Branched Nanowire Architectures for Compact Power Sources

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This research project has exploited advances in nanoscience to enable new capabilities in biofuel cells that advance compact power sources critical to future Air Force and DoD mobile technologies, such as micro unmanned aerial vehicles and electronic systems. To achieve this overall objective the research program focused on controlled synthesis and characterization of nanowire building blocks that can function as probes of fundamental biofuel cell processes, the development of novel methods for hierarchical assembly of these nanoscale structures to enable studies of power scaling, and the development and fabrication of new nanoscale electrodes enabling studies of microbial fuel cells down to the level of single bacteria. The results from these studies have advanced significantly our fundamental knowledge of the controlled synthesis and organization of novel nanoscale building blocks, and have opened up new opportunities for fundamental studies elucidating the factors limiting electrochemcial power output from biological fuel cells. In this manner, the research has provided significant new data critical to understanding and developing compact power sources for future Air Force and DoD needs, and has also provided underlying knowledge to impact commercial technologies such as implantable power systems for sensing, diagnosis and treatment of diseases.

15. SUBJECT TERMS
nanostructured electrodes; nanowires, biofuel cell, hierarchical assembly

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I. Executive Summary

Efficient compact power sources are critical to future Air Force and DoD mobile technologies, such as micro unmanned aerial vehicles and electronic systems, yet limitations with existing sources have restricted significantly development in these areas. The overall objective of this proposed research will be to exploit advances in nanoscience to enable new capabilities in compact biofuel cells that can advance this critical area of technology. To achieve this overall objective the research program has focused on (i) controlled synthesis and characterization of nanowire building blocks that can function as probes of fundamental biofuel cell processes, (ii) the development of novel methods for hierarchical assembly of these nanoscale structures to enable studies of power scaling, and (iii) the development and fabrication of new nanoscale electrodes enabling studies of microbial fuel cells down to the level of single bacteria. First, methods for the predictable and controlled synthesis of branched nanaowires consisting of well-defined single crystal silicon backbones with metal nanowire branches, which serve as active electrodes, have been developed. Nanocluster catalyzed growth was used to control the diameter and dopant concentration of silicon nanowire backbones, and metal branches were prepared using a novel nanocluster seeded solution phase growth. Second, a general and scalable approach for large area, uniformly-aligned and controlled density nanowire and nanotube films that involves expanding a bubble from a homogeneous suspension of these materials was developed. The blown-bubble films allow the unique properties of nanowires and to be exploited in applications that require large surface areas, such as in compact biofuel cells. Third, nanofabrication was used to define electrode arrays in which the exposed electrode area of individual elements was designed to limit interactions specifically with one or more bacterial cell, and in addition, fabrication of optically-transparent electrode arrays was carried out on transparent substrates to enable *in-situ* imaging of individual cells during electrochemical measurements. The results from these proposed studies advance significantly our fundamental knowledge of branched nanoscale building blocks, create new methods for large-scale hierarchical assembly of nanostructure such as nanowires and carbon nanotubes, and open up new opportunities for fundamental studies elucidating the factors limiting electrochemcial power output from biological fuel cells down to the limit of a single bacterial cell. In this manner, our research provides significant new data critical to understanding and developing biofuel cells for future Air Force and DoD needs, and will also provide underlying knowledge to impact commercial technologies such as implantable power systems sensing, diagnosis and treatment of diseases.

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V. Technical Report
A. Scientific Results

Charles M. Lieber, Harvard University

I. Introduction and Background

Efficient compact power sources are critical to future Air Force, DoD and commercial mobile technologies ranging from micro-to-nanoscale unmanned aerial vehicles to widely-dispersed and continuously monitoring surveillance networks. A promising approach for meeting this critical need involves the development of microbial fuel cells (MFCs). MFCs have been studied in different formats for almost 100 years. However, it is recent studies, which have focused on both electrochemical cell design and microbiology, that have begun to demonstrate the substantial promise of this energy technology. Indeed, the potential of biological fuel (biofuel) cells has been well-recognized and has been the focus of considerable research effort, which has defined two basic types of cells: these are typically classified as either enzymatic or whole cell/microbial. In enzymatic biofuel cells, redox enzymes that carry out highly specific oxidation and reduction reactions are coupled to anode and cathode electrodes, respectively, of the cell, while in microbial fuel cells living microorganisms are used to produce an electrochemically-active species that is subsequently used as 'fuel' in a more conventional fuel cell. Both of these basic types of biofuel cells have been reviewed.

In both of these basic types of biofuel cells, many of the fundamental limits on electrochemical power extraction remain unknown due to challenges in carrying out well-defined electrochemistry at the level of oriented protein/enzymes and/or single bacterial cells, such as *Shewanella oneidensis* MR-1. To address such fundamental issues a major emphasis of our project has been to develop new nanoscale materials and electrodes that can interact with redox enzymes and MR-1 in unique ways. For example, nanowire branch electrodes have sizes comparable to the redox enzymes used in the biofuel cells (Fig. 1), and thus offer the opportunity to investigate charge transport in a unique regime where behavior may deviate from more 'macroscopic' electrodes that have been studied extensively in the past.

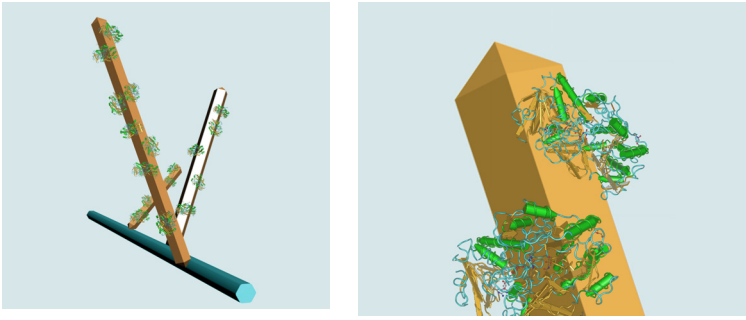

Figure 1. Low and high resolution schemes illustrating the relative sizes and overall structures of the branched nanowire electrodes and enzyme redox catalyst.

