The Effect of Electroosmotic Flow on the Dielectric Assembly of Nanowires

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Abstract. The assembly of nanowires is important to the manufacture of microelectronic components, and dielectrophoresis is a method of assembling nanowires with low cost, good operability, accurate positioning and high assembly efficiency. In this paper, a model of the dielectric assembly of nanowires in the microelectrode system is established, and the dielectrophoretic force and electroosmotic flow of the nanowires are analyzed, and the regulations of the dielectric assembly of nanowires is obtained. Based on the preparation of planar microelectrode pairs, the nanowire dielectric assembly experiment was performed. Through the analysis of the experimental results, the regulations of nanowire dielectric assembly are consistent with the simulation.

1. Introduction

With the development of integrated circuits and the increasing requirements for chip integration, the demand for miniaturization of electronic components has become increasingly urgent. Nanomaterials just meet this demand and have received widespread attention. Nanomaterials include nanoparticles, nanowires, nanofilms, nanobulks, and so on. Among them, nanowires have a wide range of applications in the field of microelectronics like flexible inorganic light emitting diodes, flexible UV photodetector and so on [1-3]. In order to improve the performance of the device, the assembly of nanowires is particularly important. There are many ways to assemble nanowires, including optical, acoustic, electrical and magnetic methods [4,5]. Among them, dielectric assembly of nanowires are widely used in laboratories due to the advantages of high positioning accuracy, easy operation, and high assembly efficiency [6].

In order to optimize the assembly results of nanowires, the dielectric assembly regulations of nanowires have been studied in depth. Among them, the dielectrophoretic force is the main driving force for the assembly of nanowires and is affected by parameters such as voltage peaks and driving frequency [7,8]. Under low frequency conditions, electroosmotic flow is also a factor that cannot be ignored [9]. Many nanowire assembly models have been established, and the force condition and movement trajectory of the nanowire can be calculated through the simulation method of finite element analysis. Yu et al. proposed a two-stage motion planning algorithm. The algorithm can minimize the total travel distance of multiple nanowires in a two-dimensional space [10].
In order to deeply explore the rules of dielectric assembly of nanowires, a planar microelectrode system was established. In order to build a flat microelectrode system, a flat microelectrode pair must be prepared first.

2. Process and experiment
As shown in Fig. 1, this experiment uses the lift-off stripping method to prepare the microelectrode system. First, spin-coated EPG533 photoresist on a substrate containing SiO₂, then expose, develop, sputter chromium and palladium, and then peel off to obtain the required microelectrode structure. z

![Figure 1. Process flow of lithography lift-off preparation of microelectrode system](image)

Then, connect the circuit and apply AC voltage across the electrodes. By changing the voltage and frequency, the relationship between the dielectric assembly of nanowires and the voltage and frequency is studied. The experimental circuit diagram is as follows:

![Figure 2. Schematic representation of the experimental setup](image)

3. Results and Discussion
3.1 The principle of dielectrophoresis to manipulate nanowires
For a nanotube or nanowire, both have cylindrical characteristics, the dielectrophoretic force is

$$ F_{dep} = \frac{\pi}{2} r^2 l \varepsilon_m Re \left( \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_m} \right) \nabla |E|^2 $$

(1)
r and l are the radius and length of ZnO nanowires, respectively. \( \varepsilon_m \) is the dielectric constant of the medium, \( E \) is the amplitude of the applied electric field. \( \varepsilon_p \) and \( \varepsilon_m \) are the complex permittivity of the nanowire and the medium, respectively [11]. The calculation is as follows:

\[
\varepsilon_p = \varepsilon_0 - j \sigma_p / \omega, \quad \varepsilon_m = \varepsilon_0 - j \sigma_m / \omega
\]

