Dielectrophoresis Assembly of Nanowires in a Conductive Island-based Microelectrode System

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Abstract. Dielectrophoresis has attracted much attention in the field of nanowire assembly because of its high precision, high efficiency. However, the research on the mechanism related to the motion trajectory in the process of nanowire assembly is still in development. In this paper, a conductive island-based microelectrode system is reported to optimize the dielectric assembly process of nanowires. The existence of conductive islands can improve the positioning accuracy of nanowires during their assembly process. A simulation model of nanowire dielectric assembly based on the conductive island-based microelectrode system is established to analyze the dielectrophoresis force and motion trajectory of the nanowire during the assembly process. The simulation results show that the final position of the nanowire is mostly located in the gap between the electrode and the conductive island due to the dielectrophoretic force in the near field. Moreover, the nanowire has a tendency to move parallel to the tangent of the electric field line due to the action of the dielectrophoretic force. Therefore, the nanowire connects the electrode and the two ends of the conductive island in parallel.

1. Introduction
One-dimensional nanomaterials refer to materials with a diameter of less than 100nm and a length of up to millimeters. Inorganic nanowires in one-dimensional nanomaterials have extremely high application value in optoelectronics, sensing, and high-density storage [1]. In order to prepare nanowire-based application devices, the research on the assembly method of nanowires is a very important topic. There are many ways to assemble nanowires, including capillary force assisted method, physical template, molecular template [2], flow-assisted alignment, Langmuir-Blodgett assembly, bubble blown technique, electric/magnetic field directed assembly, contact/roll printing, knocking-down, etc.[3], while the manipulation of nanowires by the dielectrophoretic force has been widely used due to their high precision, high efficiency and strong adaptability.

The dielectrophoretic assembly of nanowires is affected greatly with experimental parameters such as voltage and frequency. Ding et al. found that as the frequency increases, the number of ZnO nanowires manipulated by dielectrophoresis decreases significantly at the same assembly time. When the AC frequency is 600kHz, only one nanowire is trapped between the microelectrode pairs [4]. In addition, compared with the traditional two-electrode DEP process, floating electrode dielectric electrophoresis (FE-DEP) provides better control in limiting the number of deposited nanowires, which is useful for the large-scale assembly of nanowires (NW) on silicon chips. Sachin K. Singh et al. estimated that the assembly method of floating electrode dielectrophoresis for a single NW deposition assembly in a large
array has a very high yield, about 87% [5].

In order to improve the assembly efficiency of nanowires and better control the positioning of nanowires, it is also important to study the movement trajectory during the assembly process of nanowires. Yaling Liu et al. found that when the ratio of gap size to NW length is 0.85-1.0 the DEP force becomes more great. The magnitude and sign of the DEP torque is influenced with this ratio, the orientation angle, the pattern of the electrode[6]. S D Berger et al. found through simulation research on carbon nanotubes, CNTs positioned directly above the electrode gap will bridge the electrodes. CNTs far from the gap contact a single electrode because of the near vertical electric field forces. They move towards the electrode gap after they contact [7]. In order to analyze the motion trajectory of nanowires and explore the related mechanisms in more depth, we used finite element analysis software (Comsol Multiphysics) to establish a three-dimensional nanowire assembly model, and calculated the force of the nanowires and analyzed the motion trajectory of the nanowires.

Junya Suehiro et al. used dielectrophoresis to assemble nanowires and found that the nanowires are trapped in the electrode gap where the electric field is stronger[8]. Yang Z et al. used the dielectrophoresis method to assemble ZnO nanowires on Au interdigital electrodes with different gaps and found that the dielectrophoresis method is flexible in manipulation[9]. Garcia NC et al. prepared a large-area array of photodetectors based on ZnO nanowires by precisely controlling the parameters of dielectrophoresis[10]. Guohua Jiang et al. used the dielectrophoresis method to assemble ZnO nanowires and adjusted the number of ZnO nanowires by changing the AC voltage[11]. Guo L et al. used the dielectrophoresis method to assemble a large number of ZnO nanowires parallel to each other in the interdigital electrode gaps[12]. In this paper, the dielectrophoretic force, electric heat flow and trajectory of the nanowires in the conductive island-microelectrode system are analyzed to study the assembly regulations.

2. Experiment Details
This experiment uses the lift-off 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. 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.

3. Results and Discussion

3.1 Experimental results

Figure 1. Electron microscope image of nanowire assembly with a voltage of 3V and a frequency of 150kHz (the scale is 2µm): (a) assembly time is 90s; (b) assembly time is 130s; (c) assembly time is 200s.