In a similar manner, branched-nanowire electrode structures could enable uptake of the nanoscale electrode into MR-1 cells (Fig. 2), thus opening up unique electrochemical opportunties.

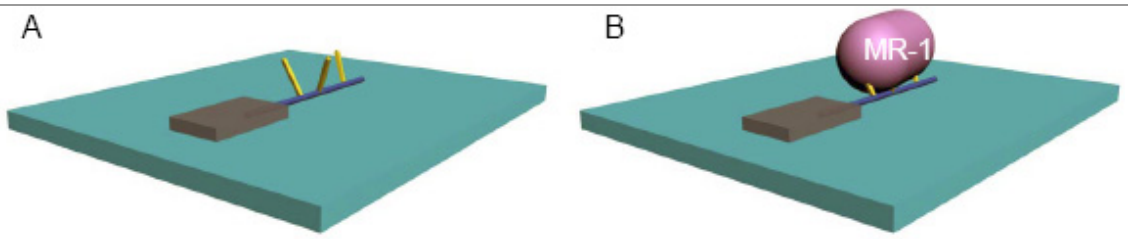

Figure 2. Schematics illustrating (A) a branched nanowire nanoelectrode and (B) nanowire branches in a MR-1 cell.

II. Results and Discussion

Branched nanowire synthesis and characterization. Hetero-branched nanostructures, defined as structures incorporating distinct backbone and branch grafts, offer unique opportunities as electrodes for biofuel cells. With well-controlled variations in composition and/or doping, it is possible to exploit unique materials science at nanoscale, which is different from conventional planar heterostructures and to realize novel electronic devices *via* structure/functionality integration at branched junctions. Moreover, the implementation of more complicated and integrated nanodevice systems, could be more easily and reproducibly achieved in branched structures *versus* bottom up NW crossbar devices because of the better defined junctions. We developed a general multi-step approach for the controlled synthesis of a great diversity of hetero-branched nanostructures, with fine control over structure, composition, doping. Our design for the branched structures incorporates a semiconductor/metal topology. As shown in Figure 3, the synthesis starts from a bare semiconductor nanowire backbone followed by selective deposition of Au nanoparticles (NPs) on the backbone surface via galvanic surface reduction polylysine-assisted adsorption. Then nanowire/nanoparticle composite is subject to branch growth *via* solution-phase synthesis.

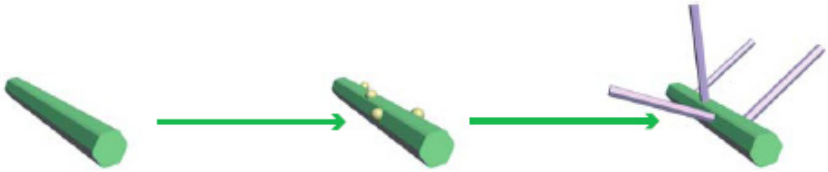

Figure 3. Schematic diagram of the general synthesis of branched nanostructures.

Figure 4 shows the Scanning Electron Microscropy (SEM) image of Si/Au branched nanostructures prepared *via* seed mediated solution phase growth. The aspect ratio of Au branches is around 15-30, and their diameter could range from 15 to 80 nm, depending on the specific synthesis parameters. Generally, smaller Au NP seeds (*e.g.* 5 nm), lower C_{HAuCl4} (*e.g.* 2×10^{-4} M) or higher C_{CTAB} (*e.g.* 0.1 M) favors the formation of Au branches with larger aspect ratio and smaller diameter. The spacing between the adjacent Si/Au junctions could be scaled down to below 100 nm (Fig. 4, inset), which is promising for high density device integration. Higher-resolution TEM images of Si/Au branched nanostructures further show the twinned nature of Au branches and distinct backbone/branch junctions. High-resolution

transmission electron microscopy (HRTEM) image of Si/Au junction detail unambiguously the twinned planes of facetted Au branches, and combined with selected area electron diffraction (SAED) patterns, show that the Au branches typically feature five-fold twinning symmetry and grow along <110> axis.

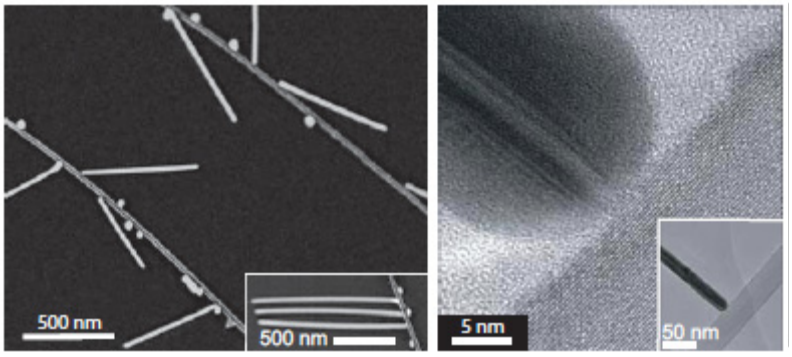

Figure 4. (left) SEM image of Si/Au branched nanowires. (right) HRTEM and TEM (inset) images of Si/Au branched junction.

