

## A Nickel Nanowire Diluter Operating through the Principle of the Dielectrophoretic Attraction Force

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**Abstract** - This paper presents a microfabricated nanowire diluter which dilutes the concentration of nanowires in solution instead of by the conventional centrifuge process. The device has 16 pairs of gold electrodes in a micro channel composed of a glass substrate and PDMS. We prepared nickel nanowires by the template-directed electrodeposition method using nanoporous anodized aluminum template (AAO). We injected the Dimethylformamide (DMF) solution containing nanowires into the inlet of the diluter while applying square wave voltages on the electrodes to trap the nanowires at the subsequent gold electrodes by means of dielectrophoretic attraction forces. The concentration of nanowires at the outlet of the micro channel was changed as we expected, which illustrates that the device can effectively dilute nanowires and can be applied to a controlled assembly of nanowires.

**Key Words** : Nanowire diluter, Dielectrophoretic attraction, Nickel nanowires, Template-directed electrodeposition

### 1. Introduction

One-dimensional (1D) nanowires are considered as outstanding materials due to their high aspect ratio and unique properties. Several types of nanowires have been used in electronic and nanoelectromechanical devices as well as biosensors, where nanowires have to be statically assembled between two counter electrodes. In general, we need to assemble a single wire to assess its behaviour. A controlled assembly of nanowires is essential for cross-disciplinary applications. The dielectrophoretic (DEP) assembly process enables a simple and efficient control of nanoparticles. However, control of the number and dimensions of nanowires forming a bridge between electrodes is extremely complicated. Several methods of assembling nanowires onto electrodes have been established. Amongst these, an electric-field assembly method of manipulating microscale particles has been widely utilized due to its simple and convenient way of aligning nanowires[1-2]. This method is operationally based on a dielectrophoretic assembly. When an electric field is applied to two opposing electrodes, nanowires are

polarized and aligned parallel to the direction of the electric field.

The electric-field assembly method requires firstly a repeated dilution of nanowires since their suspension is highly concentrated. Typically, one can decrease the number of nanowires by adjustment of the nanowire concentration in suspension through a repeated centrifuging process[3]. However, this does not guarantee the precise positioning of individual wires between electrodes and requires time and a series of trials. Therefore, we developed our proposed device, a nanowire diluter, to align individual wires between electrodes without the requirement of diluting the nanowire suspension in water using a centrifuge.

We present experimental details including the fabrication process for nickel (Ni) nanowires and their diluter. Subsequently, the dilution test is performed by injecting the nanowire suspension through the diluter using a syringe pump and inspecting a droplet of nanowire suspension using an optical microscope. The effects of the applied frequencies and voltages are evaluated through repeated tests.

### 2. Dielectricphoretic attraction

Dielectricphoretic(DEP) forces are widely utilized to manipulate nanoscale particles. DEP arises from the force imbalance exerted on the induced dipole moment of an uncharged dielectric or a conductive particle in an electric field[4-6]. The direction of the DEP force depends on

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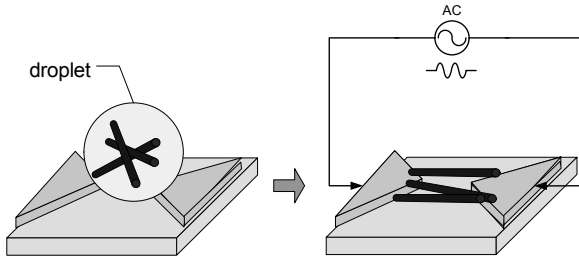


