Photoelectrochemical synthesis of DNA microarrays

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Optical addressing of semiconductor electrodes represents a powerful technology that enables the independent and parallel control of a very large number of electrical phenomena at the solid-electrolyte interface. To date, it has been used in a wide range of applications including electrophoretic manipulation, biomolecule sensing, and stimulating networks of neurons. Here, we have adapted this approach for the parallel addressing of redox reactions, and report the construction of a DNA microarray synthesis platform based on semiconductor photoelectrochemistry (PEC). An amorphous silicon photoconductor is activated by an optical projection system to create virtual electrodes capable of electrochemically generating protons; these PEC-generated protons then cleave the acid-labile dimethoxytrityl protecting groups of DNA phosphoramidite synthesis reagents with the requisite spatial selectivity to generate DNA microarrays. Furthermore, a thin-film porous glass dramatically increases the amount of DNA synthesized per chip by over an order of magnitude versus uncoated glass. This platform demonstrates that PEC can be used toward combinatorial bio-polymer and small molecule synthesis.

Results

Photoconductor Fabrication and Characterization. From bottom to top, the photoconductive anode (Fig. 1C) is composed of indium tin oxide-coated glass (ITO-glass) as the rear electrical contact, 1 μm-thick undoped amorphous silicon (a-Si), and 100 nm-thick platinum pads (with 15 nm-thick titanium adhesion layers). Amorphous silicon was chosen as the photoconductive material because it is optically transparent, and its large internal surface area. In contrast to addressable complementary metal oxide semiconductor (CMOS) electrodes that often require over 30 mask steps to fabricate, the entire substrate here can be cheaply fabricated with a single, unaligned mask. It should be noted that not all photoconductors are suitable for PEC synthesis, and that the nature of the substrate fabricated here was critical to the success of the system, as will later be discussed.

To understand the nature of the photoconductor, extensive solid-state and PEC analyses were performed. Diode measure-

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ments showed that the substrate behaves like a very lightly doped n-type Schottky diode that generates photopotentials as large as $+205 \text{ mV}$ above $500 \text{ mW/cm}^2$ illumination power [SI Text (Supporting Note 1) and Fig. S1]. Fig. 2B shows a cyclic voltammogram (C-V) of 2.5 mM hydroquinone with 100 mM tetrabutyllumonium hexafluorophosphate salt in acetonitrile, taken using the a-Si photoconductor as a light-activated working electrode versus a platinum quasi-reference electrode (QRE) (see ref. 20 for an explanation of voltammetric methods). The “light” and “dark” substrates were irradiated with 1 W/cm$^2$ and 1 mW/cm$^2$ white light, respectively. The PEC oxidation rates increase upon illumination, as proposed in Fig. 1A. Notice that a characteristic mass transport-limited peak is observable in the light C-V (asterisk in Fig. 2A), but no such peak is observable in the dark C-V (inset), Fig. 2B, which plots the relative potential drop across the semiconductor and electrolyte of the SEI ($\Delta \Phi_{\text{SEI}}$) versus illumination intensity, shows that the surface potential at the SEI is larger in the light state, as proposed in Fig. 1B.

**Microarray Synthesis.** “Dose tests” measuring deprotection efficiency of the acid-labile DMT group vs. illumination time were assayed by coupling Cy3-phosphoramidite and fluorescence quantification by confocal Fluorescence microscopy (Fig. 3A). Electrochemical solutions were composed of 100 mM hydroquinone with 100 mM tetrabutylammonium hexafluorophosphate in acetonitrile. The substrates were biased at $+1.7 \text{ V}$ with respect to ground and illuminated at 1 W/cm$^2$ white light. Complete deprotection or detritylation was achieved without noticeable acid diffusion halos typically between 20–28 s. Variations exist between pads due to nonuniformities in the optical field and the porous glass (e.g., pinholes, film thickness).