Large-scale hierarchical assembly. Every year several billion pounds of polymers are processed into plastic products (e.g. bags, films) by the blown film extrusion technique. The commercial process involves continuous expansion of a polymer melt through a die as a bubble which is then processed as a continuous film. We have adapted the basic ideas underlying this commercial film production method to make thin films containing well organized nanostructures. This approach for assembly large area films of nanomaterial, which we term the blown bubble film (BBF) approach, represents a very general platform technique for nanotechnology and may enable many applications. Our basic approach illustrated in Figure 5 involves the preparation of a homogeneous solution containing dispersed nanomaterials, which is analogous to the polymer melt used in industry, expansion of a bubble from the nanomaterial solution at a controlled direction and speed, and then transfer of the bubble to substrates to yield well-defined nanomaterial-incorporated thin films.

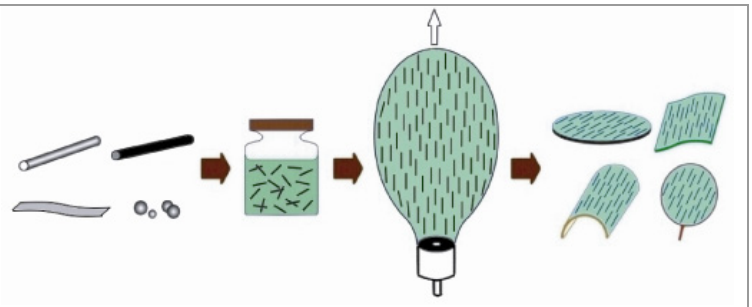

Figure 5. Blown bubble film (BBF) approach.

The BBF approach for assembling nanostructures has several distinct advantages compared with other methods described briefly above. First, this approach is general and can be used for organizing a wide range of nanoscale materials, including electronically and optically active NWs, multi-walled NTs (MWNTs) and SWNTs, and in principle could be used to assemble nanobelts, graphene sheets, nanoparticles, and even heterojunctions. Second, this approach is highly scalable with potential to achieve at least meter-scale dimensions based on results for pure films. We have demonstrated bubbles with diameters over 30 centimeters using epoxy and a 50 mm die, and larger bubbles should be possible by further optimizing the materials and process. Third, this approach yields ordered nanostructures in thin films that are robust as freestanding films, and that can transferred to rigid, flexible and curved substrates

A homogeneous solution consisting of a specific nanomaterial uniformly dispersed in epoxy resin was prepared by functionalization of nanomaterial surface and then mixing with

epoxy. For example, purified SWNTs (Carbon Solutions, Inc.) were functionalized with octadecylamine (ODA), and then a know mass of the ODA-SWNTs dispersed in tetrahydrofuran (THF), transferred to known mass of epoxy resin, and then mixed until homogeneous. The mixture was stirred to achieve a uniform solution, and hardener as added, and the mixture was capped and allowed to cure (i.e., polymerize) until the viscosity increased to a range, 15-25 Pa·s, suitable producing stable bubbles. A similar method was used prepare homogeneous silicon nanowire/epoxy solutions except that 5,6-epoxyhexyltriethoxysilane was used to functionalization the surface of the silicon nanowires. A homogeneous solution, which can be aided by appropriate nanostructure surface functionalization, is important for uniform distribution of nanomaterials in the resulting bubble films.

Controlled bubble initiation, expansion, and transfer were done using a 50 mm diameter circular die with a gas inlet at the bottom and outlet at the top surface (Fig. 6a). The nanomaterial-epoxy solution was deposited on the die surface and blown into a bubble by flowing gas at a pressure of 150 to 200 kPa (Fig. 6b-d). The upward bubble expansion was stabilized and controlled by a motor-driven ring. Typically, bubbles were expanded upwards at a speed of about 15 cm/min until the outer surface of the bubble conformally coated silicon wafers (Fig. 6d) or other substrates. Bubbles with diameters of >30 centimeters have been blown from about 0.5 g nanostructure/epoxy solution and transferred conformally to 150 mm wafers. The wafers with BBF coatings were characterized by optical and electron microscopy to determine the distribution and orientation of nanomaterials.

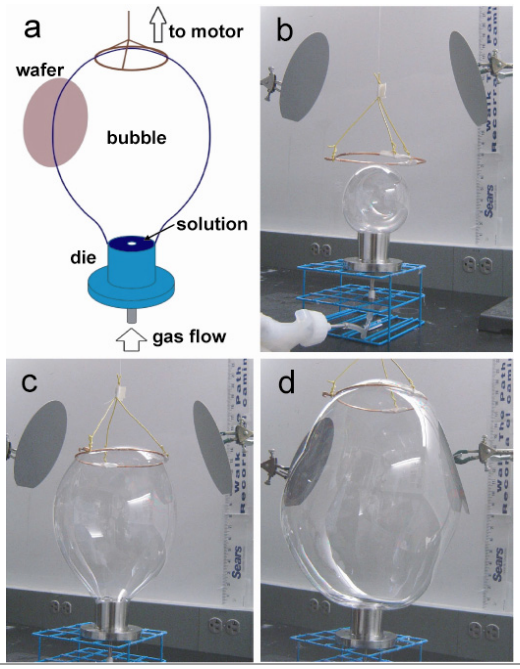

Figure 6. Bubble expansion process. (a) Illustration of the apparatus including a 50 mm circular die with epoxy solution deposited on the top surface, and bubble expansion in gas flow directed upward using a ring connected to a motor. Wafers are fixed near the bubble for BBF transfer. (b), (c), (d) Snapshots of the initial, middle, and final stages of bubble expansion and coating of BBF on two 150 mm wafers.

Silicon nanowire-BBFs were transferred to 150 mm diameter wafers to characterize the distribution and orientation of the NWs within the film. Representative dark-field optical images recorded from widely separated regions on a transferred BBF (Fig.7) show that the silicon nanowires have similar orientation and good alignment along the expansion direction of the bubble. The angular spread of the silicon nanowires is less than 10^{o} over the entire 6 inch diameter substrate. In addition, excellent orientational alignment of the silicon nanowires within the BBFs over large areas is a general characteristic observed for all of the stable Silicon nanowire-epoxy solutions we have studied, concentration from 0.01 to 0.22 wt%.

