# Site-Specific Magnetic Assembly of Nanowires for Sensor Arrays Fabrication

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***Abstract*—The effect of variation in local magnetic field on magnetic assembly of 30 and 200 nm diameter Ni nanowires synthesized by template directed electrodeposition was investigated with different materials (Ni–Ni and Ni–Au) and shapes of electrodes. Ni–Au paired electrodes improved confinement of the assembled Ni nanowires across the electrode gap because of the narrower distribution of magnetic field around the gap between the two electrodes. Simulation results indicated a local magnetic field strength at the electrode tip increased by a factor of 2.5 with the use of a needle-shape electrode as compared to rectangular-shape electrode. The resistance of nanowire interconnects increased as the applied voltage was raised, and under the same applied voltage, the increase in resistance is further enhanced at lower temperatures because of higher current density.**

***Index Terms*—Anodized aluminum oxide (AAO), electrodeposition, local magnetic field, magnetic assembly, nanowires, Ni.**

## I. Introduction

ONE-DIMENSIONAL nanostructures, such as nanowires, nanobelts, and nanotubes, are extremely attractive materials for sensors because of their high aspect ratios and unique properties, which arise from size-dependent quantum confinement effects [1]. These components can directly convert physical, chemical, and biological information into an electric signal for real-time monitoring, which is also desirable for interfacing existing low-power microelectronics, leading to multiplexed sensing systems that require minimal sample volumes. As basic building blocks of nanotechnology, these structures can be further complexed forsensing applications by axial and radial heterostructures for segmented, superlattice, and core/shell configurations. These features may also enable a high enough sensitivity to realize single molecule detection in chemical and biological sensors [2], [3].

Various 1-D nanostructures have been synthesized using different processes, including chemical vapor deposition (CVD), high-temperature catalytic processes, pulse-laser ablation, vapor–solid–liquid (VLS) growth processes, molecular beam epitaxy (MBE), and wet-chemical synthesis [4]. As increasing emphasis is placed on nanomanufacturing (i.e., high volume, low cost, high throughput, and low capital cost), template directed electrodeposition has emerged as a promising process for the synthesis of nanowires. Electrodeposition is operated at near room temperature and ambient pressure with minimum capital investment. The crystallographic structure and orientation of nanostructures can be tailored for specific material properties through solution composition, deposition conditions, and additives [5]. Electrodeposition is also a powerful tool to deposit various materials including metals, semiconductors, and conducting polymers.

However, before these nanostructures can be fully exploited as sensing transducers, they must be precisely positioned and interfaced to microscale or mesoscale features. Moreover, these materials should be addressed in a reliable and repeatable manner that facilitates low contact resistance without exceeding physical and thermal limitations. Several methods have already demonstrated control assembly of nanowires on prefabricated electrodes, including Langmuir–Blodgett [6], [7], electric field assisted alignment [8], and magnetic field assisted alignment [9], [10]. Among them, magnetic alignment technique is the most benign, achieved by simply applying an external magnetic field, requiring no surface modification or potentially damaging of nanostructures by electric fields. Previously, we demonstrated alignment of Ni nanowires on ferromagnetic electrodes by applying external magnetic fields [10], [12], and more complex hierarchical structure of nanowires fabricated with magnetic assembly was also reported [11]. Magnetotransport phenomena ferromagnetic nanowires such as Ni and CoNi were also investigated with magnetically assembled nanowire [13], [14].

In this paper, spatial positioning of ferromagnetic Ni nanowires, fabricated by template-directed electrodeposition on different shapes and configurations of ferromagnetic electrodes, were investigated experimentally and compared with mathematical simulation data. By controlling the shape of electrodes (i.e., needle and rectangular shape) and materials, single nanowires could be assembly on prefabricated electrodes more preciously. A postannealing technique in a reducing environment

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was used to make good contact with the nanowires. The resistance between the two electrodes, including line resistance of Ni nanowire and contact resistance, was measured as a function of temperature.

