Electrical characteristics of individual FeNiCo-Au core-shell nanowires integrated into microelectrodes on plastic substrate

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ABSTRACT

Synthesis, characterization and integration of single metallic nanowires with enhanced electrical and mechanical properties into plastic substrate is a vital task for the development of transparent/flexible electronics as well as nanosensors. Among metallic nanowires, heterogeneous core-shell nanowires can provide benefits of more than one nanowire material and thus create unique properties to solve the drawbacks of respective nanowire materials. In this paper, we will show synthesis, electrical characteristics, and integration of a new FeNiCo-Au core-shell nanowire consisting of a mechanically strong FeNiCo core and highly conductive Au shell, promising both enhanced mechanical properties and electrical conductivity. A home-built alignment system based on an optical microscope and a xyz piezo positioner was developed to transfer individual nanowires into microelectrodes formed in plastic substrate. Electrical conductance of single FeNiCo-Au core shell nanowires was measured using the two-probe electrodes. The results were compared to that of FeNiCo nanowires. By decoupling the conductance through respective FeNiCo core and Au shell in the FeNiCo-Au core shell nanowire, the conductance of the Au shell was obtained.

Keywords: Core-shell nanowires, electrical transport measurement, transparent electronics, polymer microchips

1 INTRODUCTION

Transparent and flexible electronics are the crucial elements of smart phones/glass, touch screens, liquid crystal display (LCD), organic light-emitting diodes (OLED) [1, 2]. Metallic nanowires have great potential to be used as electrical components for the abovementioned transparent electronics because of the availability of nanowires with high electrical, mechanical, corrosion-resistive properties [3]. Metallic nanowires are usually grown via electrodeposition in a nanoporous template such as porous alumina or track-etched polycarbonate. The properties of metallic nanowires formed via electrodeposition can be controlled by changing the type of metals, their compositions, and conditions of electrodeposition.

Compared to homogenous nanowires [5-7], core-shell nanowires [8, 9] can provide the benefits of more than one homogenous nanowire material and reveal unique properties to solve the drawbacks of the homogenous nanowires [10]. An example include nanowires with a Ni core and an iron oxide (Fe_2O_3) shell, which exhibit two distinct magnetic behaviors [11].

FeNiCo nanowires are magnetic nanowires with high mechanical strength, but their application as electrodes is rather limited due to their poor electrical conductance. Herein, we introduced a novel iron-nickel-cobalt-gold (FeNiCo-Au) core-shell nanowire to achieve the high mechanical strength of the FeNiCo nanowire and high electrical transport property of Au simultaneously. We measured electrical conductance through the core-shell nanowire and compared it with that of the FeNiCo nanowire. For the electrical measurements, two probe electrodes were formed on plastic substrates via stencil lithography and single nanowires were placed on the electrodes with a home-made alignment system.

2 EXPERIMENTAL

2.1. Nanowire synthesis

The FeNiCo composite nanowires with 0.2 µm diameter and up to 40 µm length were fabricated by electrodeposition in a porous alumina template. Details of the electrodeposition process can be found in [12]. After the electrodeposition, the alumina template was dissolved by soaking the template in 2 M NaOH solution within a couvette overnight. The nanowires were then rinsed with NaOH, water and ethanol three times. After dissolving the alumina template, the nanowires were kept in ethanol to prevent oxidation. Some of the nanowires were broken during the preparation process, so that the nanowires had different lengths. For the FeNiCo-Au core-shell nanowires the same procedure was followed by removing the ethanol, soaking the nanowires in a 1:3 gold to DI water solution and centrifuge at 3000 rpm for 3 minutes. The gold solution was removed and the nanowires were kept in ethanol afterwards.

2.2. Fabrication of two-probe microelectrodes

Pt microelectrode arrays were fabricated by stencil lithography on poly(methyl methacrylate) PMMA substrates. A stencil membrane was fabricated by photolithography on a SU8 resist layer over a thin layer (250 nm) of water soluble resist (Dextran) on a silicon wafer. A piece of thermal release tape (Nitto Denko, No3198MS) was used to transfer the membrane to a PMMA substrate after dissolution of Dextran in water. The thermal release tape was detached from the membrane by heating followed by a thin (~50 nm) platinum deposition and membrane lift-off.

2.3. Alignment setup

An optical microscope based nanowire alignment setup was built to allow a high accuracy placement of single nanowires on the two-probe electrodes formed in PMMA substrates in an ambient condition. Figure 1 shows the schematics of the alignment setup. The setup consists of a long distance (1 cm, 40X) objective Nikon microscope, a micro-positioning stage (miniature XYZ positioner) [13] and a holder. The micro-positioning stage is again composed of two parts: a stationary stage and a moving stage controlled by three piezo driven step motors in the three (xyz) directions. The stationary stage is installed on the microscope stage which moves only in z direction. The moving stage holds the position without power and it has a travel distance of up to 10 mm with the resolution of 10 nm driven by a USB controller CF30. A steel rotary disc with 10 mm in diameter is attached to the top surface of the moving stage to add the rotation freedom to the substrate on the moving stage. The holder substrate is a 76 mm × 76 mm flat Teflon plate with 2 mm thickness having a 50 mm × 25 mm through hole.