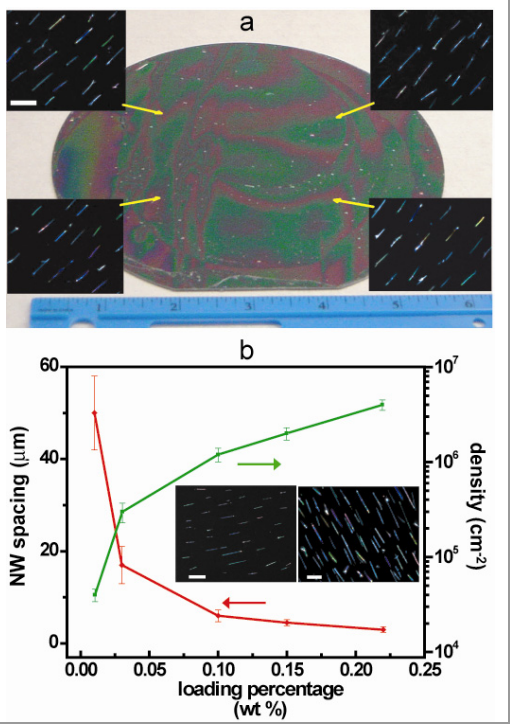

Figure 7. Characterization of nanomaterial alignment and density. (a) optical image of a 0.10 wt% Silicon nanowire-BBF on 150 mm Si wafer. Insets, dark-field (DF) optical images showing aligned Silicon nanowires at different locations. Scale bar: 10 μm. (b) The NW spacing and density versus NW loading plot. Insets, two DF optical images taken from 0.03 and 0.15 wt% Silicon nanowire-BBFs. Scale bars: 20 μm (left), 10 μm (right).

We characterized the density and separation of the aligned nanowires in transferred films as a function of wt% solution used for bubble expansion. The transferred silicon nanowire-BBFs show a clear decrease in nanowire separation and increase in density as the starting silicon nanowire concentration increases from 0.01 to 0.22 wt%. We find that the nanowire separation can be systematically varied over an order of magnitude from 50 to 3.0 μm as concentration increases from the 0.01 to 0.22 wt%, respectively; correspondingly NW density increases from 4.0×10^4 to $4.0 \times 10^6/cm^2$. Compared with submicron spacing achieved by LB technique, the NW spacing produced by the BBF approach is relatively modest, but it is still useful for applications such as nanoelectronic sensor arrays. The spacing (density) versus wt% curves show some saturation at the higher silicon nanowire concentrations. This tendency towards saturation is believed to be in part attributed to nanowire aggregation observed at higher concentrations. Further optimizing the surface chemistry for preparing uniform higher wt% solutions would allow us to test the separation limits achievable with this approach and also to extend to different polymer systems besides epoxy, which offers great flexibility and compatibility with polymer industry.

Another unique key feature of the BBF approach is that BBFs with aligned nanostructures can be transferred to a broad range of substrates with virtually any material composition or shape. For example, silicon nanowire- and SWNT-BBFs were transferred directly to thin plastic sheets, a half-cylinder, a watch glass, and suspended across open frames as free-standing films (Figs. 8a-d), thus demonstrating much greater flexibility of this approach over other assembly approaches reported previously. Our BBF approach also has the potential to be scaled to very large area structures, in analogy to large plastic films manufactured in industry.[24-26] As an initial demonstration of this point, we have successfully transferred SWNT-BBFs to 200 mm wafers (Fig. 8e), where the embedded SWNTs are uniformly aligned across the wafer surface, and transferred a Silicon nanowire-BBF to a rectangular 9 inch x 12 inch flexible plastic sheet (Fig. 8f) with good control of Silicon nanowire alignment and density across the entire flexible sheet. Both of these examples are the largest demonstrations to date for aligned nanowires and carbon nanotubes.

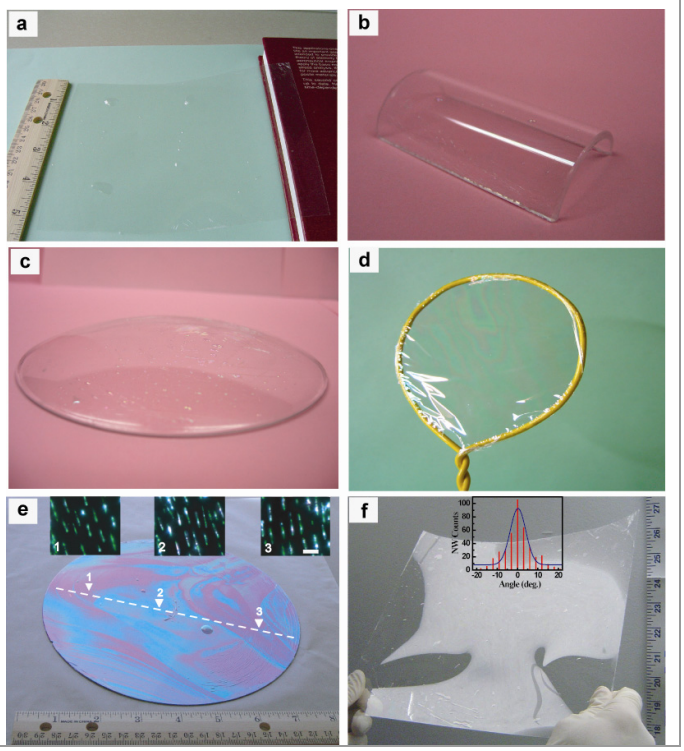

Figure 8. BBFs transferred to different surfaces and very large substrates. The transferred surfaces include thin plastic sheet (a), a half cylinder surface (b), a curved watch glass (c), and an open frame (d). (e) Optical image of a SWNT-BBF transferred to a 200 mm wafer with aligned SWNTs shown in insets. Scale bar: 2 μm. (f) Optical image of a Silicon nanowire-BBF transferred to a rectangular 9 inch x 12 inch flexible plastic sheet. Inset, histogram of angular distribution of NWs from different locations of the film.