Such a time window during which the protons are spatially confined to the electrode presumably exists because the proton diffusion profile is anisotropic, with the preferred direction away from the surface rather than laterally along it (20). Although our data confirms that the initial profile is indeed highly anisotropic [SI Text (Supporting Note 2) and Fig. S2], it is unclear whether the spatial confinement is lost because an accumulation layer grows thick enough for the diffusion profile to become isotropic, or merely broadens (i.e., still anisotropic). As will be shown, the anisotropy provides sufficient proton containment to successfully synthesize a DNA microarray, but future versions will likely require increased control over the diffusion of reactive species, some options for which are discussed later.

Fig. 3B shows a fluorescence intensity map of Cy3-phosphoramidite coupled to the surface after one 22-s detritylation step, spelling “MIT.” Control experiments were performed to verify that this selective coupling indeed resulted from selective detritylation by PEC-generated acids, as opposed to direct electrochemical protecting group removal or damage to the growing strand [SI Text (Supporting Note 3) and Fig. S3]. Once suitable detritylation conditions were determined, microarrays were synthesized and assayed by the hybridization of fluorescently labeled oligonucleotides. Two different 12-mers were synthesized in a checkerboard pattern, where the middle 2 base positions contain the exact same match/mismatch combination to the complementary pair of targets (AT or TA). Each spot is perfectly complementary to 1 target strand in solution, and contains both A-A and T-T mismatches to the other. Fig. 4A shows the fluorescence image of the substrate after simultaneous hybridization of both target molecules labeled at the 3’-end with Cy3 or fluorescein dyes, demonstrating successful microarray synthesis.

The average stepwise yield was determined by methods similar to those previously described to measure the stepwise yield using photocleavable reagents (21, 22). Briefly, oligonucleotides of varying lengths, from 1 to 10 bases, were first randomly PEC synthesized (mixture of equal parts dA, dG, dC, and dT phosphoramidites). Next, Cy3-phosphoramidite was coupled to the entire chip after treatment with commercial halo-acid deblocking solution, and finally, the average stepwise yield was calculated based on the fluorescence signal intensity of each N-mer,
Chow et al. still spatially uniform (so long as the porous glass is uniform) metal pad is illuminated in the PEC system, the deprotection is synthesis errors in such a system. However, if only part of the field (27). Thus, optical misalignment and drift directly result in UV-photocleavage platforms, the spatial uniformity of protect-
table-based films, suitable semiconductors and device architectures (e.g., nanopar-
structing an improved optical projection system, examining other future studies will aim to optimize system parameters by con-
data of others (22). The 93% stepwise yield is in line with additions, has also been reported (21) or can be inferred from the
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**Fig. 2.** PEC characterization of the substrate. The “light” and “dark” states have been illuminated with 1 W/cm² and 1 mW/cm² white light, respectively. (A) Cyclic voltammogram (C-V) of 2.5 mM hydroquinone with 100 mM salt in acetonitrile. A diffusion- or mass transport-limited peak is observable (red asterisk) in the light state, whereas no such peak can be seen in the dark state (Inset). (B) Relative potential drops across the SEI (left ordinate) and measured electrode surface potential (right ordinate) as a function of illumination intensity. A 1.7-V bias was applied across the PEC cell. A and B verify the mechanisms proposed in Fig. 1B and C, respectively.

normalized against adjacent spots that were never illuminated. The stepwise yield (Fig. 4B) rose from 90% for strand length \( n = 1 \) to \( \approx 93\% \) after \( n = 5 \). This trend, in which the stepwise yield is particularly poor at first and then stabilizes after several base additions, has also been reported (21) or can be inferred from the data of others (22). The 93% stepwise yield is in line with previous first reports, which have ranged from 91–98% (21–25). Future studies will aim to optimize system parameters by constructing an improved optical projection system, examining other suitable semiconductors and device architectures (e.g., nanoparticle-based films, n-i-p diodes, microfabricated fluidic channels), and altering the coupling cycles (16, 26).