Fig. 1 Principle of the DEP attraction

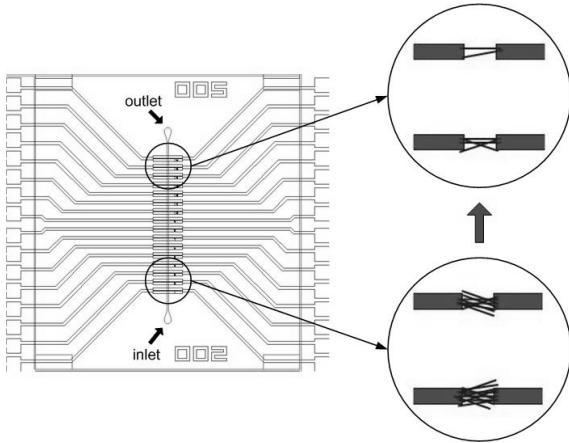


Fig. 2 Structure of the nanowire diluter

total polarization capacity of the particle and the medium and the strength of the DEP force depends on the particles' shape and size and the frequencies of the electric fields[7]. Therefore, the signal frequency as well as the electrode architecture have to be carefully considered for the purposes of precise control of the nanowire assembly. However, this scheme does not guarantee the precise positioning of individual nanowires between electrodes.

The DEP force is derived from a Maxwell-Wagner theory[8], and the time-averaged  $F_{DEP}$  is given by

$$F_{DEP} = 2\pi\epsilon_m r^3 Re[f_{cm}(\omega) \nabla |\vec{E}_s|^2] \quad (1)$$

where  $E$  is the electric field,  $r$  is radius of a colloidal particle ( $p$ ), and  $\tilde{\epsilon}_p$  and  $\tilde{\epsilon}_m$  are complex permittivity of  $p$  and that suspended in a medium ( $m$ ), respectively. The  $f_{cm}$  is the dipolar Clausius-Mossotti factor that determines the orientation of induced dipoles.

$$f_{cm} = (\tilde{\epsilon}_p - \tilde{\epsilon}_m) / (\tilde{\epsilon}_p + 2\tilde{\epsilon}_m) \quad (2)$$

Frequency ( $\omega$ ) is dependent on medium conductivity on account of the complex permittivity,  $\tilde{\epsilon} = \epsilon - i\sigma/\omega$  where  $\epsilon$  is the static permittivity and  $\sigma$  is the conductivity. Therefore, the DEP force can vary particle mobility due

to AC induced dipoles on colloidal particles[8].

Fig. 1 shows the principle of DEP based nanowire attraction. When an electric field is applied to two counter electrodes, the nanowires are polarized and aligned parallel to the direction of the electric field if nothing but an electric field is applied on the electrodes. The assembling efficiency of nanowires is nearly proportional to the frequency of the applied AC voltage and the gradient of electric field squared[9]. As a result, the manipulation of larger number of nanowires requires a suitable frequency of applied voltage[10].

We propose a nanowire diluter that is able to control a number of nanowires captured at an electrode pair as shown in Fig. 2. A solution containing nanowires is injected into the inlet of the microchannel and square wave voltages are applied to 16 pairs of electrodes.

The nanowires have a tendency to accumulate at the inlet when they are controlled by the frequency of the applied voltage. Nanowires are trapped or released and the expected number of nanowires that are consequently produced at the outlet depends on the frequency of the electric field.

### 3. Fabrication

Nickel nanowires are fabricated by a template-directed electro-deposition process using nanoporous anodized aluminum templates(AAO) possessing pores of 200 nm diameter as shown in Fig. 3. A thin film of Ag/Au is used as a seed layer, and Ni is electroplated on the template using electroplating(Galvanostat2563A-1). The conductive thin film of Ag is then removed with concentrated HNO<sub>3</sub> to obtain individual nanowires and the AAO template is removed by dissolution in 5 M NaOH solution for 30 min. The resulting nanowires were 200 nm diameter and 30  $\mu$ m in length.

The fabrication of the nanowire diluter device was performed by a basic lithographic process(Fig. 4). The device consists of a glass substrate with 16 pairs of gold electrodes and a PDMS cover layer covered with the microchannel.

In order to make electrode pairs, we deposited Ti/Au on the glass substrate 10 and 100 nm respectively and patterned using photolithography. The PDMS layer was fabricated using an SU-8 mold through soft lithography; the SU-8 was spun on the silicon substrate, followed by patterning by UV-lithography to create the 100  $\mu$ m-wide microchannel. Subsequently, PDMS was cast on the SU-8 mold and heated at 70  $^{\circ}$ C for 3 hours after degassing for 40 min. The fabricated PDMS layer peeled off from the substrate was then boned to the glass substrate. The bonding process was performed using an O<sub>2</sub> plasma. Fig. 5 shows photographs of the fabricated nanowire diluter device.