\( \omega \) is the angular frequency of time-harmonic excitation, \( \varepsilon_p = \varepsilon_0 \) and \( \varepsilon_m = 80 \varepsilon_0 \) represent the permittivity of nanowires and liquid media, \( \varepsilon_0 = 8.85 \times 10^{-12} \text{F/m} \) is the vacuum permittivity, \( \sigma_p = 0.01 \text{S/m} \) and \( \sigma_m = 0.004 \text{S/m} \) represent their electrical conductivity. The translation speed of the midpoint of nanowires is calculated as follows:

\[
v = \frac{F_{\text{dep}}}{f}
\]

The movement of the nanowire in the liquid medium will be affected by the drag force due to the flow of the liquid. It can be approximated by the average drag factor \( f \), which is calculated as follows:

\[
f = \frac{3 \pi \eta l}{\ln(l/r)}
\]

\( \eta = 0.001 \text{Pa} \cdot \text{s} \) is the dynamic viscosity of the fluid.

### 3.2 Three-dimensional dielectrophoresis assembly model

We use Comsol Multiphysics 5.3a multiphysics coupling simulation software to establish a three-dimensional conductive island microelectrode system model, as shown in Figure 3. In order to facilitate analysis and calculation, two cross-sections are selected. One is the symmetry plane, that is, the CS1 section; the other is the assembly plane, that is, the CS2 section.

![Figure 3. Three-dimensional dielectrophoresis assembly model. (a) the microelectrode system model; (b)CS1 section in red; (c) CS2 section in red.](image)

The calculation space of this model is 9.5\( \mu \text{m} \times 7\mu \text{m} \times 6\mu \text{m} \), the applied voltage amplitude is 10V, the AC frequency is 50kHz. In order to obtain the spatial distribution of the dielectrophoretic force, the electric field \( \mathbf{E} = -\nabla \varphi \) in the device should be solved. The charge conservation equation under the sinusoidal steady state is

\[
\nabla \cdot \left( (\sigma + j \omega \varepsilon) \nabla \varphi \right) = 0
\]

\( \varphi \) is the potential amplitude complex phasor. \( \varepsilon \) and \( \sigma \) are the permittivity and conductivity of the relevant calculation area [12]. This equation in the fluid needs to be solved. In order to calculate the electric double layer capacitance at the metal/electrolyte interface, the metal surface has RC boundary conditions:

(a) \( \sigma_m \mathbf{n} \cdot \nabla \varphi = j \omega C_{DL} (V - V_{\text{app}}) \) is applied on the electrode surface. \( C_{DL} \) is the dielectric capacitance, \( V_{\text{app}} \) is the voltage amplitude of the applied AC signal, and the two electrodes are specified to be 3V and 0V respectively;

(b) \( \sigma_m \mathbf{n} \cdot \nabla \varphi = j \omega C_{DL} (V - V_0) \) is applied to the surface of the conductive island. \( V_0 \) is the electric potential to the surface;

(c) On all insulating surfaces, it is considered that the normal direction has zero voltage flux, \( \mathbf{n} \cdot \nabla \varphi = 0 \).
3.3 simulation results

The nanowires were not fully polarized at 50kHz. A considerable part of the alternating potential difference applied between the electrodes fell in the shielding cloud of the metal/electrolyte interface diffusion layer. It led to the decrease of the dielectric trapping performance. As shown in Figure 4, although the above two factors limit the magnitude of the dielectrophoretic force, the nanowire is attracted to the electrode tip by the positive dielectrophoretic force. At the same time, the tangential component of the electric field exerted on the transient induced charge of the electric double layer diffused at the electrode/electrolyte interface produces a discontinuity of velocity, that is, the electroosmotic flow along the solid surface, which further causes the volume of the liquid to change through the viscosity effect.

![Figure 4. Dielectrophoresis flow velocity graph of nanowires on CS1 section (unit: 10⁻ m/s)](image)

As shown in Figure 5, at 50 kHz, a pair of counter-rotating micro vortices that induce convective flow of electroosmotic flow are induced in the electrode gap. Above the center of the electrode gap, the electroosmotic flow is induced to flow downward, then sweep across the metal surface, and finally form a closed convective vortex upward.