## II. Device Fabrication and Measurements

Anodized alumina templates, which have 200 nm diameter and 30 nm diameter, were used for synthesizing the nanowires. The template with a 200 nm pore size is commercially available from Whatman Corporation (Anodisc 25, total template diameter = 21 mm), and the 30 nm pore size template was prepared in our laboratory by anodization of high purity aluminum foils (>99%). Anodization conditions for fabricating alumina template and the procedure for acquiring the Ni nanowires were well described in previous work [12].

Ferromagnetic electrodes were microfabricated on a (1 0 0) oriented silicon wafer. A 50-nm-thick insulator layer of $SiO_2$ film was grown on the wafer using CVD to insulate the substrate, followed by lithographic pattering of electrode area. After e-beam evaporation of an Au 200 Å/Cr 100 Å layer, the electrodes were patterned using liftoff technique. Prepared Au electrodes were electrodeposited with Ni to form ferromagnetic electrodes. Electrodes with different shapes (i.e., rectangular and needle electrode with tip angles of 60°) were produced to investigate the influence of local magnetic flux on the yield of magnetically trapped nanowire. The external magnetic fields, which were used to generate the intense local magnetic field in the gap of two electrodes, were applied by placing the microfabricated electrodes between two permanent magnets. The strength of external magnetic field could be adjusted by varying the distance between two permanent magnets.

Nickel nanowires were assembled on electrodes by placing isopropyl alcohol containing the suspended nanowires between electrodes in the applied magnetic field. Nanowires can move freely in the droplet until isopropyl alcohol is evaporated. During this time, nanowires align parallel to magnetic field due to the magnetic shape anisotropy of nanowires. After the assembly of nanowires, electrical characteristics of ferromagnetic nanointerconnects were investigated using a semiconductor parameter analyzer (HP 4155 A) and physical property measurement system (PPMS) at various temperature.

## III. Results and Discussions

To construct a multifunctional device with different types of nanowires possessing various functionalities, the configuration of one bar type electrode working as a common electrode with several microband electrodes was utilized. On this pattern, nanowires having different functionality can be positioned respectively between different microband electrodes and common electrode. In magnetic alignment, strength and distribution of local magnetic field around the tip of electrodes could be the critical factor to control the directionality and population of nanowires, which are aligned parallel to magnetic field. To verify the effect of the distribution of local magnetic field on magnetic alignment, two different sets of electrode patterns, which are Ni-coated microbands, Ni-coated ferromagnetic common electrode

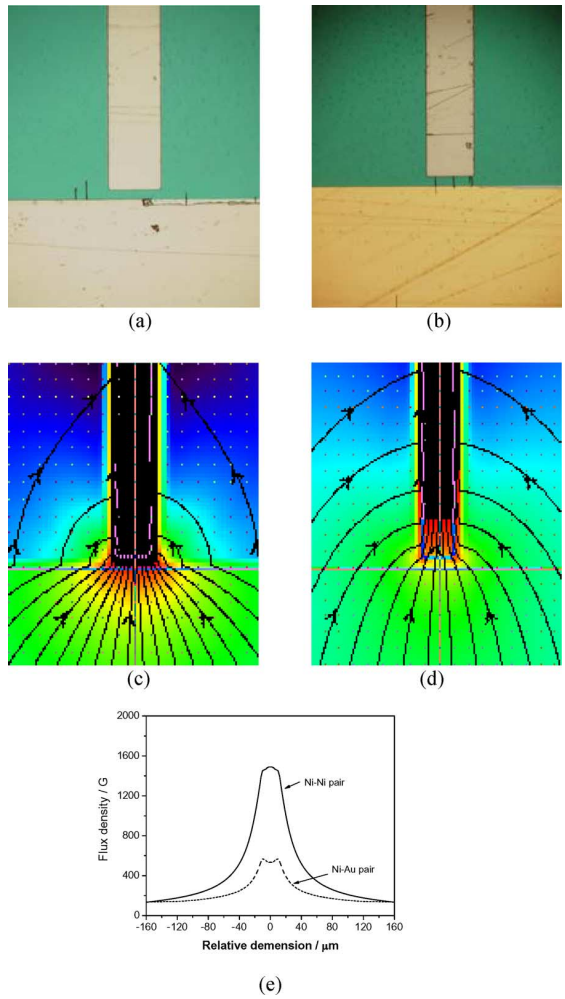



Fig. 1. Optical images of magnetically assembled Ni nanowires (diameter = 200 nm) on Ni–Ni electrode (a) and Ni–Au electrode (b), and corresponding computational simulation results (c), (d), (e).

