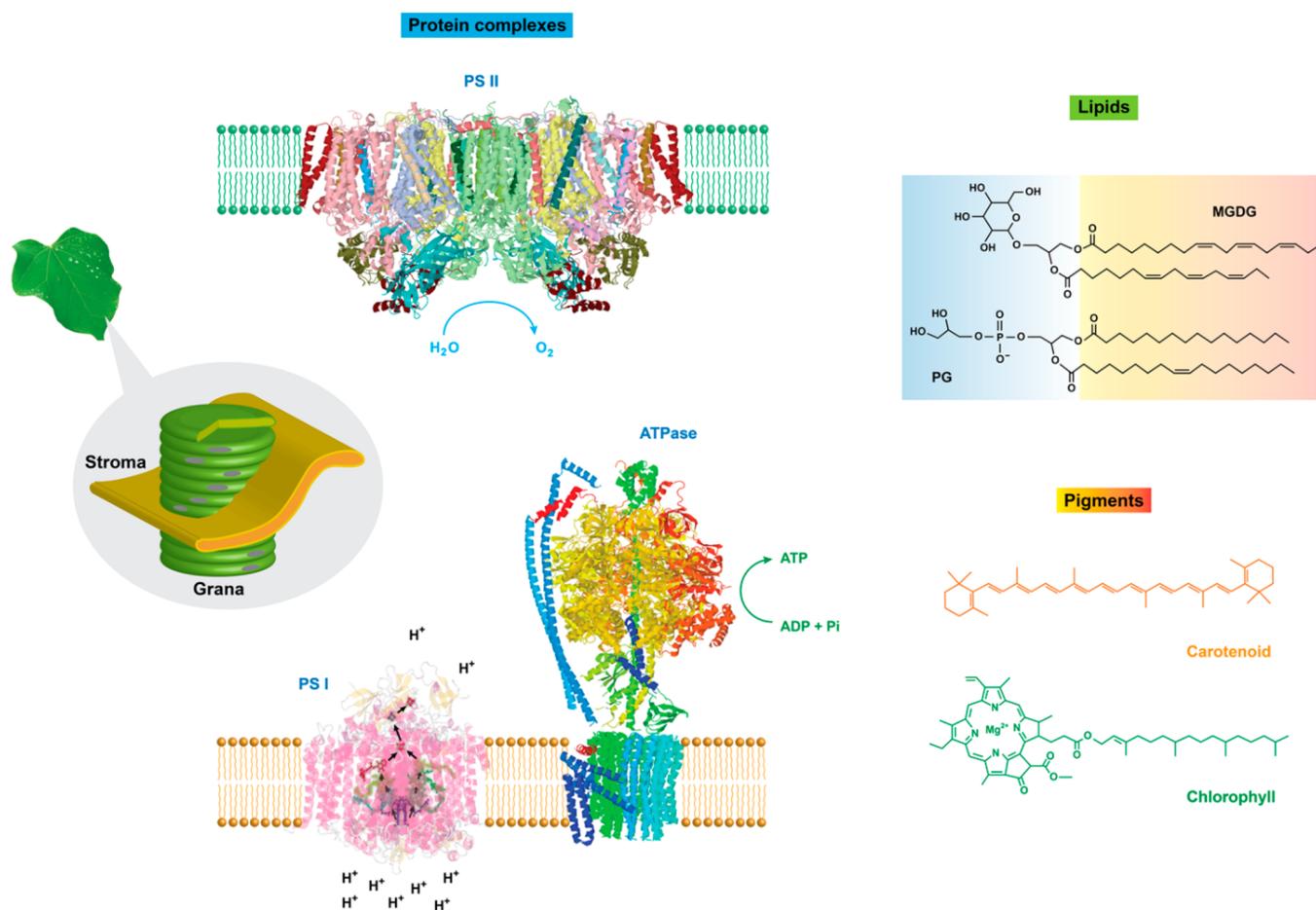


Figure 1. Photosynthetic components of green plants at a glance. Lipid bilayers hosting various photosynthetic proteins are color-coded in terms of their locations: grana (green) vs stroma (golden brown). The carotenoid shown here is β -carotene. PS I and II, photosystem I and II; MGDG, monogalactosyldiacylglycerol, the most abundant lipid in thylakoid membrane; PG, phosphatidylglycerol.

version. By contrast, lipids and their assemblies, though ubiquitous, are often cast in the shadow, owing to their passive, largely structure-related functions. Behind this static character of lipids, however, are the predictable assembling chemistry and respectable mechanical stability of such assemblies, which make these nanostructures ideal molecular scaffolds in building artificial photosystems. It is on mimicking photosynthesis with several solid-supported lipid bilayers that this Account is primarily focused. In particular, we share with the reader the sort of photoelectrochemistry one can design and examine by precisely organizing these amphiphilic species on electrodes, which we first started eight years ago.

