Automatic microcircuit formation based on gold-coated SU-8 microrods via dielectrophoresis*

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To explore the application of the characteristics of metallic microparticles, alternating current electric trapping of the SU-8 microrods coated with a thin gold layer by the chemical approach is investigated. Positive dielectrophoresis is used to absorb the gold-coated SU-8 microrods at the edge of the parallel electrodes, thereby forming chains to connect the electrodes. This is a fast automatic microcircuit formation process. Moreover, a non-charged molecule is modified on the surface of the gold-coated SU-8 microrod, and the modified microrods are controlled by the alternating electric field to form a number of chains. The different chains between the parallel electrodes consist of various parallel circuits. In order to compare these chains with different electric surfaces, the impedances of the metallic and modified microrods are measured and compared, and the results show that the gold-coated microrods act as pure resistors, while the microrods functionalized by a non-charged molecule behave as good capacitors.

Keywords: AC electrokinetics, gold-coated microrods, microcircuits, microfluidics

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1. Introduction

The assembly of colloidal particles could be helpful for miniaturizing photonic and electrical circuits, as well as for their development in the third dimension.[1] Developments in this field of creating miniaturized electrically functional structures include the synthesis of electronic elements by templated growth in membrane channels,[2] and the formation of electrical connections through carbon annotates, etc.[3–5] Many kinds of semiconductor nanowires have been synthesized by chemical or electrochemical growth, which is promising for micro-electromechanical system (MEMS) electronic devices. Microwires have also been designed and fabricated using microfluidic devices,[6] which are accurate and controllable. However, the connection and the interface of the small elements in microfluidic research are still a challenge.

Dielectrophoresis (DEP) is a powerful tool for meeting the above requirements, and it can selectively and accurately push the suspended bio-particles towards or away from the microelectrodes, and has been widely used in microfluidic systems to manipulate, transport, separate, and characterize bioparticles.[7–9] In theory, DEP is the controlled motion of uncharged polarizable particles in a non-uniform electric field. In a spatially non-uniform AC electric field, dielectric particles experience a translational force as a consequence of the interaction of the polarization of the particle induced by the electric field with the non-uniform electric field.[10] The resulting particle motion was termed DEP by Pohl.[11] When the particle experiences positive DEP, it moves toward the strong field region, which normally occurs on the electrode surfaces, while the negative DEP gives rise to the opposite situation.

Following the improvement on MEMS technology, microelectrodes with smaller characteristic dimensions were fabricated for DEP experiments in order to generate stronger electric field gradients, allowing the manipulation of small particles such as viruses or even proteins.[12,13] However, most of the literature has focused on nonconducting particles, and conducting particles or particles with a conducting surface have been investigated less.[14,15] Only recently has DEP been used to manipulate conducting particles, such as nanowire formation through gold nanoparticles by AC trapping[16] and the dielectrophoretic assembly of metallic particles to study induced charge electrophoresis.[17] Among the metallic particles, core-shell beads composed of dielectric cores coated with a variety of metals have attracted considerable attention because of their unique electrical, optical, mechanical, and magnetic properties.[18]

We first carried out a few AC electrokinetic experiments for gold-coated microspheres, and the results showed that the metallic microspheres experienced a strong DEP force compared with the insulating particles under the same conditions in a large frequency range (10 Hz–40 MHz).[7] In

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traditional work, based on the Maxwell–Wagner model prediction, the conducting particles should be governed by the positive DEP at low frequencies, but by negative DEP at high frequencies.[19] In essence, the behavior of metallic particles suspended in liquids should be affected obviously by the metal/electrolyte interfacial polarization, which can be reflected by the charged double layer at the interface. The RC time, T_{RC}, of the double layer is the time required to charge the double-layer capacitance through the resistance of the bulk electrolyte, and it is estimated to be $T_{RC} = a\varepsilon/\sigma\lambda$ (where σ is the liquid conductivity, ε the permittivity, λ the double layer thickness, and a the typical length of the particles). For frequencies much less than $\omega_{RC} = 1/T_{RC}$, the particle behaves as an insulator, and the electric field outside the particle is the sum of the applied field and the field of the induced dipole, with a direction opposite to the applied field (Fig. 1(a)). For frequencies much greater than $\omega_{RC} = 1/T_{RC}$, there is negligible induced charge quantity in the double layer and the electric field lines intersect the particle surface perpendicularly, and the particle behaves as a perfect conductor. The electric field outside the particle is the sum of the applied field and the field of an induced dipole that now lies in the direction parallel to the applied field (Fig. 1(b)). Therefore, the metallic microparticles can be attracted on the surfaces of the electrodes easily by positive DEP when the energized frequency is much larger than ω_{RC}.