Nanoscale and transparent electrodes for cellular electrochemistry. We have designed a nanoelectrochemical chip fabricated on 1"x3" quartz or Si/SiO_2 substrates using the following steps. First, two sequential steps of photolithography (PL) and metal deposition are used to define the inner and outer regions of the nanoelectrodes. Two independent steps of PL are used because (i) it allows for optimized lithography conditions for the different size features (i.e., fine inner and larger outer) and (ii) enables the inner nanoelectrode design to be varied without remaking the entire PL mask for each iteration. Our studies have been carried out using Au with thin Ti-adhesion layer (Fig. 9), but it is also possible to fabricate optically-transparent electrodes using indium-tin-oxide (ITO) and ITO/Au sandwich structures. Second, the inner chip/electrode region exposed to solution is passivated with a dielectric layer to isolate the electrodes from solution. In our initial experiments, we have used silicon nitride (Si_3N_4) deposited at room-temperature by plasma-enhanced chemical vapor deposition (PECVD), a process well-established our laboratory. Third, the basic nanoelectrode chip is completed in a final of PL and reactive ion etching (RIE) that opens windows of defined size over the end of the electrodes (Fig. 9). The exposed region of the

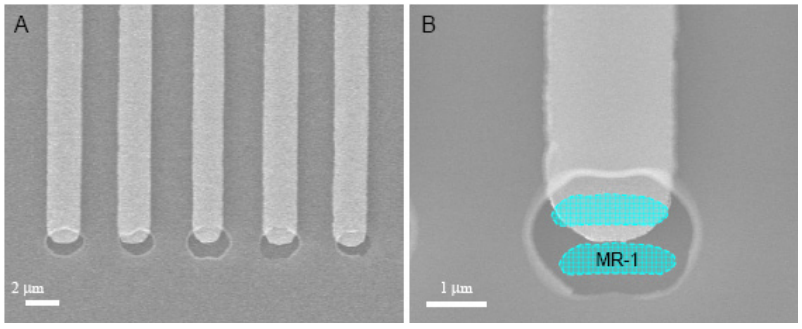

Figure 9. (A) SEM image of an array of five independently addressable electrodes. (B) The access window exposing the electrode end to solution is sufficiently large to fit at most two MR-1 cells.

metal is the only active electrochemical surface. An attractive feature of this approach is that a number of electrodes with similar characteristics can be fabricated in parallel, and moreover, with appropriate PL mask design different size windows can be opened at different electrode regions on the chip in this last step. This can, for example, allow two total MR-1 cells to fit in window defined in Fig. 9B with only one over the nanoelectrode.

In addition, we have designed novel electrodes that enable *in-situ* optical imaging with an upright microscope (through the electrochemical cell media) as shown in Fig. 10. Initial experiments of MR-1 suspensions on quartz substrates demonstrated that individual bacteria could be well-resolved using differential interference contrast (DIC) mode of imaging (Fig. 10B). In experiments carried out using our standard Au-nanoelectrodes,

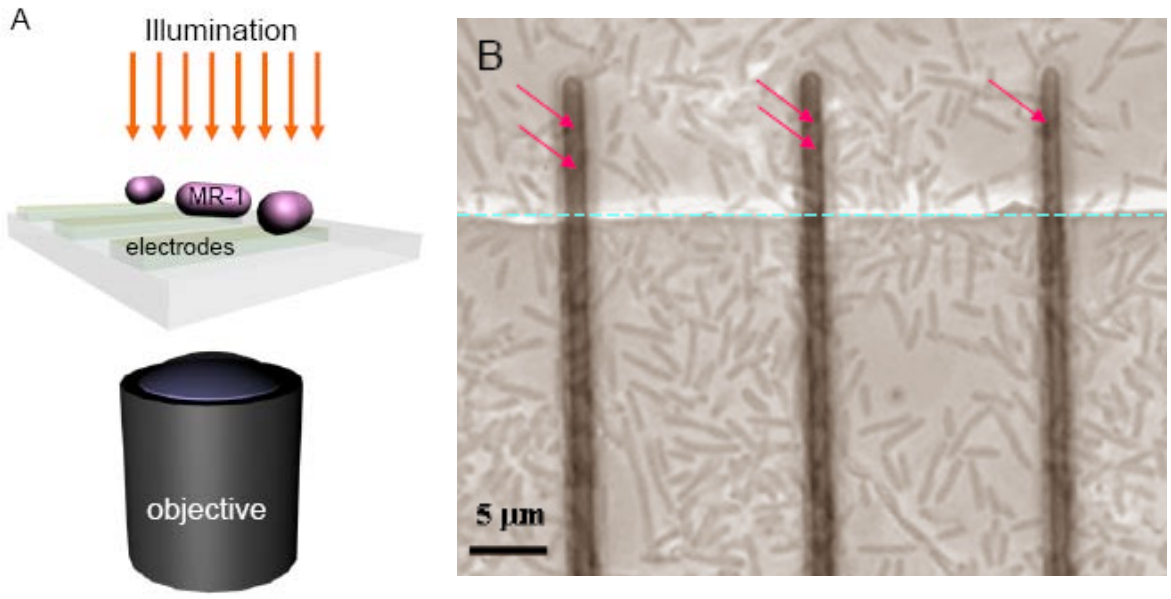

Figure 10. (A) Microscopy set-up for *in-situ* imaging of electrodes and MR-1 during electrochemical measurements illustrating detection of individual MR-1 cells using inverted microscope imaging through transparent substrate/electrodes. (B) Phase-contrast optical image recorded with an inverted microscope as illustrated in Fig. X. The vertical semi-transparent electrodes consists of a lower layer of indium-tin oxide (ITO) and upper layer of gold, and the electrodes are passivated below the dashed line and open above it. Red arrows highlight the positions of several MR-1 on the open electrode ends; recorded *in-situ* in solution.