From basic cell biology, we are already familiar with lipids and their most common aggregate formation, bilayers, which fulfill such important structural functions as cellular compartmentalization and hosting membrane proteins. In photosynthetic organisms and organelles, their involvement in many photosynthetic processes goes well beyond these passive “routines”. Here, one can readily witness how the billion-year-long evolution has perfected the photosynthetic machinery, so much so that photosynthetic proteins mesh their functions seamlessly with assembled lipids by exhaustively exploiting what the latter have to offer on molecular, structural, and material levels. As a molecular scaffold, lipid bilayers provide suitable sites for photosynthetic protein fragments to anchor, and their well-defined aqueous/lipid interfaces and hydrophobic interior further guide protein’s folding and assembling.²

As the common host, these lipid bilayers also hold small amphiphilic species such as plastoquinone within close proximity with their protein electron-transfer partners.¹ Being a low-dielectric material, these lipid bilayers help ensure that photogenerated charges only flow along designated paths with minimal leaking to the surroundings. The same attribute also makes it possible to maintain a pH gradient across biomembranes, which provides the driving force for bilayer-embedded ATP synthase³ to produce ATP (Figure 1). Many photosynthetic protein complexes, including ATP synthase and cytochrome *b*_c₁, in addition undergo substantial motions or conformational changes while carrying out their functions, only possible thanks to the mechanical strength of lipid bilayers and their robust association with the anchored proteins.

The inventory of lipid assemblies goes beyond single bilayers. In order to boost light-harvesting capacity and successfully handle incident light of fluctuating quantity and quality, many natural photosynthetic systems also employ interconnected lipid bilayer stacks. In the thylakoid membrane^{4,5} of green plant chloroplasts, for example, the lipid network differentiates into two domains with distinct topology: cylindrical stacks of multiple lipid-bilayer discs called grana and more spaced-out bilayer sheets, that is, stroma, which wind around and join with grana at the margins (Figure 1). Within this network, bilayer interspacing provides a simple yet elegant mechanism for size-sorting photosynthetic proteins, with grana primarily hosting photosystem II complex (including oxygen-evolution complex),

and stroma enriched with photosystem I complex and ATP synthase, which are too bulky to fit in grana stacks. The association and dissociation of neighboring bilayer discs in grana, accordingly, control the level of transverse light energy propagation. Laterally, such zipping and unzipping processes constantly change grana/stroma boundaries, which facilitate redistribution of light-harvesting complex II between the two photosystems, and hence, light energy spent in ATP vs oxygen production.^{4,5}

Such rich offerings of lipids tickle one's curiosity. To what extent can we reproduce their functions in photosynthesis, without enlisting the mighty proteins? Or, taking a reductionist approach, can we prepare artificial lipid systems, so that key photosynthetic steps can be examined and understood one at a time? Trying to answer these intriguing questions has occupied many workers over the years, including us.

The rest of this Account is organized as follows. After a quick introduction to lipid-based artificial photosynthesis and an equally brief survey on solid-supported lipid bilayers, we will recount our expedition to mimicking photosynthesis with these supported lipid nanostructures. When the lipid-supporting solid is in addition an electrical conductor such as gold, one gets planar lipid membranes that can be immediately subjected to photochemical and electrochemical manipulation and interrogation. We highlight fine architecture control, versatile system design, and physical insights enabled by these electrode-supported lipid nanoassemblies. We also discuss strategies that can take us beyond single lipid-bilayer based mimicking systems, as well as other research opportunities that may arise.