pair (Ni–Ni electrode), and Ni-coated microband, Au common electrode pair (Ni–Au electrode), respectively, were prepared [see Fig. 1(a) and (b)]. The gap of ferromagnetic electrodes was fixed at 10 $\mu$m. Magnetic alignment of 200 nm diameter Ni nanowires was performed with these two pair of electrodes. As shown at optical images, Ni nanowires that were placed on the patterns were aligned along the direction of external magnetic field in both cases. However, in case of Ni–Ni electrode [see Fig. 1(a)], positions of nanowires were widely scattered, and the nanowires were not bridged between electrodes. On the other hand, they were successfully confined in the gap between Ni–Au electrode [see Fig. 1(b)]. For a better understanding of the distribution of Ni nanowires on two different pair of electrodes, mathematical simulations were employed [15]. Dimension of electrodes in the simulation are identical to the electrodes utilized in these experiments. The relative permeability of Ni electrode and applied external magnetic field were fixed at 100 and 200 Oe, respectively. Fig. 1(c) and (d) illustrates the simulation results of the distribution of magnetic field of Ni–Ni and Ni–Au electrodes, and Fig. 1(e) represents the strength of magnetic field at the edge of common electrode. As shown, the Ni–Ni electrode can produce stronger magnetic field at the

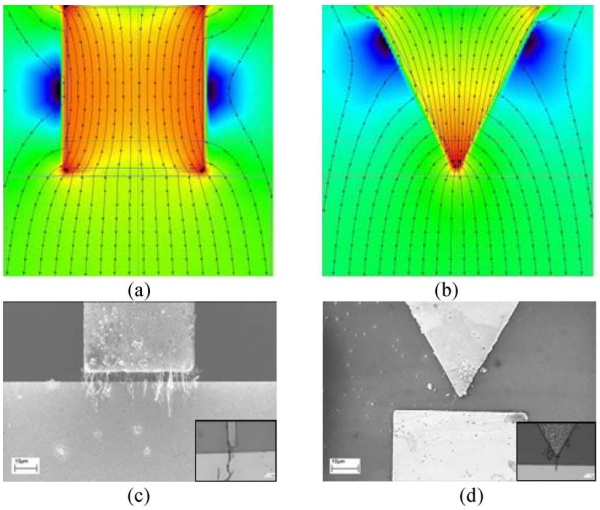



Fig. 2. Computational simulation results of magnetically assembled Ni nanowires (diameter = 30 nm) on needle-shape electrode (a) and rectangular-shape electrode (b), and corresponding SEM images (c), (d). Inset figures are aligned Ni nanowires with 200 nm of diameters at same conditions.

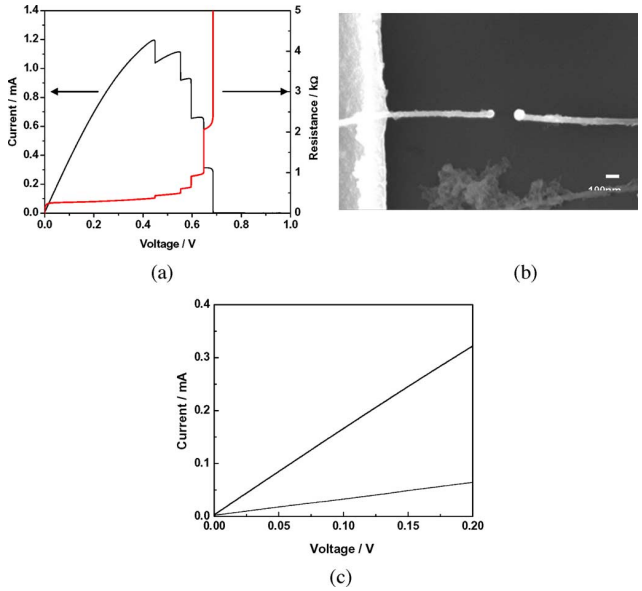



Fig. 3. *I–V* characteristics and breakdown behavior of electrically bridged five Ni nanowires (diameter = 30 nm) on Ni–Au electrode (a), and SEM image of electrically brokendown nanowire (b). Comparison of *I–V* characteristics of multiple Ni nanowires (total number = 3) and single Ni nanowire after breaking down two nanowires.