A notable aspect of the synthesis platform is that the sharpness of the synthesis area is largely defined by the metal pad itself. In UV-photocleavage platforms, the spatial uniformity of protecting group removal corresponds to the uniformity of the optical field (27). Thus, optical misalignment and drift directly result in synthesis errors in such a system. However, if only part of the metal pad is illuminated in the PEC system, the deprotection is still spatially uniform (so long as the porous glass is uniform) because the metal pads spread the charge carriers. Fig. 3D shows Cy3-phosphoramidite coupled to prepatterned electrodes that spell “GeneFab.” Even though the letters in “Gene” were only partially illuminated at the locations indicated by the boxes, the fluorescence is homogenous across the pad. The lateral electron spreading relaxes the image locking requirements (27) to maintain spatial homogeneity of the acid PEC-generation, although it is important to note that image locking is still extremely important for the beam to maintain registration with the metal pads, particularly at high spot densities.

**Porous Glass Characterization.** The porous glass film that coats the surface could benefit other microarray technologies, as well as chemical sensing applications that require a large-pore immobilization matrix (28). It can easily be formed on virtually any substrate with tunable thicknesses (75 nm–1.4 μm) in a 1-step spin-coating process (Fig. S4). It is optically transparent with >98% transmission from 350–700 nm (Fig. S4). The pores were typically 15–85 nm in diameter, as determined by low-voltage scanning electron microscopy and atomic force microscopy (Fig. S4). The current density during cyclic voltammetry using a coated electrode was \( \approx 60\% \) of the value from an uncoated one (Fig. S4).

The film is necessary to physically space the DNA from the electrode surface to limit direct electrochemical damage to the growing DNA strands and surface linker molecules. However, perhaps the most interesting property of the film is its large surface area that increases the oligonucleotide concentration per spot (i.e., amount of DNA synthesized per chip) by emulating
controlled-pore glass. Although porous films have previously been used with microarrays to enhance fluorescence hybridization signal and sensitivity (29, 30), the film reported here was more robust and permitted larger electrochemical current densities. UV-Vis absorbance analysis of cleaved molecules showed an 87-fold increase per μm film thickness in the initial loading density of 5'-O-DMT-2'-dT-3'-O-succinate (DMT-dT-succinate), as well as a 16-fold (also per μm thickness) increase in 40-mers synthesized with a standard synthesis cycle after desalting (Fig. 5A). Note that the area density was defined with respect to 2-dimensional chip area (not available surface area), and that the concentration was defined with respect to the geometric volume of the film. It should be noted that the measured value of 1.9 × 10^{13} molecules/cm² on flat glass is quite high compared with typically reported values of approximately 2 × 10^{12} molecules/cm², although several others have reported similar or even higher values (see ref. 23 for a list of reported densities). The measured density is most likely large because the unpolished glass used in this work has more microscopic surface area than typical microarray glass that is polished to near-atomic flatness.

The synthesis yield of 2.5 × 10^{14} molecules/cm² (or 415 pmol/cm²) using the porous glass film means that a microarray (equal size spots and spacing) on a 1 inch × 3 inch coated microscope slide would produce over 2 nmol DNA (the unpatterned synthesis area reported here produced 325 pmol). To put this yield increase into perspective, Fig. 5B shows the difference in fluorescence intensity one would see between hybridization assays on coated and uncoated glass. Wells were buffered-oxide etched to expose the bare glass of a coated slide, and then a 30-mer was synthesized on the patterned substrate using standard synthesis procedures. Therefore, after hybridizing the complementary Cy-3 labeled oligonucleotide, the relative ratio of fluorescence intensity between the wells and the crossroads of the grid represents the signal difference between uncoated and coated glass, respectively.

## Discussion

Although several light-addressable electrodes have been demonstrated for biomolecule sensing and manipulation (3, 5–7), the properties of the one reported here were critical to the success of the system. Very few semiconductor films that were tested actually succeeded for PEC synthesis. Testing of various α-Si deposition conditions, pad compositions (TiO₂, Pd, and Pt without an adhesion layer), and other semiconductor films (including silicon wafers of various doping, thin-film sputtered TiO₂, and spun-coat CdSe quantum dots) led to 2 empirical requirements for success. First, the film resistivity when illuminated must be relatively low (R < ~10³ Ω·cm) at the applied bias to ensure reasonably short deprotection times. Likewise, the thickness of silicon wafers precluded their use due to the resultant high impedance and shallow penetration of light. Second, the surface defect density must not be large enough to impede the PEC reaction by creating barriers to hole-injection into solution (1, 2).