however, it was only possible to image MR-1 around the essentially opaque electrode structures. To overcome this last limitation we have implemented transparent electrodes consisting of ITO/Au sandwich. Significantly, data recorded with the ITO/Au nanoelectrode chips show clearly that individual MR-1 can be resolved on top of the active electrode regions *in-situ*.

B. Publications Stemming from Research Effort

Y. Li, J. Xiang, F. Qian, S. Gradecak, Y. Wu, H. Yan, D.A. Blom and C.M. Lieber, "Dopant-Free GaN/AlN/AlGaN Radial Nanowire Heterostructures as High Electron Mobility Transistors," *Nano Lett.* **6**, 1468-1473 (2006).

Y. Li, F. Qian, J. Xiang and C.M. Lieber, "Nanowire electronic and optoelectronic devices," *Materials Today* **9**, 18-27 (2006).

F. Patolsky, G. Zheng and C.M. Lieber, "Fabrication of silicon nanowire devices for ultrasensitive, label-free, real-time detection of biological and chemical species," *Nat. Protocols* **1**, 1711-1724 (2006).

W. Lu and C.M. Lieber, "Semiconductor nanowires," *J. Phys. D: Appl. Phys.* **39**, R387-R406 (2006).

C. Yang, C.J. Barrelet, F. Capasso and C.M. Lieber, "Single p-Type/Intrinsic/n-Type Silicon Nanowires as Nanoscale Avalanche Photodetectors," *Nano Lett.* **6**, 2929-2934 (2006).

C.M. Lieber and Z.L. Wang, "Functional Nanowires," *MRS Bull.* **32**, 99-104 (2007).

F. Patolsky, B.P. Timko, G. Zheng and C.M. Lieber, "Nanowire-Based Nanoelectronic Devices in the Life Sciences," *MRS Bull.* **32**, 142-149 (2007).

G. Yu, A. Cao and C.M. Lieber, "Large-area blown bubble films of aligned nanowires and carbon nanotubes," *Nature Nanotech.* **2**, 372-377 (2007).

A. Javey, S. Nam, R.S. Friedman, H. Yan and C.M. Lieber, "Layer-by-Layer Assembly of Nanowires for Three-Dimensional, Multifunctional Electronics," *Nano Lett.* **7**, 773-777 (2007).

G. Yu, A. Cao and C.M. Lieber, "Large-area blown bubble films of aligned nanowires and carbon nanotubes," *Nat. Nanotechnol.* **2**, 372-377 (2007).

C.M. Lieber, "The Incredible Shrinking Circuit," *Sci. Am. Special Ed.* **17**, 64-71 (2007).

B. Tian, X. Zheng, T.J. Kempa, Y. Fang, N. Yu, G. Yu, J. Huang and C.M. Lieber, "Coaxial silicon nanowires as solar cells and nanoelectronic power sources," *Nature* **449**, 885-890 (2007).

W. Lu and C.M. Lieber, "Nanoelectronics from the bottom up," *Nature Mater.* **6**, 841-850 (2007).

G. Yu, X. Li, C.M. Lieber and A. Cao, "Nanomaterial-incorporated blown bubble films for large-area, aligned nanostructures," *J. Mater. Chem.* **18**, 728-734 (2008).

F. Qian, Y. Li, S. Gradečak, H.-G. Park, Y. Dong, Y. Ding, Z.L. Wang and C.M. Lieber, "Multi-quantum-well nanowire heterostructures for wavelength-controlled lasers," *Nature Mater.* **7**, 701-706 (2008).

H.-G. Park, C.J. Barrelet, Y. Wu, B. Tian, F. Qian and C.M. Lieber, "A wavelength-selective photonic-crystal waveguide coupled to a nanowire light source," *Nature Photon.* **2**, 622-626 (2008).

T.J. Kempa, B. Tian, D.R. Kim, J. Hu, X. Zheng and C.M. Lieber, "Single and Tandem Axial p-i-n Nanowire Photovoltaic Devices," *Nano Lett.* **8**, 3456-3460 (2008).

B. Tian, T.J. Kempa and C.M. Lieber, "Single Nanowire Photovoltaics," *Chem. Soc. Rev.* **38**, 16-24 (2009).

C. Presentations of Research STEMMING FROM RESEARCH EFFORT
C. M. Lieber, Harvard University, Invited Talks

26 April 2006 – Peking University College of Engineering Distinguished Lecture, Beijing China
"Nanowires and Pathways to Nanotechnologies"

21 June 2006 – Gordon Research Conference on Single Molecule Approaches to Biology, New London NH
"Nanowire Electronic Devices for Detection of and Interfacing to Biological Systems"

8 August 2006 – Accelrys Nanomedicine Kick-off, Cambridge MA
"Nanoelectronic devices for detection of and interfacing to biological systems"

11 October 2006 – International Institute for Nanotechnology Symposium, Northwestern University, Evanston IL
Plenary: "Nanowires, Nanoscience, and Emerging Nanotechnologies"

3 November 2006 – Novartis Institutes for Biomedical Research Symposium:
Nanotechnology in Medicine and Drug Discovery, Massachusetts Institute of Technology
"Nanowire Nanoelectronics: A Platform for Ultrasensitive, Real-Time, Label-Free Detection"