■ LIPID-BASED ARTIFICIAL PHOTOSYNTHESIS: EARLIER WORK

The year 1963 witnessed the arrival of two artificial lipid models that remain widely used today: black/bilayer lipid membranes⁶ (BLMs) and liposomes.⁷ A few years after, Tien, a co-inventor of BLMs, demonstrated for the first time photovoltage generation in BLMs⁸ containing natural photosynthetic pigments, such as chlorophyll and xanthophyll. To form a BLM, a lipid precursor dissolved in organic solvents (e.g., octane) is first brushed onto a pinhole in a thin Teflon sheet partitioning two aqueous compartments. Once in water, the hydrophilic/hydrophobic mismatch drives the organic-dissolved lipids to reorganize and redistribute, which, over time, produces a continuous lipid/organic mixed membrane structure with a bilayer-thin center segment expanding into a much thicker organic body (i.e., the Plateau–Gibbs border⁸) adhering to the rim of the aperture (Figure 2). BLMs are highly amenable to photoelectrical measurements, in that their open architecture allows straightforward electrode placement and reagent exchange in both compartments. The first demonstration of artificial photoconversion based on liposomes, on the other hand, was made in 1976 by Mangel,⁹ who was motivated to bypass the apparent limitations of BLMs, such as the presence of organic solvents and uncertain lipid composition associated with the bilayer region. By sonication or extrusion, lipid aqueous suspensions can be induced to roll into spherical colloidal nanoparticles, closing within them an aqueous core separated from the bulk by a single lipid bilayer¹⁰ (Figure 2). By centrifugation or column separation, it is further possible to exchange the bulk medium in which liposomes are suspended. Provided that no species permeate the lipid bilayer appreciably, a cross-bilayer chemical gradient, for example, in pH or redox level, can be established and maintained this way.

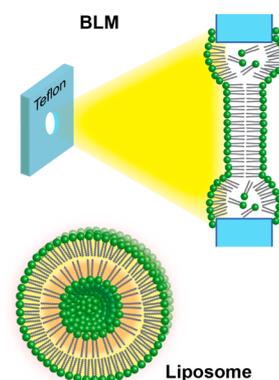


Figure 2. Classical artificial lipid models: black/bilayer lipid membrane (BLM) and liposome. The latter structure is shown here as a truncated hemisphere.

On the downside, however, one often has to settle for indirect spectroscopic characterization when mimicking photosynthesis with liposomes, due to their small size and closed architecture.

Equipped with these lipid models and spurred in part by a worldwide energy crisis in 1970s, lipid-based artificial photosynthesis had blossomed into an active research field in the following years. Compared to the initial demonstrations, work done in this period skillfully exploited the well-defined nanoscopic interfaces of lipid bilayers, often featuring a lipid host scaffolding multiple synthetic components. Using liposomes, for example, Calvin and co-workers¹¹ showed that efficient photosensitized electron transfer across a lipid bilayer could be established between membrane-bound ruthenium tris(bipyridyl) complexes and aqueous viologen and ethylenediaminetetraacetate (EDTA). More recently, Gust, Moore, and Moore demonstrated that a quinone–porphyrin–carotene triad conjugate could be used in place of cytochrome *b_c1* complex to establish a proton gradient across liposome bilayers to drive ATP synthesis.¹² With BLMs, successful photovoltage generation from membrane-incorporated quantum dots¹³ and fullerenes¹⁴ were demonstrated by Fendler and Mauzerall, respectively. For a full account of activities in this area, the reader may consult several existing reviews.^{15,16}

■ SOLID-SUPPORTED LIPID BILAYERS

Continuous monolayer/bilayer lipid formation^{17,18} on planar solid substrates, such as glass and quartz, was first developed by McConnell and co-workers in the early 1980s. In either case, lipids to be deposited need to be preassembled in some fashion, for example, monolayer patches prepared in a Langmuir–Blodgett trough or lipid vesicles by sonication. By controlling hydrophobicity of the substrate surface, one can conveniently switch between monolayer and bilayer lipid deposition. For example, when a self-assembled monolayer (SAM) of alkane silanes is formed on glass, the resulting hydrophobic surface only accommodates a lipid monolayer¹⁷ at the top. On the other hand, bilayer lipid formation¹⁸ on hydrophilic surfaces can often be straightforwardly obtained by immersing clean substrates into a liposome suspension (typically in low millimolar total lipid concentrations) for a few hours. The final structure thus obtained typically features a tilted lipid bilayer separated from the substrate surface by a water layer 10–20 Å in thickness.¹⁹ This water layer exists because both the hydrophilic substrate surface and polar lipid headgroups are initially hydrated, and removal of such surface-bound water