As previously mentioned, the chemical gradient and applied electric field create an anisotropic diffusion profile that kept PEC-generated protons sufficiently localized to the electrode of interest. However, future research will need to further address the control of proton diffusion, especially as the electrode size approaches “ultra-microelectrode” regime (typically <10 μm) (20), in which the diffusion is always isotropic. Several strategies could be beneficial to implement. Pulsed illumination could limit the accumulation layer by allowing protons to move away from the accumulation layer by proton diffusion while maintaining a constant flux into the film. Another useful strategy would be “inverse capping” (27), in which the areas between the spots are selectively deprotected and chemically capped before microarray synthesis, effectively setting a boundary beyond which there are no reactive groups. Inverse capping would reduce errors or halos by significantly increasing the distance the proton would have to diffuse before an unwanted detritylation.
Among the electrochemical DNA microarray synthesis platforms (17, 31), the use of proton scavengers is popular. Scavengers can be electrochemically generated by placing the ground electrode in between the pads (i.e., crossroads to a grid) to create a chemical wall that contains the protons. This strategy was initially attempted in this work using benzoquinone, which can be reduced to proton-consuming radical at the ground/counter electrode. However, it was not pursued because of the extra microfabrication steps required. Weakly basic scavengers can also be placed in solution to slow down proton diffusion (31). This strategy was also initially attempted in this work (Fig. S3), but inclusion of the weak base in the deprotection solution quickly degraded the hydroquinone.

An interesting feature of a microarray platform based on PEC is increased generality versus other light-driven DNA microarray platforms, which in practice provide the highest spot densities. In context of more general combinatorial chemistry, chemically labile protecting groups are by far more varied and widely used than photolabile groups, as well as significantly cheaper in biopolymer synthesis. Considering that electrochemical protecting group removal has been demonstrated in biomolecule synthesis and surface-immobilization by electro-reduction (32), -oxidation (33), -catalysis (34, 35), and -generation of acids and bases (17, 18), PEC-gated reactions should be applicable to the in situ combinatorial synthesis of other biopolymers and small molecules.

The flexibility of semiconductor PEC also makes it attractive as a basis for a solid-phase combinatorial synthesis platform. A compelling future application would be the construction of a highly versatile, integrated biomolecule synthesis, manipulation, and biosensing platform. Photoelectrophoretic transport (5–7) has already been demonstrated to influence DNA hybridization rates and stringency (6). PEC is also a powerful tool in chemical sensing. Both label-free (3) and dye-sensitized (4) PEC biomolecule detection schemes have been reported, in which surface bound biomolecules alter the photocurrent through the irradiated semiconductor electrode. Thus, one could imagine that a properly designed PEC platform could be used to first synthesize the microarray, then improve the rate and stringency of target strand hybridization at illuminated areas (6), and finally detect the hybridization event as a light-addressable electrochemical sensor. For example, Fig. 2 demonstrates the capability for the chip to serve as a virtually addressed electrochemical sensor; C-V’s with single virtual-electrode resolution have also been recorded, but with currently insufficient signal-to-noise ratio to report here.

The large synthesis capacity of the porous glass film may greatly benefit applications that use custom microarrays to drive down the cost per base for genomic research, such as multiplexed gene synthesis (16, 26, 36), library construction (37, 38), and genomic selection for targeted sequencing (39–41). It effectively further lowers the cost per base by reducing the spot redundancy required to obtain biologically relevant quantities of each sequence, and also limits the need for amplification protocols. The use of a high-loading support may become increasingly important as the complexity of the DNA pool increases, because the quantity of each sequence decreases with the spot area. It should be noted that parallel gene synthesis in microfluidic devices may also address issues associated with the minute quantities of DNA obtained from cleaved microarrays (42).