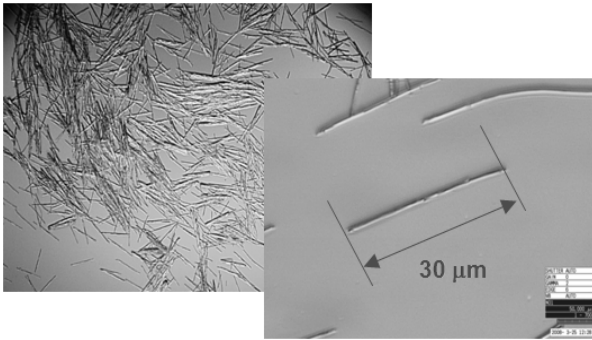


Fig. 3 Fabricated Ni nanowire

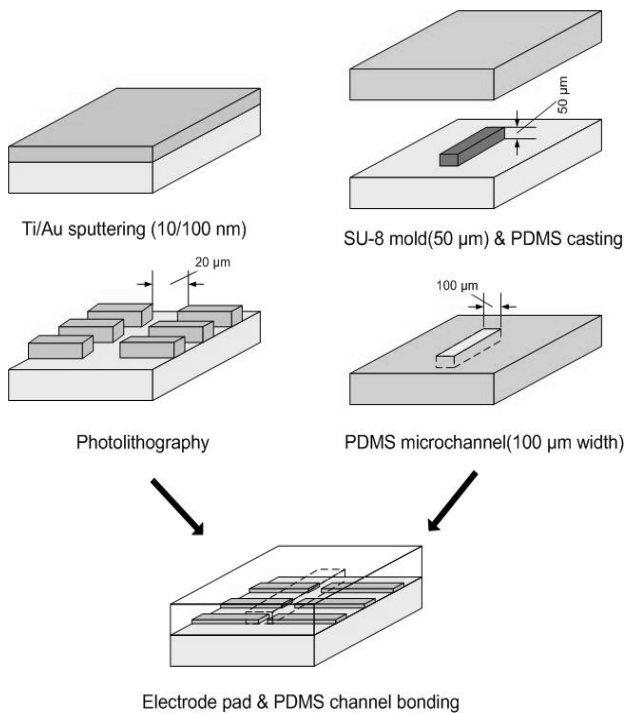


Fig. 4 Fabrication process of the nanowire diluter

#### 4. Dilution tests

An optical microscope was used to inspect real-time digital images. Solution containing Ni nanowires was injected into the inlet of the microchannel in the fabricated diluter using a syringe pump that uniformly controls the velocity of the fluid. During the experiment, the syringe needle was removed so as to avoid nanowires sticking to the inner surface of the needle (i.e. the needle was made of Fe and the nanowires were also ferromagnetic materials). A function generator was used to generate the timing signals required to control the pulsed voltage.

Fig. 6 shows the trapped nanowires between electrode pairs in the microchannel. DI water and dimethylformamide (DMF) solution were mixed in a 1:9 ratio along with the