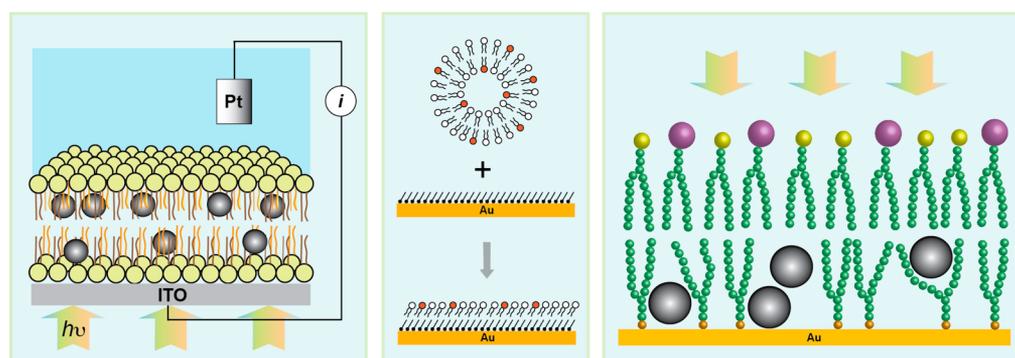


Figure 3. New photosynthetic mimics, based on lipid bilayer supported on ITO (left), lipid/alkanethiol hybrid bilayer (middle), and gold-tethered lipid bilayer (right). Adapted from refs 23, 27, and 28. Copyright 2008, 2009, and 2010 American Chemical Society.

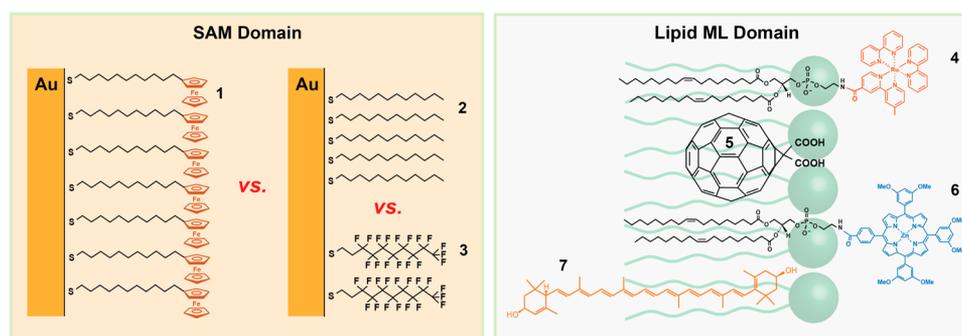


Figure 4. Hybrid lipid bilayers as a new biomembrane model for photoelectrochemical studies, with chemical identity and composition associated with each monolayer (ML) tunable. See the main text for more details. Adapted from ref 30. Copyright 2013 John Wiley and Sons.

molecules, that is, dehydration, is energetically prohibitive.²⁰ In both monolayer and bilayer formations, the deposition process is self-limiting, in that the newly formed lipid/aqueous interface does not afford further lipid buildup or multiple lipid–bilayer deposition. This important restraint arises mainly because of steric repulsion between opposing lipid headgroups and lack of water ordering thereof.²⁰ Besides the apparent difference in having the trapped water layer or not, solid-supported monolayers and bilayers also differ from each other in lipid layer thickness and symmetry.

Replacing alkane silanes employed by McConnell et al. with alkanethiols, Plant demonstrated monolayer lipid deposition on SAMs grafted on gold in 1993, that is, lipid/alkanethiol hybrid bilayers.²¹ This adds an important new member to the solid-supported lipid bilayer family, owing to the well-established thiol/gold formation chemistry and opportunities in photo/electro-chemistry offered by noble metals. Similar deposition can also be fashioned on SAMs formed by thiolated lipids, that is, gold-tethered lipid bilayers,²² which present yet another solid-supported lipid model closely resembling native biomembranes.

NEW PHOTOSYNTHETIC MIMICS BASED ON SOLID-SUPPORTED LIPID BILAYERS

Coming off postdoctoral training working on liposome-based electroanalytical chemistry and incentivized by another energy crisis, the senior author of this Account started investigating the possibility of advancing lipid-based artificial photosynthesis using solid-supported lipid bilayers in 2008. Our initial effort²³ was focused on lipid bilayers supported on planar indium tin oxide (ITO), a transparent conducting substrate (Figure 3). To render these bilayers photoactive, we chose fullerene C₆₀, a

photoagent with suitable size (~1 nm diameter), excellent electron-accepting capability, and stability. The task at hand, therefore, was to first assemble hydrophobic C₆₀ into the hydrocarbon region of liposomes and then transfer these lipid-associated photoagents onto electrodes via liposome fusion and bilayer formation on ITO. This failed quickly, however, because we were not able to get liposomes to homogeneously carry more than 0.2% (mol % vs total lipids) fullerenes. Without a reasonably high fullerene loading, our new system would immediately suffer poor light absorption. Such lack of C₆₀ incorporation puzzled us, because not only were much higher loadings, 2–4%, experimentally demonstrated previously^{24,25} but also more recent molecular dynamics simulation²⁶ depicted fast (microsecond) penetration of C₆₀ into lipid bilayers even in very high concentrations (>10%). When we followed these reported procedures by sonicating C₆₀ into liposomes, we observed similar fullerene aggregation and its constant settling out from liposomes. Putting this sonication-yielded lipid/fullerene mixture through an extrusion procedure, in order to obtain unilamellar liposomes, we found most fullerenes being filtered out by the nanoporous extrusion membranes, instead of staying together with the lipids. Right there, we learned our first lesson: harmonious assembling requires precise molecular design, on which one simply cannot force matters (sonication in this case). While the bilayer interior potentially offers a hydrophobic environment for water-exposed fullerenes to escape and gain stability, an energy price has to be paid in disrupting the association between the lipid hydrocarbon chains so as to accommodate the bulky fullerene buckyballs. As such, aggregation among fullerenes becomes an affordable alternative state of existence. To avoid this course and increase fullerene's tendency to associate with phospholipids, therefore, one has to