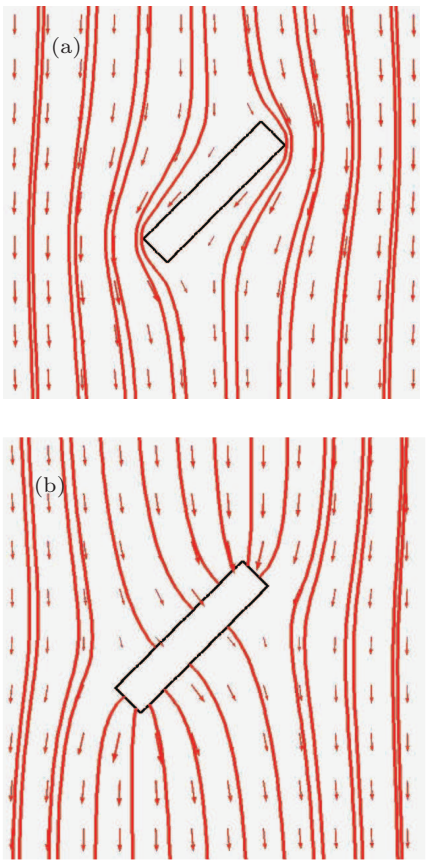


Fig. 1. (color online) The electric field lines in two cases: (a) $\omega \ll \omega_{RC}$ and (b) $\omega \gg \omega_{RC}$.

In the present paper, we extend the application of the metallic microspheres governed by the positive DEP force. The gold-coated SU-8 microrods are chosen as an analytical sample because of their perfect chemical activity, and the positive DEP is used to trap the gold-coated microrods between a pair of parallel electrodes. Moreover, gold is easy to be modified by chemical components, so the gold-coated microrods are coated by another insulating chemical layer in order to form different micro-circuits. Finally, the resistances of the different arrangements are studied each as a function of the number of parallel connections in the electrode gap.

2. Materials and methods

The experimental setup has a glass chip with fabricated microelectrodes, as shown in Fig. 2(a). The electrodes consist of two parallel electrodes of 0.5 mm in width, 2 mm in length, and 120 nm in thickness, while the distances between the electrodes are 50 μm and 20 μm, respectively. The electrodes themselves consist of a layer of gold sandwiched between two layers of titanium, because this metal resists corrosion in air or saline solutions very well.[20] A square PDMS chamber was constructed around the electrode array as a reservoir, and an AC signal was applied to the electrodes, using signal generators at 1 MHz, in order to avoid electrolysis.[21] An impedance analyzer was used to measure the impedance of the microcircuit after disconnecting with the signal generator. All the experimental data were obtained with an applied signal of 2 Vpp or 1 Vpp at a frequency of 1 MHz, with the electrode gaps being 50 μm and 20 μm, respectively.

The SU-8 microrods were fabricated using photolithographic methods similar to those in Ref. [22], and the sizes were 11 μm in diameter and 47 μm in length. The gold coating process started by functionalizing the surface of the particles with thiol groups. The 2-mg particles were resuspended in a solution of dimethyl formamide (DMF) and 30-mg cysteamine (30070, Sigma) for 4 h and then washed with DMF (6 × 1 ml). The amine group of cysteamine reacted with the unreacted epoxide rings present on the surface of the particles, thereby opening it and forming a covalent bond. After washing, the particles were resuspended in a solution of gold colloids prepared following Lim *et al.*[23] and gently shaken overnight. The particles were then washed carefully with deionized (DI) water to remove all the gold colloids not reacting with the thiol groups and therefore in solution. The decorated particles were spun down and the supernatant was replaced with a-200 μl plating solution composed of 34-mM gold (III) sodium thiosulfate (39741, Alfa Aesar) and 57-mM L-ascorbic acid (A5960, Sigma) in 1 ml of DI water. 20-μl 1-M NaOH was then added to trigger the reducing reaction of gold, and the

test tube was shaken for a few minutes. The end of the chemical reaction was indicated by the suspended particles changing color. The reaction was then quenched by adding 1-ml DI water and the supernatant was discarded and replaced with another 200-μl plating solution to repeat the previous step. The plating was repeated again with 200-μl and finally with 400-μl solution. A scanning electron microscope (SEM) image of the gold-coated SU-8 micro-rods is shown in Fig. 2(b). The thickness of the gold layer is estimated to be about 200 nm from the scanning electron microscope image. Figures 2(c) and 2(d) show the microscopic images of the native and gold-coated micro-rods, respectively.