center of the gap between electrodes. However, the magnetic field for the noncomplimented region of the common electrode is also stronger than that of the center of the Ni–Au electrode, which is substantially enough to attract ferromagnetic nanowires. As a result, in the Ni–Ni electrode pair, the positioning distribution of nanowires is not confined to the electrode gap, but scattered to adjacent sections of the gap. In contrast, even though the maximum magnetic field of the Ni–Au electrode is comparably lower than that of the Ni–Ni electrode, the magnetic field at the outside of the gap is sufficiently low, so that nanowires are confined within the gap region.

The electrode shape is another important parameter for controlling the positional distribution of nanowires during magnetic alignment, as the shape of the tip significantly impacts the strength and distribution of the magnetic field. The variation of the distribution of magnetic fields with different shapes is mathematically simulated [see Fig. 2(a) and (b)]. From the magnetic field simulation data, the local magnetic field at the tip of needle-shape electrode was ∼2.5 times higher than that of standard rectangular-shape electrode under the same external magnetic field, and it is concentrated on the center of tip, whereas the highest magnetic field positions in rectangular-shape electrode were the two corners of electrodes. This indicates that it is easier to confine the number of nanowires bridging two electrodes with needle-shape electrode. Fig. 2(c) and (d) shows the magnetically aligned Ni nanowires with 30 nm in diameter on prefabricated rectangular and needle-shape electrodes, respectively. The needle-shape electrode creates a more confined magnetic field at the tip of the electrode, which results in single nanowire connections, as presented in Fig. 2(d). Nickel nanowires of 200 nm diameter were also assembled with two different shapes of electrodes, which are shown as inset images.

The electrical contact resistance is an important factor for establishing nanowire-based devices, because high contact resistance significantly degrades the electrical signals during the operation of devices. The contact resistance between the electrode materials and nanowire could be reduced effectively by annealing in a hydrogen-reducing environment [12]. The *I–V* characteristic of multiple numbers of bridged nanowires, which are positioned on the gap between rectangular-shape Ni–Au electrode, is represented in Fig. 3(a). In this graph, current responding with low voltage region was linear. However, as the applied voltage increased, i.e., higher than ∼0.3 V, a nonlinear response of current with respect to voltage was observed. This deviation from the linear region of the *I–V* curve could be caused by two different mechanisms: Joule heating and electromigration. Joule heating, which can increase the local temperature of nanowires, is directly governed by the total current flowing through the resistor according to the following equation:

$$B = \frac{I^2 \rho}{S^2} \tag{1}$$

where $B$ is the homogeneous Joule power density, and $I$, $\rho$, and $S$ are the current, resistivity, and cross-sectional area, respectively. From our previous report on Ni nanowire temperature dependent resistance [13], the temperature coefficient of resistance (TCR) of a Ni nanowire with 30 nm diameter was 0.002 $K^{-1}$, and it allows ∼20% resistance increase when the temperature approaches the melting point. However, the variation of resistance from the low voltage region to the break down point was ∼40%, which strongly supports that increasing the temperature of the Ni nanowire by Joule heating might not be the only reason for the increasing resistance with voltage. Coupled with Joule heating and higher current densities, electromigration could further increase the resistance by diminishing the cross-sectional area of the nanowire. Further increasing of applied voltage causes a sudden drop of responding current, which means that the nanowire was electrically and physically broken down. The SEM image of a bridged nanowire shows the physical breakdown of the Ni