render fullerene with similar assembling characteristics as the latter. This led us to [6,6]-closed-ring bridged malonic fullerene (Figure 4, structure 5), which combines desired amphiphilicity and shape with relatively undisturbed electronic structure. With this fullerene derivative, we achieved quantitative, high-concentration (up to 4%) incorporation of fullerenes in liposomes with minimal aggregation.²³ Critically, these fullerene-studded liposomes still behave like regular ones, rupturing and forming bilayer on ITO surfaces and in doing so, transferring and immobilizing fullerenes onto electrodes. Stable photocurrents are reliably generated from these ITO-supported lipid nanoassemblies, which can be repeatedly used for days at a stretch.

Following this initial success, we set our eyes next on phospholipid/alkanethiol hybrid bilayers (Figure 3). The photoagent used here was Ru(bpy)₃²⁺ (bpy = 2,2'-bipyridine, Figure 4 structure 4), another champion molecule whose elegant photo- and electrochemistry continues to draw interest after over 50 years of extensive research. With a lipid anchor (e.g., phosphoethanolamine), Ru(bpy)₃²⁺ can be straightforwardly introduced into liposomes, which, upon further incubation with a preformed SAM, quantitatively deliver the photoagent onto gold electrodes.²⁷ This bilayer formation then enabled us to examine the dependence of photocurrent output on the underlying SAM. Of the three *n*-alkanethiols investigated (C6, C12, and C18), the C12-SAM based bilayers constantly produce higher currents (~15%), likely because they afford high-quality lipid packing atop (vs C6) and suitable electron-tunneling distance (vs C18) at the same time. Compared to fullerene in ITO-supported bilayers, a sizable photocurrent decay was observed in this case, a result of the highly reactive excited-state dye, Ru(bpy)₃^{2+*}, oxidizing lipids and thus deteriorating the bilayer. While this decay can be partially forestalled using sacrificial species such as ascorbate, it shows the finite inertness of phospholipids and their assemblies as a scaffolding material.

Encouraged by these findings, we then explored the feasibility of multicomponent photoconversion on tethered lipid bilayers (Figure 3). Taking advantage of the sequential formation of this structure, we were able to decorate each of the two leaflets of the bilayer quite flexibly with electron donor, a zinc-coordinated porphyrin, or its acceptor, fullerene again, which all together yielded seven distinctively configured photocells.²⁸ Comparing their performance and stability then provides several insights into the photoelectrochemical processes involved. Above all, to help photogenerated electrons to propagate through the low-dielectric hydrocarbon region of a bilayer successfully, photo- and redox-active agents should be present in both leaflets so that a continuous electron transfer (eT) pathway spanning the whole structure can be established. Moreover, it is essential for the photogenerated charges to be transported away as soon as they are generated. Failure to do so leads to either low conversion efficiency due to charge recombination or, in some cases, translocation of photoagents and destabilization of this lipid-assembled system. Photocurrents resulting from lateral vs vertical eT processes can be separately produced or combined, with the final optimized device outperforming its single-agent counterparts by more than 50-fold. This improvement is quite striking, considering the fact that it is achieved all within a lipid matrix only about 5 nm thick.

■ GOLD-SUPPORTED HYBRID BILAYERS AS A NEW PHOTOELECTROCHEMICAL MODEL

Behind the seemingly plain thiol/lipid hybrid bilayers lies ample room for system design and experimental maneuvering, which we will demonstrate in this section. Once assembled, this hybrid structure consists of precisely one thiol and one lipid monolayer each. Their packing is also ordered, with lipids sitting on top of thiols that are directly grafted on the gold surface. Each monolayer in addition displays a preferential orientation, owing to the Au–S bonding at the bottom and ordered lipid headgroups interfacing water at the top. Because the two monolayers are introduced onto the gold surface sequentially, one also possesses uncompromised control over the physicochemical characteristics and photo- and electro-active species assembled into each layer.