15 December 2006 – 18th Annual Jacob Bigeleisen Endowed Lecture, Stony Brook University, NY
"Nanowires, Nanoscience and Emerging Nanotechnologies"

25 February 2007 – 58th Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy 2007, Chicago IL
Plenary: "Nanowire Nanoelectronic Devices for Detection of and Interfacing to Biological Systems"

10 April 2007 – National Academy of Sciences Sackler Colloquium: Nanomaterials in Biology and Medicine: Promises and Perils, Washington DC
"Designed Nanobiosensors"

24 April 2007 – NanoMaterials for Defense Applications Symposium: Accelerating the Transition, San Diego CA
"Building Functional Nanowire Nanoelectronic/Neuron Artificial Synapses"

8 May 2007 – George C. Pimentel Memorial Lecture, University of California, Berkeley
"Nanowire, Nanoscience and Emerging Nanotechnologies"

24 May 2007 – Lund University Department of Physics Colloquium, Lund, Sweden
"Nanowires, Nanoscience and Emerging Technologies"

18 June 2007 – MITRE Corporation JASON Program Nanotechnology Study, San Diego CA
"Nanowire and Nanotube Electronics"

19 August 2007 – 234th ACS National Meeting, Boston MA
"Nanoelectronic devices for visualizing and interacting with biological systems"

19 August 2007 – 234th ACS National Meeting, Boston MA
Presidential Keynote: "Nanowire nanoelectronics and the life sciences: From ultrasensitive detection to cellular communication"

21 August 2007 – 234th ACS National Meeting, Boston MA
Langmuir Lecture: "Nanowires, nanoscience and nanotechnologies"

28 September 2007 – James W. Neckers Memorial Lecture, Southern Illinois University, Carbondale IL
"Nanowires, Nanoscience and Emerging Nanotechnologies"

24 October 2007 – University of Pennsylvania Nano/Bio Interface Center Award for Research Excellence in Nanotechnology, Philadelphia PA
Award Keynote: "Nanotechnology and the Life Sciences: From Ultrasensitive Disease Detection to Hybrid 'Smart' Materials"

26 October 2007 – E. Roger Washburn Memorial Lecture, University of Nebraska-Lincoln
"Nanowires, Nanoscience & Emerging Nanotechnologies"

6 November 2007 – Cheng Tsang Man Professorship, Nanyang Technological University, Singapore
"Nanowire Electronics: From Fundamental Device Properties to Three-Dimensional Integrated Circuits"

8 November 2007 – Rohm and Haas Student Hosted Colloquium, Stanford University
"Nanowires, Nanoscience, and Emerging Nanotechnologies"

14 November 2007 – Beijing University of Technology International Exchange Symposium, Beijing China
Keynote: "Nanowires, Nanoscience and Emerging Nanotechnologies"

15 November 2007 – 6th Chinese Conference for Advanced Functional Materials, Wuhan China
Keynote: "Nanowires, Nanoscience and Emerging Nanotechnologies"

26 November 2007 – MRS Fall Meeting, Boston MA
"Nanowires: From Functional Building Blocks to Integrated Nanoelectronics"

9 December 2007 – IEDM Short Course: Emerging Nanotechnology and Nanoelectronics, Washington DC
"Nanowires, Nanotubes and Nanoribbons for Digital Computation and Data Storage Applications"

6 May 2008 Institute for Molecular and Nanoscale Innovation Nanoscience Forum, Brown University, Providence, RI
"Nanowires, Nanoscience and Emerging Nanotechnologies"

20 May 2008 Institute for Molecules and Materials Symposium, Radboud University, Netherlands
Keynote Lecture: "Nanowires, Nanoscience and Emerging Nanotechnologies"

10 June 2008 Peking University, China
"Nanowires: A Platform for Nanoscience and Nanotechnology"

11 June 2008 Chinese Academy of Science, China
Einstein Lecture: "Nanowires, Nanoscience and Emerging Nanotechnologies"

27 June 2008 David H. Koch Institute for Integrative Cancer Research Symposium, Massachusetts Institute of Technology
"Nanotechnology and Cancer: The Power of Small Science"

21 July 2008 International Conference on Nanoscience and Technology 2008, Keystone CO
Plenary Talk: "Nanowires: A Platform for Nanoscience and Nanotechnology"

23 July 2008 Nanobiotechnology: Principles and Applications, The MITRE Corporation, Mclean, VA
"Intersection of Biomaterials with Nanoelectronics and Nanophotonics"

19 August 2008 ExxonMobil Solid State Chemistry Faculty Fellow Award Symposium, American Chemical Society National Meeting, Division of Inorganic Chemistry
"Nanowires, NanoScience and Future Opportunities"

27 September 2008 Julius Springer Forum on Applies Physics 2008, Harvard University
"Nanowires: A Platform for Nanoscience and Nanotechnology"

C. M. Lieber Group , Harvard University

Invited or Contributed Talks/Posters

14 March 2006 – 2006 APS March Meeting, Baltimore, MD
"Gallium Nitride-Based Nanowire Radial Heterostructures for Nanophotonics"
(Fang Qian – Invited Talk)

17 March 2006 – 2006 APS March Meeting, Baltimore, MD
"Challenges and Issues in Nanowire Nanodevices"
(Robin Friedman – Invited Talk)

26 March 2006 – 231st ACS National Meeting, Atlanta, GA
"General and Powerful Platform for Large-scale, Label-free Parallel Electrical Detection of Biomolecules by Ultrasensitive Nanowire Transistor Arrays"
(Gengfeng Zheng – Contributed Talk)