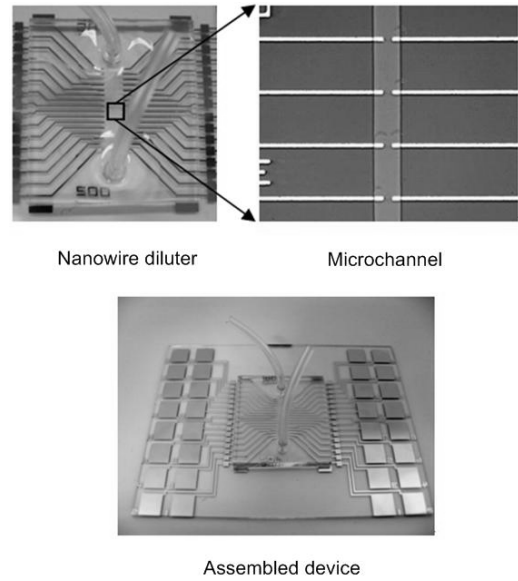


Fig. 5 Photographs of the fabricated nanowire diluter

Ni nanowire suspension. Sonication was performed for 1 min in an ultrasonic bath before injection of the nanowire suspension into the channel. The frequency and voltage utilized to align nanowires were 5 MHz and 10 V<sub>p-p</sub> respectively. The solution containing the nanowires was moving across the channel from the inlet to the outlet and the number of the nanowires was dramatically reduced as a result of nanowires being trapped between the electrode pairs.

A droplet of the nanowire suspension was inspected before the injection as shown in Fig. 7. After the same nanowire suspension passed through the channel, the presence of a smaller number of nanowires was clearly indicated.

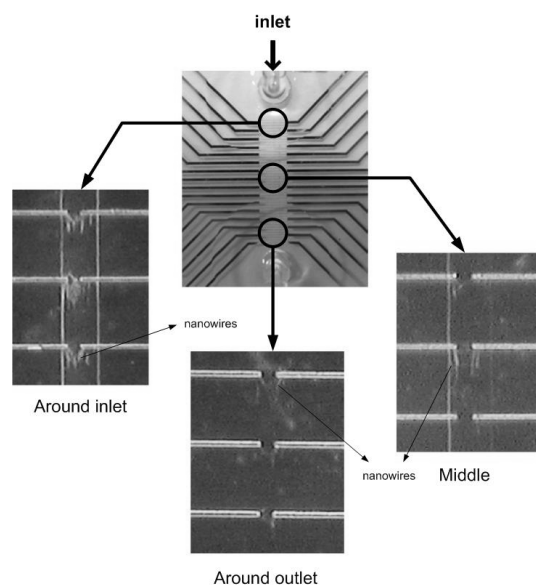


Fig. 6 Trapped nanowires in the microchannel

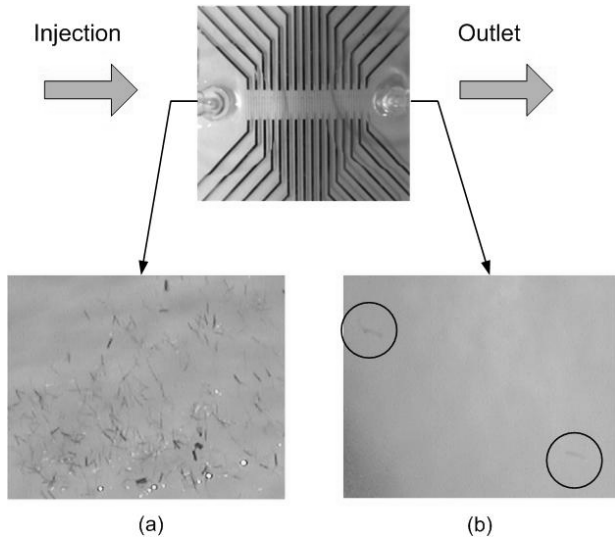


Fig. 7 The number of Ni nanowires in the solution ((a)before injection, (b)after dilution)

The number of nanowires in suspension can be adjusted by modifying the droplet when it is placed between the electrode pairs. This result demonstrates the efficacy and tenability of the device.

### 5. Conclusions

A microfabricated nanowire diluter has been demonstrated. The required assembly of nanowires between electrodes is obtained by starting with a larger number of nanowires and then by adjusting the nanowire concentration in water suspension through a repeated centrifuging process. In a related development, the diluter presented in this paper enables the controlled trapping of nanowires so that the required number of wires at the output can be obtained. The function of the device was demonstrated by adjustment of the pulsed electric fields whilst the nanowires drifted through the channel in order to reduce and control the number of the passing nanowires. The result shows that the number of the assembled nanowires can be controlled with a high-throughput for integrated chips suitable for several cross-disciplinary applications including nanoelectronics and sensors. Further study is required to improve the device performance and to understand the effect of the electric field frequencies and the electrode geometries.

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