Towards Nanowire (Bio) Sensors

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Abstract. Nanowire based electrochemical devices represent a new and emerging class of sensors. In this work, we fabricate gold nanowires with well controlled critical dimensions using hybrid-electron beam lithography. Individual nanowire electrodes are routinely fabricated and are easily electrically contacted using overlay electrodes. Following fabrication, nanowire device performance is assessed using both electrical and electrochemical characterization techniques. We observe low electrical resistances (~ 900 Ω) with typical linear Ohmic responses from fully packaged nanowire devices. Steady-state cyclic voltammograms in ferrocenemonocarboxylic acid demonstrate scan rate independence up to 1000 mV s⁻¹, with low interfacial capacitance. The applicability of these nanowire electrodes for sensing was explored using square wave voltammetry.

1. Introduction
In recent years, the application area of biosensors has experienced substantial growth with the global biosensor market estimated to exceed $10.6 billion by 2013. [1] The emerging trend for point-of-care instrumentation is driving the development of miniaturized systems capable of reliable and rapid quantification of a wide range of biomolecules. [2-5] To address this opportunity, nanosensors based on one-dimensional nanostructures such as silicon nanowires and carbon nanotubes FET devices are being explored since these nanostructures offer the potential to achieve highly sensitive integrated sensors with direct electrical readout. [6-8] In these sensor systems, the perturbation in the local electrostatic environment of a nanowire-based FET by a charged analyte alters the conductance, which is employed as the sensor signal. [6] While elegant, sensor technologies such as this require complex heterogeneous integration approaches following fabrication and certain device architectures, may require the application of back gate voltages as high as 40 V to be applied. [9]

By contrast, electrochemical sensors typically have much lower voltages (-1.5 – 1.5 V) requirements. Nanoscale electrodes have tremendous potential as electrochemical sensors exhibiting enhanced performance, compared to traditional macroelectrodes. As critical dimensions of the electrodes enter the nano regime, radial analyte diffusion profiles dominate with a corresponding increase in mass transport rate, higher current densities giving rise to an increased $I_p/I_c$ ratio (due to smaller surface area), higher S/N ratios and steady-state sigmoidal voltammograms. [10]

Nanowires represent a new and emerging powerful class of sensors and to date have been utilized for direct, sensitive and rapid detection of biological and chemical species. [2, 3, 11-14] Noble metal nanowires such as gold, platinum and silver, are of particular importance due to their excellent

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electrical and optical properties. Nanowire sensors based on surface enhanced Plasmon resonance, electrochemical, and surface enhanced Raman scattering detection mechanisms have been reported. [15-17] Gold nanowires are of particular interest due to their high chemical and thermal stability and biocompatibility. However, widespread take-up of nanoscale electrodes has been limited by the lack of practical and effective methodologies for fabrication of robust nanoelectrodes.

A great variety of nanowire fabrication techniques for have been reported to date, [14, 17-23] a versatile approach for fabrication of robust and reproducible nanowires is electron beam lithography (EBL), metal deposition and lift-off. This approach delivers on-chip nanowires with reproducible well defined geometries that are easily contactable with overlaid interconnecting electrodes (using standard micron-scale photolithography techniques). In this work, standard electroanalytical techniques such as cyclic voltammetry and square wave voltammetry were employed to investigate the electrochemical characteristics and the potential applications of nanowire electrodes fabricated by hybrid-EBL as future sensors.

2. Experimental
2.1. Nanowire Fabrication
Nanowire electrodes were fabricated using a hybrid EBL-photolithography process on silicon substrates with a ~300 nm layer of silicon dioxide thermally grown. Nanowire structures were patterned by direct electron beam writing in resist (ZEP 520 Nippon Zeon, beam voltage 50k V, beam current 100 pA and beam dose 120 µC cm⁻²), followed by metal evaporation (Ti/Pt/Au 5/3/30 nm) and lift-off. Optical lithography was employed to overlay contact electrodes and metal interconnection tracks were onto pre-fabricated nanowires using optical lithography, with metal evaporation (Ti/Au 10/200 nm) and liftoff. A passivation layer of photoresist (~1 µm) was spin coated onto a chip and a trench opened in this passivation layer directly over nanowire electrode to allow contact the electrolyte solution and the nanowire exclusively. To complete device packaging, chips were assembled onto specifically designed printed circuit boards, electrically contacted using wedge wire bonding (25 µm gold wires) and the bond wires protected using epoxy.