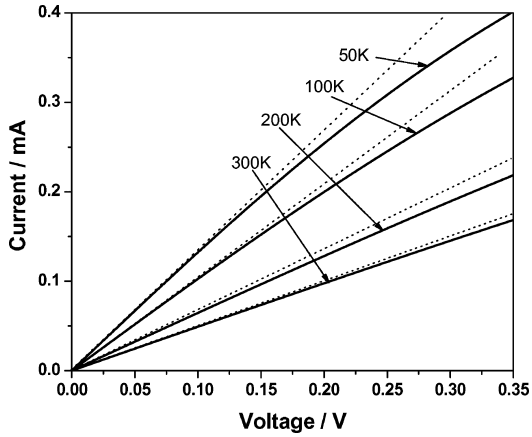



Fig. 4. *I–V* characteristics of single Ni nanowire (diameter = 30 nm) at different temperatures.

nanowire [see Fig. 3(b)]. The gap between two parts of the Ni nanowire was ∼189 nm, and each end of the nanowire has a droplet shape, which means that even though the increasing resistance during the voltage sweep was influenced by combined effects of Joule heating and electromigration, the final breakdown was mainly caused by local melting as a result of Joule heating accumulation [16].

In the *I–V* curve, five steps are observed that could be interpreted as the breakdown of five nanowires electrically bridging two electrodes. Because of different surface condition, with slight variation of diameters and respective internal defects, each nanowire shows different electrical breakdown voltages during the voltage sweeping, resulting in multiple stepwise breakdown behavior. From the current at the breakdown of the last nanowire, the current density causing the local melting of 30 nm Ni nanowire was 44.3 MA/cm$^2$.

Such uneven breakdown characteristics can be utilized to achieve single nanowire bridging. From Fig. 3(a), total resistance between two electrodes bridged with five nanowires was ∼360 Ω, and after four nanowires are broken down, the resistance of the remaining nanowire was ∼2070 Ω. This strategy can be used to create single nanowire circuits by breaking the nanowires one by one with an applied voltage, stopping the applying voltage when the resistance approached similar value of 2000 Ω. Fig. 3(c) illustrates the *I–V* characteristics of three of nanowires bridged circuit, and single nanowire bridged circuit after sequential nanowire breakdown with applied voltage. It shows that the resistance was decreased from ∼620 to ∼2900 Ω by diminishing the number of bridged nanowire with an applied voltage. With this method, single-bridged circuit can be effectively achieved from multiple-bridged nanowire circuits.

The *I–V* characteristics of Ni nanowires at different temperature (from 300 K to 50 K) are shown in Fig. 4. When the temperature is decreased from 300 K to 50 K, the increase in resistance at higher potentials is more prominent. At 50 K, the resistance was 750 Ω at 0.05 V, and it increased to 870 Ω at 0.35 V. The change in resistance as a function of applied voltage $[\Delta R/R_{0.05V}, (\delta R = R_{0.35V} - R_{0.05V})]$ at 50 K was ∼13.5% larger than that at 300 K. This deviation in resistance of the Ni nanowire at low temperature is a result of higher current density flowing through the nanowires. The relatively low resistance at lower temperature, which is achieved by reducing the thermal scattering of electrons, allows for a higher current density, and, in turn, may enhance the Joule heating at the same voltage as compare to that of higher temperatures. Understanding this relationship between resistance and applied voltage is important for nanowire structures, as a steady base-line resistance is crucial for reliable operation of sensing devices.

## IV. Conclusion

Magnetic alignment with variable local magnetic fields is demonstrated as a site-specific assembly technique to integrate multiple nanowires or single nanowire in sensor arrays. The high controllability and ease of approach facilitate the use of this method for nanowire assembly. Spatial manipulation of Ni nanowires (30 and 200 nm in diameter) was magnetically aligned for the application on nanowire-based, resistor-type sensing devices. The gap between ferromagnetic electrodes positioned the nanowires to bridge the electrodes. Magnetic assembly with Ni–Au electrode more confined distribution of nanowires than Ni–Ni electrode. Simulation results indicated that a local magnetic field strength at the tip of electrodes could be increased by a factor of 2.5 by fabricating needle-shape electrode as compared to a standard rectangular-shape electrode, which could increase the probability of single nanowire bridging between two electrodes. Experimental data supported this finding. Resistance of the nanowire interconnect increased as the applied voltage was raised due to electromigration and Joule heating, which results in the electrical and physical breakdown of nanowire with high applied voltage. This breakdown behavior can be utilized for achieving single-nanowire-based circuits from multiple nanowires.