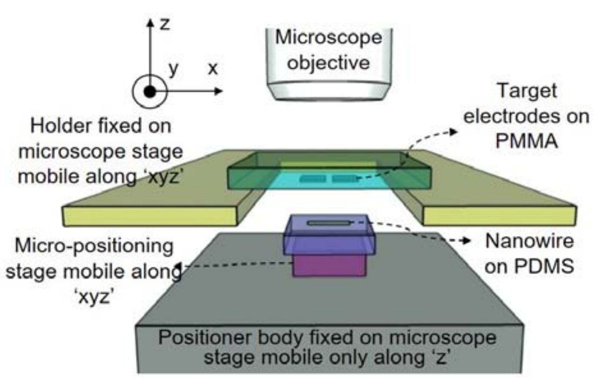

Figure 1: Alignment setup for placing individual nanowires on two-probe electrodes.

2.4. Nanowire placement on microelectrodes

The first step is to align the nanowires on a blank PMDS substrate via electromagnetic nanowire alignment [12]. The electromagnetic alignment results in a preferential direction on the FeNiCo nanowires on the PDMS substrate. Then, the PDMS substrate with aligned nanowires was put on the micro-positioning stage of the alignment setup. The target PMMA substrate with microelectrodes was placed on the microscope stage. After the PDMS substrate and target PMMA substrate were brought into contact with each other while the target nanowire was observed by the optical microscope. After that, the nanowire on the PMDS substrate was thermally transferred to the electrodes on the PMMA substrate in a nanoimprint lithography machine (Obducat) at 100°C, 45 bar for 5 minutes.

2.5. Conductance measurements

The I-V curves for the FeNiCo-Au and FeNiCo nanowires were obtained by connecting the micro-electrode contact pads to the working electrodes of a DY2300 series potentiostat connected to a desktop computer.

3 RESULTS AND DISCUSSION

Figure 2 shows optical micrographs of the FeNiCo nanowires after the electromagnetic alignment on a blank silicon surface. The red arrow shows the direction of the electromagnetic field during the deposition of nanowires. The micrographs show a preferential direction of the nanowire alignment along the electromagnetic field line. However, not all the nanowires on the substrate were usable for electrical measurements. Figure 2 (a) and (b) shows nanowires transferred with contaminants and nanowire agglomerates, respectively. The contaminants and agglomerations make the processes for single nanowire alignment and transfer more difficult. The nanowires in Figure 2(c) and (d) were individual nanowires which can be used for subsequent electrical measurements.

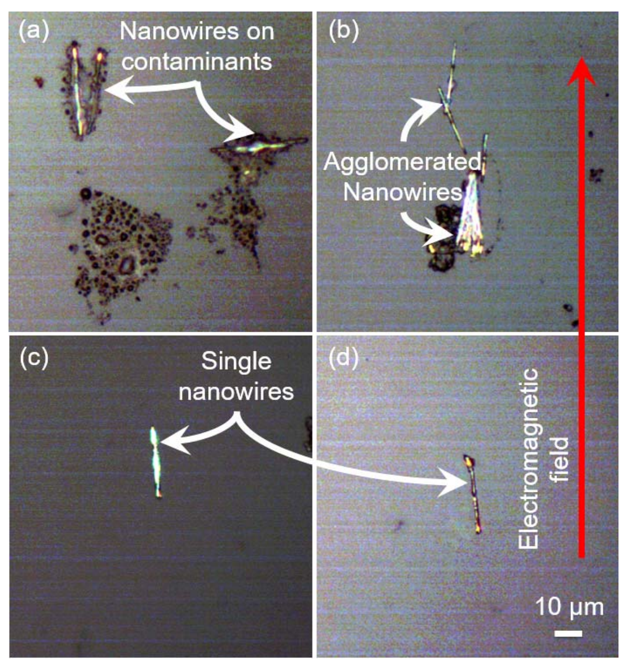

Figure 2: FeNiCo nanowires placed on a Si substrate via electromagnetic alignment.

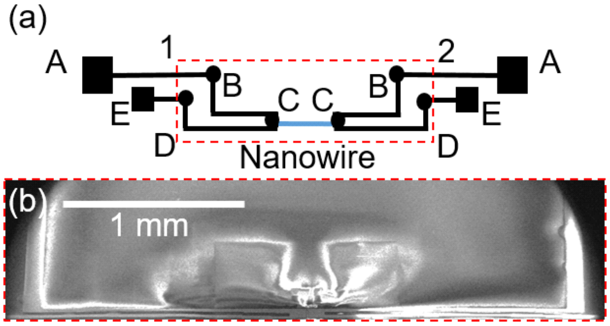

Figure 3: (a) A schematic for the configuration of microelectrode pair and the connected nanowires and (b) SEM image of the center part of the electrode pair.