2.2. Nanowire characterisation:
Scanning electron microscopy (SEM) images of single Au nanowires were acquired using a field emission SEM (JSM-6700F, JEOL UK Ltd.) operating at beam voltages between 5 and 10 kV. Optical micrographs were acquired using a calibrated microscope (Axioskop II, Carl Zeiss Ltd.) equipped with a charge-coupled detector camera (CCD; DEI-750, Optronics). Two point electrical measurements were performed on a probe station (Model 6200, Micromanipulator Probe Station) in combination with a source meter (Keithly 2400) using a dedicated LabVIEW™ V8.0 program. For these current-voltage (I-V) measurements, the source electrode was grounded, a bias sweep up to ± 10 mV was applied to the drain electrode, and the current through the nanowire was measured.

2.3. Electroanalysis at Nanowire Electrodes:
All electrochemical studies were performed using a CHI660a Electrochemical Analyzer and Faraday Cage CHI200b (CH Instruments). Experiments were carried out in a three-electrode cell employing the single nanowires as working electrodes, with platinum coil (BAS Inc) as counter electrode and Ag/AgCl (KCl sat) reference electrode (CH Instruments). Voltammetric experiments on ferrocene monocarboxylic acid, FeCOOH (1 mM) (Alfa Aesar) were carried out in phosphate buffered saline, PBS (10 mM) (Sigma Aldrich) solutions at pH 7.4, (0.0 to 0.6 vs Ag/AgCl). Square wave voltammetry was performed in across a potential range of 0.0-0.5 V, applying an increment potential of 1 mV, pulse amplitude of 25 mV and a frequency of 25 Hz. All solutions were prepared with deionized water; 18.2 MΩ cm (ELGA Pure Lab Ultra).
Figure 1: (a) SEM micrograph of individual nanowire electrodes with overlaid metal contacts (1,000x mag). Inset: A high resolution SEM micrograph of single gold nanowire electrode (70,000x mag) fabricated by EBL. (b) An optical micrograph of fully integrated and passivated nanowire electrodes.

3. Results and Discussion:
3.1. Nanowire Structural Characterization:
Individual gold nanowire electrodes were fabricated using a hybrid EBL and photolithography process at silicon wafer substrates bearing a 300 nm layer of thermally grown silicon dioxide, see experimental section. Following device fabrication, nanowire electrodes were characterized using a combination of, SEM and optical microscopy. Individual single nanowire electrodes of width ~ 100 ± 6 nm were routinely fabricated by EBL, as depicted at 70,000x magnification in figure 1a inset. Electrical contacts and interconnection tracks were overlaid onto nanowire electrodes by standard optical lithography, followed by metal deposition and liftoff. Each nanowire electrode was individually contacted as depicted in figure 1a. Figure 1b shows an optical micrograph of a fully packaged array of individual nanowire devices, electrically contacted and passivated with an overlaying insulating photore sist layer. The insulating overlayer facilitated prevention of unwanted electrochemical reactions occurring between metal interconnection tracks and electrochemically active species. To allow direct interaction exclusively between a nanowire and electrolytic solution, photolithography was employed to pattern a trench (40 x 50 µm), which was selectively opened in the photosensist layer, directly above the nanowire array.

3.2. Nanowire Electrical Characterization:
Electrical characterization using standard two-point I-V measurements was performed to confirm the functionality of packaged nanowire devices in the voltage range of -10 mV to +10 mV. Several nanowire electrodes were characterized in this fashion and each displayed Ohmic linear responses confirming electrical contact to the nanowires by the interconnection tracks. Fully packaged nanowire devices exhibited low resistance (890-911 Ω); shown in figure 2a. Standard open- and short- circuit control experiments were also performed on the packaged chips to confirm the observed electrical characteristics were exclusively due to individual nanowires and without stray contributions from the substrate.

3.3. Nanowire Electrochemical Characterization:
Cyclic Voltammetry at Nanowire Electrodes: Electrochemical investigations were undertaken employing a potentiostat with a Faraday cage to apply an appropriate potential sweep range to a
nanowire working electrode with versus Ag/AgCl (saturated KCl) reference with Pt coil as a counter electrode. Ferrocenemonocarboxylic acid was selected as a suitable analyte for this study due to its good chemical stability and simple electrochemical redox behavior. Figure 2b depicts a typical cyclic voltammogram (CV) acquired using a gold nanowire device in 1 mM FcCOOH in 10 mM PBS (N₂ Sat), pH 7.4 and 25 °C. The CVs measured displayed steady-state voltammograms, typical of nanoelectrodes for the single-electron oxidation of FcCOOH. At nanowire electrodes mass transport is greatly enhanced, due to the small critical dimensions of the nanowires and becomes comparable to or larger than the rate of electron transfer from the FcCOOH to the electrode surface. Control CV experiments were also undertaken at nanowire electrodes in deaerated 10 mM PBS buffer (in the absence of FcCOOH), pH 7.4, 5 mV s⁻¹ and 25 °C. Under these conditions no Faradaic current was measured, with very low charging currents ~ 4 pA indicating that the interconnection tracks were sufficiently insulated by the resist layer from the electrolytic solution.