Two energy-lowering processes primarily drive the hybrid bilayer formation: release of lipid packing stress in liposomes and removal of the hydrophobic SAM from direct water exposure. Of the two, we reasoned that the stress release from liposomes transforming into a bilayer should be the more deciding factor, which happens to also drive the same liposomes to form symmetrical bilayers on hydrophilic surfaces (that is, in the absence of the second process). Taking it further, we hypothesized that *n*-alkanethiols, which lack functionality, might be replaced from the bilayer formation by other thiol species, as long as the substitute still affords hydrophobic, reasonably organized SAMs. This was found to be the case. Using ferrocene-terminated undecanethiol (Figure 4 structure 1), we successfully formed a new hybrid bilayer with a layer of ferrocenes sandwiched in the final structure. Together with photoagents separately introduced into the top lipid monolayer, it presents us a well-defined lipid architecture where cross-membrane photoinduced electron transfer (PeT) can now be redox-modulated.²⁹ Since the ferrocene moieties are inserted right in the PeT path, they introduce a new set of electronic states about which the photogenerated charges can hop on and off. Energetically, these new states are centered around the formal potential of ferrocene, ~0.4 V vs Ag/AgCl, which can act either as an electron sink or a relay, depending on the redox levels of coassembled photoagents as well as the electron flow direction. As a result, attenuated anodic photocurrents and enhanced cathodic photocurrents are observed on these ferrocene-embedded bilayers compared to *n*-alkanethiol-based systems. Although the same trend was seen for both photoagents, such rectification effect is almost an order of magnitude greater in the case of fullerene, likely due to its stronger electronic coupling with ferrocene caused by its location and size.

The same hybrid architecture also enabled us to specifically study oriented surface dipole, an interesting interfacial phenomenon of particular importance in organic (photo)-electronic and photovoltaic devices. Once again, we took advantage of the fact that liposome surface deposition is insensitive toward underlying SAMs, which, in this case, are formed by two thiols with opposite molecular dipole: *n*-dodecanethiol vs heptadecafluoro-1-decanethiol (2 and 3, Figure 4). Separately grafting these thiols onto gold then produced two SAMs with net dipoles oriented in opposite direction. Furnishing these SAMs with a common top lipid layer incorporated with either fullerene or porphyrin (5 and 6, Figure 4), we thus obtained a simple setup³⁰ where the influence of surface dipole on photogenerated charge injection

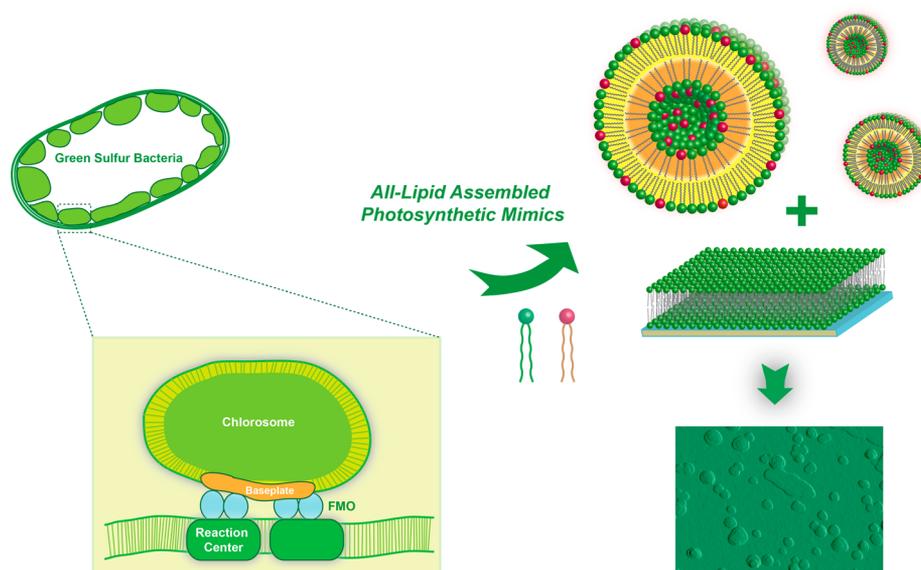


Figure 5. Mimicking photosynthesis with supercomplexed lipid nanoassemblies. Reproduced from ref 33. Copyright 2016 American Chemical Society.

could be unambiguously identified and assigned (Figure 4). Compared to *n*-dodecanethiol-based cells, lower anodic but higher cathodic photocurrent/photovoltage were generated from fluorothiols-based systems. Such modulation effects are satisfactorily explained by the different dipole potentials associated with the two SAMs, which modify the Fermi level of gold and hence its alignment with the HOMO/LUMO levels of photoagents. The resulting alignment (or lack thereof) in turn determines the height of electron/hole injection barriers and thus, the magnitude of obtained photoelectrochemical responses. This time, the lipid-embedded fullerene displays a much lower level of modulation compared to more distantly placed porphyrin, for example, 24% vs 62%, in the case of anodic photocurrents generated. This trend is noticeably opposite from the redox-modulated photoconversion²⁹ encountered earlier.