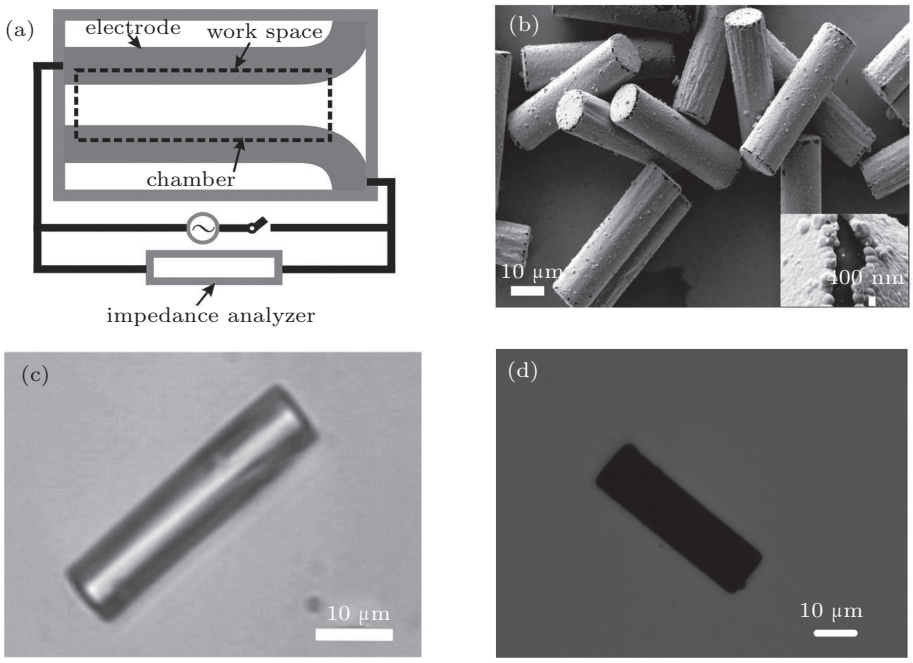


Fig. 2. The experimental set up (a), and the SEM images of gold-coated SU-8 micro-rods (b), the native micro-rod (c), and the gold-coated micro-rod (d).

In order to obtain different numbers of microwires between the electrodes, the position of the gold-coated SU-8 microrods in the electrode gap were adjusted using a laser trap. Although the laser could not go through these particles because of the metallic shielding on the surface, it could still push them away when the voltage was applied. Therefore, the microrods were aligned along the direction parallel to the electric field and stacked on the electrode surface immediately through the positive DEP force. This rapid formation of microcircuits was stable and controllable. After applying the voltage signal, the chip was heated using the microscope light in order to evaporate the suspending medium and measure the microcircuit impedance in the absence of the influence of the medium and the relative double layer. The micro-rods and electrodes stayed connected through Van der Waals forces. Once dry, the function generator was disconnected and replaced with the impedance analyzer, which performed the measurements by applying an AC signal of 0.1 V amplitude in a frequency range 1000 Hz to 10 MHz to the circuit.

3. Results and discussion

The microcircuits are formed using the two different electrode gaps via positive DEP force, consisting of one to four microwires. The chains formed by the gold-coated micro-rods in this system are analogous to a parallel circuit, while the impedances of different microcircuits are shown in Fig. 3. Different numbers of parallel chains are formed between the electrode gaps, and the length of the single connection is determined by the electrode gap, which is 20 μm (Fig. 3(a)) and 50 μm (Fig. 3(b)). The equivalent circuit formed by an arrangement of a certain number of micro-rods can be regarded as parallel impedances with a total impedance Z_s ($1/Z_s = \sum_{i=1}^{4} 1/Z_i$), with Z_i being the impedance of the single part. Since the gold-coated microrod distribution is homogeneous, the total impedance can be rewritten as $Z_s = Z_i/i$. The impedance of the system is measured in the dry state and the phase is 0° (the relevant data are not shown here), which means that the system can be treated as being composed of pure resistance elements. In Fig. 3(a), the gap between the electrodes is 20 μm, smaller than the length of one micro-rod, so the effective resistance length between the gaps is 20 μm, while

in Fig. 3(b), the 50-μm gap is bigger than the length of one micro-rod, leading to an overlap of the micro-wires between these electrodes.