In conclusion, we have successfully created a DNA microarray synthesis platform, demonstrating that photoelectrochemistry can be used toward combinatorial solid-phase chemical synthesis. In addition to optimizing the synthesis platform, future work may include the synthesis of other bio-polymers and small molecules, as well as the construction of an integrated platform that uses photoelectrochemistry to not only synthesize microarrays, but also to manipulate and detect target molecules in a massively parallel fashion.

**Materials and Methods**

All DNA synthesizer reagents were used as received from Glen Research (“Ultramild” phosphoramidites), and all other reagents were from Aldrich, unless specified otherwise. Millipore-purified water (18.5 MΩ·cm) is denoted as dH₂O.

**Substrate Fabrication.** 1 µm thick undoped amorphous silicon films were deposited by plasma enhanced chemical vapor deposition (PECVD) at 250 °C on Corning 7059 glass. The PECVD substrates were then coated with 0.1% acetic acid for 1 h, or by stripping the entire porous glass by buffered oxide etching (BOE) and subsequently redepositing the film.

**Oligonucleotide Microarray Synthesis.** Before synthesis, substrates were silanized with 0.5% N-(3-triethoxysilylpropyl)-4-hydroybutyramide (Gelest) in concentrated sulfuric acid for 1 h, or by stripping the entire porous glass by buffered oxide etching (BOE) and subsequently redepositing the film.

**Hybridization Assays and Fluorescence Analyses.** Oligonucleotides were synthesized with the sequences:

1. 5’-(TCCAGNGGGCCTCCT-3’), where NN = AT or TA.
2. 5’-(GAGCGTCCTGGGATCCGAMAM-3’), where AM = A or M.

The target sequences (1 µM in 2× SSC buffer with 0.01% SDS surfactant, Invitrogen) were simultaneously hybridized to the chip for 2 h at room temperature in a humidity chamber. The substrates were washed with 1× SSC with 0.1% SDS, 0.5× SSC, 0.1× SSC, and then dried under nitrogen. Fluorescence images were captured using a Zeiss PM1000 confocal microscope.

For the stepwise yield tests, 4 random bases were synthesized using the commercial halo-acid cycle (including capping steps) before any PEC deblock steps. This pre-PEC synthesis procedure limits unrealistically high signal intensity for short oligonucleotides by capping reactive hydroxyls that lack sufficient space to grow into full length strands.

**Electrochemical Analysis.** Surface potential measurements were measured by contacting a metal line that extended outside a Kaiser o-ring confining the electrolytic solution. Cyclic voltammetry (150 mV/s sweep rate) of 2.5 mM hydroquinone and 100 mM tetrabutylammonium hexafluorophosphate salt in...
anhydrous acetonitrile was measured by using a custom-built potentiostat that interfaced with a HP4155A semiconductor analyzer (Fig. S7). A nickel plate (McMaster) and platinum wire (Aldrich) were used as the counter and quasi-reference electrodes of the 3-electrode fluidic, respectively. The substrate was illuminated from the backside using a fiber illuminator as described in SI Text (Supporting Note 1).

**Porous Glass Characterization.** Surface loading experiments were performed on glass slides (Electron Microscopy Sciences) with and without the 840-nm-thick porous glass films. The substrates were amino-silanized with 1% 3-aminopropyltriethoxysilane in acidic methanol for 30 min. The amine was reacted with 5′-O-DMT-2′-O-TAT-3′-O-succinate (10 mM, Monomer Sciences) and 1,3-dicyclohexylcarbodiimide catalyst (50 mM, Avocado Organics) in anhydrous acetonitrile was measured by using a custom-built potentiostat with a glass substrate (Electron Microscopy Sciences) with and without the 840-nm-fiber illuminator interfaced with a HP4516A semiconductor analyzer (Fig. S7).

**Fig. S7**. A nickel plate (McMaster) and platinum wire (Aldrich) were used as the counter and quasi-reference electrodes of the 3-electrode fluidic, respectively. The substrate was illuminated from the backside using a fiber illuminator as described in SI Text (Supporting Note 1).