Carotenoids present a unique set of light-harvesting pigments that is being employed by Nature in photosynthesis alongside chlorophylls and bilins. Unlike chlorophylls and their synthetic analog porphyrins, however, efforts of adopting carotenoids as a light-absorbing pigment in artificial photosynthesis are relatively scarce. This disparity is first of all caused by the fact that most linear, heavily conjugated carotenoids lack convenient sites for functionalization. This constraint can be lifted if one instead takes an assembling-based approach. Or so we first thought. When we tried to incorporate β -carotene (Figure 1), the most readily available carotenoid, into liposomes, we encountered serious phase segregation. To achieve homogeneous incorporation, again, precise structural match among all assembling components needs to be satisfied. We then found such a match in lutein (Figure 4 structure 7), another carotenoid that differs from β -carotene mainly by the OH groups attached to the two distal six-membered rings. Situated in a hybrid lipid bilayer, lutein alone only produced negligible photoresponses, an outcome attributable to its extremely brief excited states, sluggish electron transfer and deeply buried position within lipids. The impact of these factors was so great that, no communication between lutein and porphyrin (Figure 4 structure 6) could be observed when they were assembled in the same hybrid bilayers. We then

hypothesized that the similarly lipid-embedded fullerene might be able to communicate better with coassembled lutein, which was indeed the case.³¹ When we increased the lutein loading in the hybrid bilayer from 1 to 3% and held the amount of fullerene constant at 2%, we observed a corresponding decrease in anodic photocurrents and a concurrent increase in cathodic photocurrents. This result argues strongly that PeT, instead of energy transfer, is primarily responsible for the observed photocurrent modulation; otherwise, the increased lutein loading would lead to more energy transfer and thus cause both anodic and cathodic currents to rise. As such, the directional organization of lutein/fullerene within the bilayer gives rise to vectorial charge separation upon photoexcitation, which facilitates electron flow in the case of cathodic photocurrent generation, and impedes electron flow in the other direction. This study thus provides a successful example of combining both synthetic and natural photoactive components in building molecular photovoltaic systems.

■ BEYOND SINGLE LIPID BILAYERS

All the single-bilayer based mimicking systems described thus far have one limitation in common: low light absorption, due obviously to their extremely thin optical path. In this section, we describe our first attempt to address this issue, using supercomplexed lipid nanoassemblies to mimic Nature's way of organizing multiple photosynthetic subunits. In green sulfur bacteria (Figure 5), for example, such organization is achieved with four subunits: chlorosome, baseplate, Fenna–Matthews–Olson (FMO) protein and reaction center (RC). Together, they form a four-tier architecture, through which the harvested light energy is efficiently funneled through an energy transfer cascade:^{2,32} chlorosome \rightarrow baseplate \rightarrow FMO \rightarrow RC, and only at the last stop is the light energy converted to electrochemical energy via charge separation and transfer.

Up against the grand master, our mimic is admittedly modest, which features a two-tier lipid nanoassembly³³ comprising a layer of anionic unilamellar liposomes electrostatically held on a positively charged lipid bilayer (Figure 5). With 5 mol % lissamine rhodamine B incorporated, the

liposomes serve as the light-harvesting unit of the assembly, whereas the underlying lipid bilayer contains 5% fullerene as electron acceptor to facilitate directional charge separation and electron transfer. With the liposomes and bilayer both containing 20% charged lipids, strong electrostatic attraction between the two units produces large-scale liposome deposition, which also causes extensive liposome rupturing and lipid transfer, producing flattened lipid micropatches sitting on the lipid bilayer. Nevertheless, rhodamines and fullerenes brought together this way display robust electronic communication, delivering a PeT rate constant of $6.1 \times 10^8 \text{ s}^{-1}$ and a photon-to-electron quantum conversion efficiency (QE) of 7.8%.