![Figure 5. Electroosmotic flow velocity curve on the CS1 section (unit 10⁻ m/s)](image)

Although the viscous drag force induced electroosmotic flow pulls the nanowire from the gap to the electrode tip, once the nanowire is transported to the electrode surface, due to the cooperation of the positive dielectrophoresis force and the electroosmotic flow induced by the gap area, the electroosmotic flow immediately becomes a repulsive force entraining the nanowires into the fluid (Figure 5). In other words, the effect of inducing electroosmotic flow depends on the spatial position of the nanowire, which
is consistent with the phenomenon that it is attracted by the positive dielectrophoretic force of the electrode in the electrode gap and repelled on the electrode surface.

Figure 6. Electroosmotic flow velocity curve on the CS2 section (unit m/s)

At the same time, the electroosmotic flow flows along the growth direction of the nanowires which tends to transport a large number of nanowires to the assembly area (Figure 6).

Figure 7. Frequency response curve of average electroosmotic flow velocity near the electrode tip

Figure 7 shows the frequency dependence of the average induced electroosmotic flow slip velocity on the surface near the electrode tip, which has a bell-shaped characteristic. Under the DC limit, most of the AC voltage falls on the double-layer capacitor, resulting in a negligible tangential electric field acting on the charged ions. When the field frequency is higher than the RC charging frequency, the ion charge relaxation process makes the counterion charge not have enough time to accumulate in the diffusion double layer in a single AC cycle, again resulting in no slip speed. Therefore, the ideal field frequency for driving the induced electroosmotic flow should be consistent with the characteristic relaxation frequency of the electric double layer dispersion process. The result of numerical simulation shows that the flow velocity has a peak value at 26kHz. At 1MHz, since the influence of the polarization of the electric double layer and the induced electroosmotic flow is small, along the direction of the electric field lines, a highly oriented nanowire with a line width of 100 nm can be obtained.

3.4 Experimental results

From the electron microscope photos of the nanowire assembly experiment, it can be seen that in the planar microelectrode pair system, the nanowires are assembled near the electrode gap. Most of the nanowires bridge the electrode tip and are parallel to the tangent direction of the electric field lines, and a few nanowires land on the electrode plane. When the assembly time is 100s, the number of nanowires
assembled is small and the positioning is poor. When the assembly time is 150s, the number of nanowires assembled increases, and some nanowires are poorly positioned. When the assembly time is 200s, the number of nanowires assembled further increases and the positioning is weaker.

![Figure 8. Electron microscope image of nanowire assembly (the scale is 3μm); (a) Assembly time is 100s; (b) Assembly time is 150s; (c) Assembly time is 200s.](image)

All in all, under low frequency conditions, due to the dual effects of dielectrophoretic force and electroosmotic flow, more nanowires are assembled to predetermined positions, and the assembly efficiency is higher, which is consistent with the analysis of the simulation results.

4. Conclusion
In order to study the dielectric assembly regulation of nanowires, this paper established a dielectric assembly model of nanowires in the microelectrode system. The simulation results of finite element analysis show that in addition to dielectrophoresis force, the driving force of nanowires, electroosmotic flow is also a factor that cannot be ignored. The size of the electroosmotic flow is affected by the spatial position of the nanowires. The magnitude of the electroosmotic flow is affected by the driving frequency, showing a trend of increasing first and then decreasing. The calculation and analysis of electroosmotic flow under low-frequency conditions is helpful to choose a more appropriate AC voltage and driving frequency to optimize the assembly process of the nanowires based on the consideration of the dielectrophoretic force. Based on the preparation of microelectrode pairs, the experiment of nanowire dielectric assembly was performed. The experimental results show that the assembly efficiency of nanowires is higher under low frequency conditions, which is consistent with the simulation results.

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