Figure 3(a) shows the schematic configuration of an electrode pair (ABCDE1, ABCDE2) on PMMA and the connected nanowire in the center and Figure 3(b) shows the scanning electron microscope (SEM) micrograph of the center part of the electrode pair. The contact pads (A1, A2, E1, E2) shown in Figure 3(a) were used to connect the microelectrodes to the working electrodes of the potentiostat for current-voltage measurements of microelectrodes and the connecting nanowire.

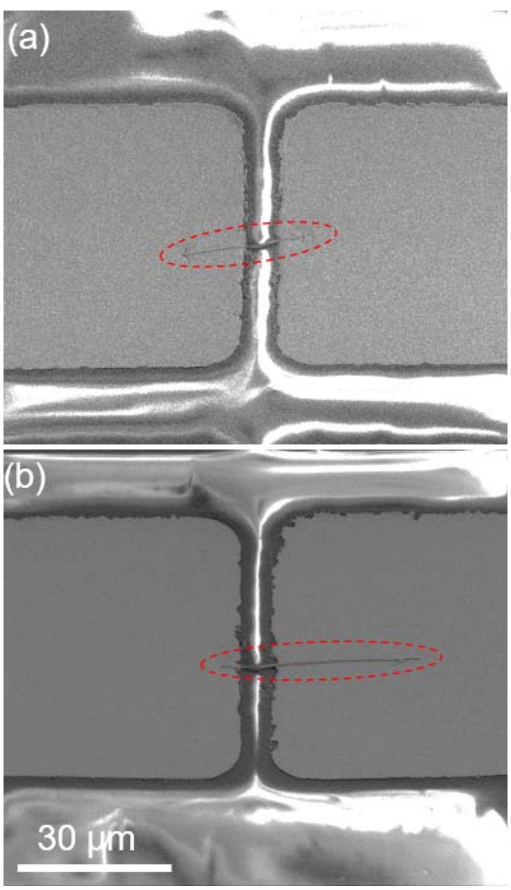

Figure 4: SEM images of (a) FeNiCo and (b) FeNiCo-Au nanowires placed on microelectrode pairs.

Figure 4 shows the SEM images of the (a) FeNiCo and (b) FeNiCo-Au nanowire samples connected to different microelectrode pairs. The positions of the nanowires are highlighted by the dashed ovals. The edge roughness and defects of the microelectrodes shown in these figures were partially due to the thermal transfer process of the nanowire. The bright areas in the figures were the PMMA substrate locations burned due to the SEM imaging due to electron beam hit to the substrate.

An applied voltage from –0.5 V to 0.5 was performed with the resolution of 10^{-9} V for each measurement and the current was recorded for each measurement. The current-voltage measurements of the electrode-nanowire-electrode ABC1-nanowire-CDE2 after connecting the nanowire were shown in Figure 5 for the FeNiCo and FeNiCo-Au nanowires. These results were used to calculate the resistance of the nanowires-electrodes. The resistance of the electrode-nanowire-electrode was 3.26 $\mu\Omega$ and 4.41 $\mu\Omega$ for the electrode-FeNiCo-Au-electrode and electrode-FeNiCo-electrode nanowires, respectively. Assuming that the lengths and diameters of the two nanowires between the electrode pairs were the same, we calculated the resistance of the Au shell on the FeNiCo-Au nanowire by deducting the the two abovementioned resistance values (R_{Au} = 1.15 $\mu\Omega$). The error for the calculated resistance of the Au shell of the FeNiCo-Au nanowires were due to slightly different length and diameter of the nanowires between the two electrodes and inhomogeneity of the microelectrode pair resistance values.

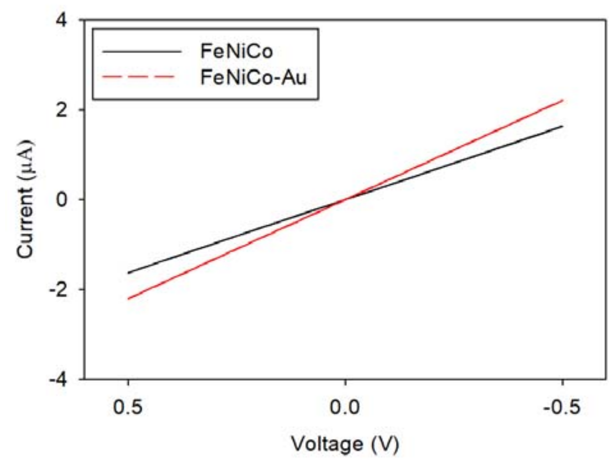

Figure 5: Formatting dimensions for manuscripts.

4 CONCLUSION

A new FeNiCo-Au core-shell nanowire with enhanced electrical, mechanical and durability properties was proposed and its electrical conductance was compared with that of the FeNiCo nanowire. Our results show that electrical conductance of the FeNiCo nanowire can be enhanced by adding a thin shell of Au around the FeNiCo nanowire via electrochemical reaction. This will allow us to achieve high mechanical and electrical properties simultaneously, which is important to utilize metallic nanowires as electrical components in many applications.

ACKNOWLEDGEMENT

The authors would like to thank the National Institutes of Health (P41EB020594) for financial support of this work.

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