It can be seen from Figure 1(a) that when the peak voltage is 10V and the AC frequency is 150kHz, a small amount of nanowires are trapped in the gap between the left electrode and the conductive island within 30s of the start of the assembly time. The simulation results of the flow coincide. The nanowire is subjected to the dielectrophoretic force to connect the electrode and the conductive island. Due to the higher potential on the left, the greater the dielectrophoretic force and the greater the speed, so the nanowires will be captured earlier than the gap on the right. From the direction of the nanowire, it can
be seen that the nanowire connects the electrode and the conductive island in parallel, which is consistent with the simulation results. The nanowire is subjected to the dielectrophoretic force and has a tendency to move parallel to the tangent of the electric field line. The electric field lines between are almost parallel to the X axis, so they are neutral, that is, the nanowires are parallel to the two ends of the electrode and the conductive island.

It can be seen from Fig. 1(b) that as the assembly process progresses, as of 120s, some nanowires are assembled into the gap between the two electrodes and the conductive island, and it can be seen that the nanowires still maintain their neutrality. By the end of 150s, more nanowires have been assembled into the gap between the electrode and the conductive island, still maintaining their neutrality, as shown in Figure 1(c).

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. The calculation space of this model is 14.6μm*10μm*8μm, the applied voltage amplitude is 3V, the AC frequency is 150kHz. In order to calculate the electric double layer capacitance at the metal/electrolyte interface, the metal surface has RC boundary conditions:

(a) \[ \sigma_f \mathbf{n} \cdot \nabla V = j \omega C_{DL} (V - V_{app}) \]  
(b) \[ \sigma_f \mathbf{n} \cdot \nabla V = j \omega C_{DL} (V - V_0) \]  
(c) On all insulating surfaces, it is considered that the normal direction has zero voltage flux, \( \mathbf{n} \cdot \nabla V = 0 \).

3.3 Simulation results

In order to facilitate the analysis of the dielectrophoretic assembly process of the nanowires, a few specific cross sections are selected in the assembly model, including symmetry plane as called CS1, a plane parallel to the YZ plane and passing through the midpoint of the connection between the tip of the left electrode and the tip of the conductive island as called CS2, a plane parallel to the YZ plane and passing through the midpoint of the connection between the tip of the right side electrode and the tip of the conductive island as called CS3 as shown in Fig.2.

Figure 2. Electric potential and electric field line distribution: (a) Conductive island microelectrode system; (b) CS1; (c) CS2; (d) CS3.
As shown in Figure 2, we analyzed the experimental model and the electric field line and potential distribution of a specific section. In the conductive island microelectrode system, due to the use of triangular electrodes in the experiment, the electrode tip has a stronger singularity of electric field modulation. The electric field lines near the two electrodes are denser and the field strength is higher. As the center of the gap moves, the intensity of the electric field gradually weakens, and the weakest when it reaches the center point.

![Image](image.png)

Figure 3. (a) Dielectrophoretic force distribution of CS1 (Unit: m/s); (b) Dielectrophoretic force distribution of CS2 (Unit: m/s); (c) The electric heat flow distribution of CS1; (d) The electric heat flow distribution of CS3.

It can be seen from Fig. 3(a) that the nanowires on the CS1 are affected by the dielectrophoretic force, which will move towards the direction of the conductive island, and the upper nanowires will move downwards and fall to the electrode plane and conductive island plane. The nanowire above the conductive island will also move to both ends, and finally the nanowires connect the gap between the electrode and the conductive island. From Fig. 3(b), it can be seen that the nanowires on both sides of the Y-axis direction will also move toward the gap between the conductive island and the electrode due to the dielectrophoretic force. It can be seen from Fig. 3(c) that the nanowires on the symmetry plane will be assembled into the gap between the electrode and the conductive island, like a vortex, being rolled into the gap under the action of electric heat flow. It can be seen from Fig. 3(d) that the nanowires on the two assembly surfaces will be assembled into the area of the system where the electric field is stronger due to the electric heat flow.

As shown in Fig. 4, we analyzed the translational motion trajectory of the nanowire from a specific position, that is, the motion trajectory of its midpoint. It can be seen that the nanowires are assembled into the gap between the electrode and the conductive island under the action of the dielectrophoretic force. The nanowire on the far left is far away from the gap and has a lower release height. It first contacts the electrode surface and then is assembled into the gap between the electrode and the conductive island. The nanowires above the gap will also be assembled into the gap. The nanowire on the far right also first contacts the surface of the right electrode, and then is assembled into the gap between the right electrode and the conductive island.
4. Conclusion

Dielectrophoresis to manipulate nanowires is a good way to achieve precise positioning of nanowires. The existence of conductive islands can increase the Schottky base and enable the nanowires to be positioned more accurately. Through simulation research, we found that the nanowires tend to move parallel to the tangent of the electric field line during the process of falling and assembling under the dielectrophoretic force. When the end position of the nanowire falls into the gap between the electrode and the conductive island, it appears to bridge the two ends of the electrode and the conductive island laterally.

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