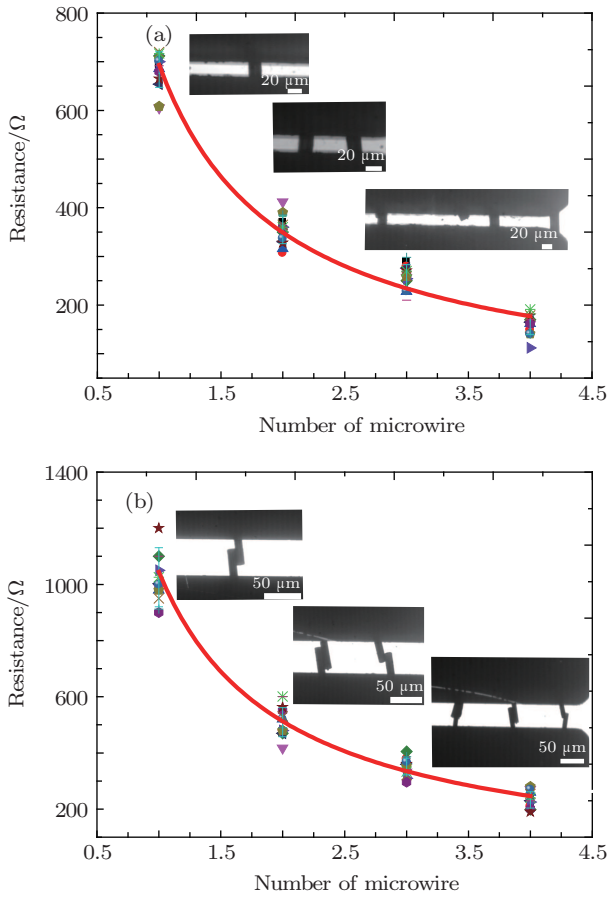


Fig. 3. (color online) The microwire resistances in the electrode gaps: (a) 20 μm and (b) 50 μm.

Sixteen measurements are taken for each kind of micro-wire arrangement in Fig. 3. The data are fit with the function $y = A/x$, where x, A, and y are the number of micro-wires, the value of the impedance of the single connection, and the total impedance of the system, respectively. The obtained values from the fitting are (688.6 ± 26.9) Ω for the 20-μm gap and (1064.2 ± 34.8) Ω for the 50-μm gap. The ratios between the gap and the impedance of the single connecting element are not the same, probably due to the overlap of the microrods, especially in the case of the rough surface of the gold-coated microrods.

Figure 4 shows the typical results for the micro-wire formation using 1H, 1H, 2H, 2H-perfluorodecanethiol functionalized gold-coated microrods within a 20-μm gap. Unlike the previous cases, the impedance magnitudes are always larger (>MΩ). In order to check the changes in the surface properties of these microrods, the impedance spectra for the native system (empty in the gap), one rod, and two parallel rods are measured, and the results are shown in Fig. 4. We do not expect the surfaces of the microrods functionalized using 1H, 1H, 2H, and 2H-perfluorodecanethiol to be conductive, so the microrods should only act as materials sandwiched between the two plates of capacitance, which can be fitted using a pure capacitance circuit. The capacitances for the above cases are (2.63 ± 0.5) pF, (4.39 ± 0.8) pF, and (9.11 ± 1.1) pF, respectively. The native system with no connection between the two electrodes has a low capacitance compared to the system with the microrod connections. The capacitance of the two microrods is roughly twice that of the one microrod, which is in accordance with the theoretical value of the parallel capacitance circuit.

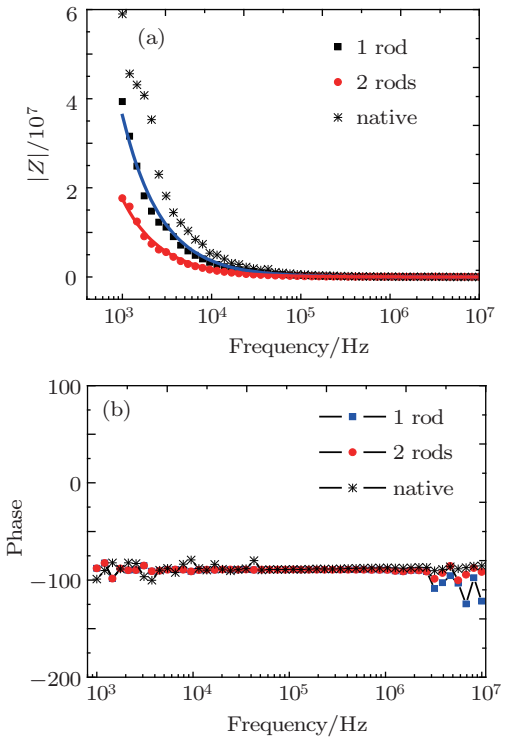


Fig. 4. (color online) (a) Impedances and (b) phase spectra of the system with electrodes connected by 1H, 1H, 2H, 2H-perfluorodecanethiol (CF3(CF2)7CH2CH2SH) fictionalized gold-coated microrods.

4. Conclusions

We demonstrate a simple method to control the formation of microwires using gold-coated SU-8 microrods via positive DEP. In order to detect the electrical properties of the microwires, the impedances of the resulting systems are measured and analyzed. We find that the gold-coated microrods can be strongly adsorbed on the surfaces of the electrodes by positive DEP because the metallic surface has a stronger polarization. For the detection results, the microrods act as pure resistors, while the microrods functionalized by a non-charged molecule behave as good capacitors. This research provides a powerful method for automatic microcircuit formation in microfluidic research.

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