Then the investigation took a dramatic turn. When 30% cholesterol was added into the liposomes to replace 1,2-dipalmitoyl-*sn*-glycero-3-phosphocholine (DPPC) while other components were kept unchanged, the otherwise similarly configured photocell produced a QE of 14.2%. Thrilled first by this >80% efficiency enhancement, we were soon sent to wonder: how was it possible?

Cholesterol is a truly unique lipid species, in that it not only can complex with phospholipids but also bears distinctive structural mismatch with the latter, due to its small hydrophilic portion (–OH) and rigid molecular framework. As such, it can not only wedge in but also modify the distribution and packing density of neighboring lipids, thereby impacting physical and mechanical characteristics of lipid membranes on a macroscopic level.^{34,35} These effects kick in first locally at low cholesterol concentrations, producing heterogeneity within the lipid matrix and hence phase separation. When cholesterol is included in the DPPC/DPPG liposomes, the initial pure gel-phase lipid matrix is partially replaced by a new liquid-ordered phase induced by cholesterol, resulting in two-phase coexistence. Of the two, the coassembled rhodamine prefers the new phase, which causes clustering of dyes in the cholesterol-rich domain and a corresponding concentration decrease of dyes in the gel phase. Because cholesterol can reduce the tilting of lipids versus the bilayer normal and thus the cross-sectional area occupied per lipid,³⁵ it effectively increases the ordering of lipids residing in this domain. To the lipid-conjugated rhodamines, critically, this ordering effect lowers the randomness in relative orientation of dye transition dipoles and improves their constructive electronic communication. This allows the clustered rhodamines to respond to light excitation collectively, producing dimer-exciton states.^{36,37} Throughout this super-complexed lipid network, this exciton-based energy transfer supersedes Förster-type energy hopping among individual dyes, facilitating a more efficient delivery of harvested light energy to the charge-separation sites. Another potential contributor to the enhanced performance is the condensed and more ordered medium, which benefits the energy transfer process by lowering the extent of energy loss due to vibrations, that is, the electron–phonon coupling,³⁸ within the lipid matrix. Ultimately, these enhancement mechanisms cause the PeT rate between rhodamines and fullerenes to triple in the cholesterol-coassembled system.

The importance of exciton formation in natural photosynthetic systems has been recognized recently,³⁹ which Nature employs to fight off energy losses due to electron–phonon coupling and disorders in soft protein matrices. With more work, this phenomenon may become a general strategy one day for improving photoconversion efficiency in artificial photosynthetic systems.

■ COMMENTS AND FUTURE PROSPECTS

Electrode-supported lipid nanoassemblies provide a powerful and versatile new platform for studying cross-membrane energy transfer and photoinduced electron transfer and mimicking photosynthesis, as illustrated by results in this Account. Compared to earlier lipid models employed in artificial photosynthesis research, these supported lipid structures often excel in stability, robustness, and precise control in composition and architecture. With these, multiple photo- and redox-active species, for example, an electron donor/acceptor pair, can be placed in lipid bilayers with well-defined location and spacing, ready for extended photoelectrochemical investigation. Since the physicochemical characteristics associated with each leaflet can often be separately controlled, a great many bilayer configurations can be accessed, enabling fundamental parameters key to photosynthetic processes to be examined, often one at a time.

These electrode-supported lipid bilayers further serve as a foundation on which multilamellar/multidomain lipid super-complexes can be built. Photosynthetic mimics based on these higher-order architectures display not only improved light collection, but also constructive electronic communication, as exemplified by cholesterol in the liposome-on-bilayer system illustrated above. Along this direction, new research opportunities still await. For example, it may be possible to extend this two-tier lipid construct to more extensive multilamellar systems comprising hundreds of lipid bilayers, on which several established formation protocols^{40,41} exist.

These electrode-supported lipid nanoassemblies are unlikely to offer us practical solar devices for sure—a quick look at how Nature operates with these delicate species should convince anyone in doubt. Rather, their true value lies in their improved stability, modular and extendable design, and ready conversion into biomembrane photoelectrochemical systems. This should make them useful in photosynthesis research, for example, as characterization tools hosting or interfacing natural photosynthetic components.

Looking beyond photosynthesis biomimicking, we feel optimistic about their potential usefulness elsewhere. After all, lipid nanoassemblies represent a diverse class of nanomaterials, which cover a wide range of morphology (i.e., particles, tubes, sheets and many more), lamellarity (one to hundreds), and size (nanometers to micrometers). Such diversity, amazingly, can all be accessed through a universal assembling mechanism played out in the most important solvent, water. This should allow these electrode-supported lipid nanoassemblies to be flexibly designed to (photo)electrochemically probe a variety of biomembrane-associated events and processes. Such is emerging.^{42–45}

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