3.3.1. Capacitance: The steady-state nature of the current response at nanowire electrodes in 1 mM FcCOOH was preserved with increasing scan rate up to 1000 mV/s, as shown in figure 3a. This permits rapid signal acquisition, which is critical for sensing applications. Slight increases in the magnitude of the limiting current may be attributed to the presence of capacitive current which increases linearly with respect to increasing scan rate as described by equation 1.

\[ I_C = 2AC_d\nu \]  

where \( I_C \) is the difference in capacitance current from the forward and reverse scans of a CV, \( A \) is the active electrode area, \( C_d \) is the capacitance and \( \nu \) denotes scan rate. To confirm this, the capacitance of individual nanowires was thus estimated from the non Faradaic region of CVs captured in deaerated 10 mM FcCOOH in 10 mM PBS at scan rates from 5 mV/s to 1000 mV/s. The difference in capacitive current (\( I_C \)) measured at 0.1 V vs. Ag/AgCl was found to have a strong linear dependence on scan rate (\( \nu \)) as depicted in figure 3b. From the slope of this relationship \( (2AC_d) \) the interfacial capacitance (\( C_d \)) of nanowire electrodes was estimated to be 15.6 ± 2 nF/cm² which is consistent with literature for nanoscale electrodes. In this case, the capacitance has been normalized to the geometric area of the passivated interconnection tracks and the exposed nanowire electrodes. The observed low capacitive contributions to CVs measured at nanowire electrodes
enable their use over fast time intervals with greater accuracy than larger electrodes. Reducing the contributions of capacitance to the overall current response at an electrode can greatly enhance the signal to noise ratio of electrode for sensing, allowing lower limits of detection to be achieved.

3.3.2. Square Wave Voltammetry: Pulse voltammetric techniques; such as square wave voltammetry (SWV), are routinely employed as methods of measurement for electrochemical sensors, as they are known to amplify electrochemical signals, enabling lower limits of detection. To demonstrate the applicability of nanowire based electrodes to future sensing square wave voltammetry was carried out in a range of concentrations of FeC OO H in 10 mM PBS (N2 Sat). SWVs were achieved at amplitude of 25 mV, frequency of 25 Hz, with a 1 mV step increment across an applied potential range of 0.0 V to 0.5 V. The resultant voltammograms, seen in figure 4, displayed typical current peaks at ~220 mV vs Ag/AgCl which is in good agreement with previous reports.[24] While capacitive current observed in SWVs appears to become more pronounced at increasingly positive potentials, the ratio of Faradaic current to capacitive current (I_f/I_c) increased linearly with concentration. This strongly suggests that pulse voltammetric current sampling at single nanowire electrodes further broadens the potential sensing applications that can be developed based on these devices.
4. Conclusions:
Individual gold nanowire electrodes, with highly reproducible critical dimensions, were fabricated a hybrid EBL-photolithography process on silicon substrates. Two point electrical experiments of fully packaged nanowire electrodes revealed low resistances. Investigations of the electrochemical properties of individual nanowires via cyclic voltammetry demonstrated reproducible steady-state behavior typical of electrodes with nanoscale critical dimensions in the presence of a standard redox mediator, ferrocenemonocarboxylic acid. This implies very fast mass transport of the analyte to electrode, which could increase the sensitivity of future sensing devices based on this platform. Preservation of the steady-state nature of CVs over a wide range of scans, coupled with low capacitive contributions demonstrates the potential suitability for such electrodes to be employed in rapid analysis at low concentrations. As a result of these findings the devices described in this work appear to be very amenable to future applications as electrochemical based sensors. To further explore this potential, nanowire electrodes have been investigated using square wave voltammetry in the presence of a redox mediator. The observed results indicated future applicability of these devices towards sensing applications in low concentrations.

5. Acknowledgments:
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