19 April 2006 – 2006 MRS Spring Meeting, San Francisco, CA
"General and Powerful Platform for Large-scale, Label-free, Parallel Electrical Detection of Biomolecules by Ultrasensitive Nanowire Transistor Arrays"
(Gengfeng Zheng – Contributed Talk)

19 April 2006 – 2006 MRS Spring Meeting, San Francisco, CA
"Integrated Silicon Nanowire Logic and Memory Arrays for Nanocomputing"
(Guihua Yu – Poster Presentation)

20 April 2006 – 2006 MRS Spring Meeting, San Francisco, CA
"Core/multishell Nanowrie Heterostructres As High-efficiency, Multicolor Light-emitting Diodes"
(Fang Qian – Contributed Talk)

4 May 2006 – 33rd Annual Spring Symposium of the American Vacuum Society-Michigan Chapter, Wayne State University
Plenary: "Nanowires for Nanoscience and Nanotechnology"
(Carl Barrelet – invited talk o/b/o CML)

25 May 2006 –CLEO/QELS and PhAST Conference 2006, Long Beach, CA
"Hybrid Single Nanowire Photonic Structure"
(Hong Gyu Park – Contributed Talk)

21 June 2006 –GRC Meeting on Single Molecule Approaches to Biology, New London, NH
"Electronic Detection of Single DNA Molecules with Silicon Nanowire Devices"
(Ying Fang – Poster Presentation)

29 June 2006 – Energy Nanotechnology International Conference, Massachusetts Institute of Technology
Plenary: "Nanowires for Nanoscience and Nanotechnology"
(Carl Barrelet – invited talk o/b/o CML)

19 July 2006 – 6th IEEE Conference on Nanotechnology, Cincinnati OH
Plenary: "Nanowires for Nanoscience and Nanotechnology"
(Wei Lu – invited talk o/b/o CML)

9 September 2006 – American Academy of Nanomedicine Annual Meeting, Washington DC
"Nanowire Biosensors: A Tool for Medicine and Life Science"
(Gengfeng Zheng – invited talk o/b/o CML)

10 September 2006 – 232nd ACS National Meeting, San Francisco CA
"Nanowire heterostructures as high-efficiency, multicolor light-emitting diodes"
(Fang Qian – invited award talk, Division of Inorganic Chemistry Young Investigator Symposium)

11 September 2006 – 232nd ACS National Meeting, San Francisco CA
"General synthesis and properties of hetero-branched nanostructures"
(Bozhi Tian – contributed talk)

12 September 2006 – 232nd ACS National Meeting, San Francisco CA
"Hybrid single-nanowire photonic crystal and microresonator structures"
(Carl Barrelet – contributed talk)

29 November 2006 – 2006 MRS Fall Meeting, Boston MA
"Pushing the Sensitivity Limits of Nanowire Chem/Bio Sensors"
(Xuan Gao – contributed talk)

24-25 January 2007 – GRC Renewable Energy: Solar Fuels, Ventura CA
"Single core/shells Si nanowire photovoltaic devices"
(Bozhi Tian – contributed poster)

6 March 2007 – APS March Meeting 2007, Denver CO
"Fundamental limits of detection with nanowire FET chem/bio sensors in subthreshold and linear regimes"
(Xuan Gao – contributed talk)

9 April 2007 – MRS Spring Meeting, San Francisco CA
"Multicolor Nanolasers from Individual Multi-quantum Well Nanowire Heterostructures"
(Fang Qian – contributed talk)

10 April 2007 – MRS Spring Meeting, San Francisco CA
"Nanowire Heterostructures for Nanophotonics"
(Fang Qian – award talk)

12 April 2007 – MRS Spring Meeting, San Francisco CA
"Advances in Nanowire Photonics"
(Fang Qian – invited talk)

11 April 2007 – MRS Spring Meeting, San Francisco CA

"General Approach to Large Area Films of Aligned Nanowires and Carbon Nanotubes via Bubble Expansion"
(Guihua Yu – contributed talk)

25 October 2007 – 20th Annual IEEE Lasers and Electro Optics Society Meeting, Lake Buena Vista FL
"Semiconductor Nanowire Lasers"
(Fang Qian – invited talk)

25 March 2008 – 2008 Spring Materials Research Society Meeting
"Hetero-Branched Nanowires: General Synthesis and Functional Devices"
Xiaocheng Jiang, contributed talk

25 March 2008 – 2008 Spring Materials Research Society Meeting
"Single Silicon Nanowires as Solar Cells and Nanoelectronic Power Sources"
Bozhi Tian, contributed talk

25 March 2008 – 2008 Spring Materials Research Society Meeting
"Single and Tandem Axial p-i-n Nanowire Photovoltaic Devices"
Thomas Kempa, contributed Poster

27 March 2008 – 2008 Spring Materials Research Society Meeting
"Label-free attomolar detection of proteins using integrated nanoelectronic and electrokinetic devices"
Jian-Ru Gong, contributed Talk

10 April 2008 – 235th Annual Meeting of the American Chemistry Society, New Orleans, LA
"Label-free attomolar detection of proteins using integrated nanoelectronic and electrokinetic devices"
Jian-Ru Gong, contributed Talk

16 June 2008 – European Science Foundation's Meeting on Nanotechnology for Renewable Energy, Obergurgl, Austria
"Nanowire Structures as Novel Photovoltaic Elements"
Thomas Kempa, Invited Talk

20 August 2008 – 236th ACS National Meeting & Exposition, Philadelphia, PA
"General assembly approaches for organizing nanowire system via chemical and biological recognition"
Guihua Yu, Contributed Talk

27 September 2008 – Julius Springer Forum on Applied Physics 2008, Harvard University
"Modulation- doped Nanostructures as Fully-integrated Photovoltaic Elements"
Bozhi Tian, Invited Poster