## References

[1] S. Sapra, D. D. Sarma, S. Sanvito, and N. A. Hill, "Influence of quantum confinement on the electronic and magnetic properties of (Ga,Mn) as diluted magnetic semiconductor," *Nano Lett.*, vol. 2, pp. 605–608, 2002.

[2] Y. Cui, X. Duan, Y. Huang, and C. M. Lieber, "Nanowires as building blocks for nanoscale science and technology," in *Nanowires and Nanobelts Materials, Properties and Devices* (Metals and Semiconductor Nanowires), vol. 1, Z. L. Wang, Ed. Boston, MA: Kluwer, 2006, pp. 3–68.

[3] Y. Cui, Q. Wei, H. Park, and C. M. Lieber, "Nanowire nanosensors for highly sensitive and selective detection of biological and chemical species," *Science*, vol. 293, pp. 1289–1292, 2001.

[4] S. J. Hurst, E. K. Payne, L. Qin, and C. A. Mirkin, "Multisegmented one-dimensional nanorods prepared by hard-template synthetic methods," *Angew. Chem. Int. Ed.*, vol. 45, pp. 2672–2692, 2006 (and the references cited in).

[5] T. Osaka, "Electrodeposition of highly functional thin films for magnetic recording devices of the next century," *Electrochim. Acta.*, vol. 45, pp. 3311–3321, 2000.

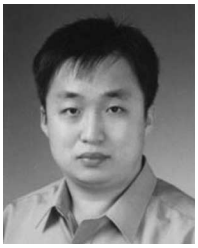
[6] Y. Huang, X. W. Duan, and C. M. Lieber, "Directed assembly of one-dimensional nanostructures into functional networks," *Science*, vol. 291, pp. 630–633, 2001.

[7] D. Whang, S. Jin, Y. Wu, and C. M. Lieber, "Large-scale hierarchical organization of nanowire arrays for integrated nanosystems," *Nano Lett.*, vol. 3, pp. 1255–1259, 2003.

[8] K. Ramanathan, M. A. Bangar, M. Yun, W. Chen, A. Mulchandani, and N. V. Myung, "Individually addressable conducting polymer nanowires array," *Nano Lett.*, vol. 4, pp. 1237–1239, 2004.

[9] M. Tanase, D. M. Silevitch, A. Hultgren, L. A. Bauer, P. C. Searson, G. J. Meyer, and D. H. Reich, "Magnetic trapping and self-assembly of multicomponent nanowires," *J. Appl. Phys.*, vol. 91, pp. 8549–8551, 2002.

[10] C. M. Hangater and N. V. Myung, "Magnetic alignment of nanowires," *Chem. Mater.*, vol. 17, pp. 1320–1324, 2005.
[11] C. M. Hangater, Y. Rheem, B. Y. Yoo, E. H. Yang, and N. V. Myung, "Hierarchical magnetic assembly of nanowires," *Nanotechnology*, vol. 18, p. 205305, 2007.
[12] B. Y. Yoo, Y. Rheem, W. P. Beyermann, and N. V. Myung, "Magnetically assembled 30 nm diameter Ni nanowire with ferromagnetic electrodes," *Nanotechnology*, vol. 17, pp. 1512–1517, 2006.
[13] Y. Rheem, B. Y. Yoo, W. P. Beyermann, and N. V. Myung, "Magneto-transport studies of a single nickel nanowire," *Nanotechnology*, vol. 18, pp. 15202–15208, 2007.
[14] Y. Rheem, B. Y. Yoo, W. P. Beyermann, and N. V. Myung, "Electro- and magneto-transport properties of a single CoNi nanowire," *Nanotechnology*, vol. 18, pp. 125204–125210, 2007.
[15] htttp://www.vizimag.com
[16] M. L. Trouborst, S. J. Van Der Molen, and B. J. van Wees, "The role of joule heating in the formation of nanogaps by electromigration," *J. Appl. Phys.*, vol. 99, pp. 114316-1–114316-7, 2006.



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