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Selective Manipulation of ZnO Nanowires by Controlled Dielectrophoretic Force

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***Abstract* — Zinc oxide (ZnO) nanowire has wide applications in optoelectronics, chemical sensing, and photovoltaics because of its unique mechanical and electrical properties. In order to manipulate ZnO nanowires, some researchers have tried to align them by dielectrophoretic (DEP) force. The traditional analysis of DEP force on nanowires is only limited to a special case when the electrical field is uniform with the nanowires. In this paper, we propose a more comprehensive method that could be applied to general cases. Simulation studies are also performed to evaluate the influences of different parameters. We find that by controlling the frequency of the electric field, ZnO nanowires can be selectively aligned to the electrodes.**

Index Terms – Dielectrophoresis, Zinc oxide, Nanowires, Nanomanipulation

I. INTRODUCTION

Zinc oxide (ZnO) nanowire is a promising nanoscale material that has been widely used in nanotechnology applications due to its attractive mechanical and electrical properties. Specifically, ZnO nanowire is a promising candidate for field-effect transistors (FET) applications in optical electronics because of its particular advantages in piezoelectricity and pyroelectricity as well as a large direct band gap of 3.3 eV [1]. Recently, people have performed extensive research in the electronic properties of the ZnO nanostructures such as ZnO nanoparticles and nanowires. One of the most critical steps for the optoelectronic applications is to manipulate and align the ZnO nanowires/nanobelts [2, 3].

Currently, some researchers tried to use dielectrophoresis (DEP) [4] forces to manipulate ZnO nanowires. By introducing a non-uniform electric field, the nanowires can be manipulated by the electrical polarization forces. A lot of experiments have been implemented to demonstrate the feasibility of this method. It is revealed that the orientation of the nanowires strongly depends on the magnitude and the frequency of the applied electric field [2, 3]. By using DEP to align ZnO nanobelts/nanowires, C. S. Lao *et al* were able to fabricate rectifying diodes of single nanobelt/nanowire-based devices [2].

Unfortunately, so far most studies on manipulation of ZnO nanowires mainly focus on experiments. There is a lack of comprehensive theoretical and simulation study on manipulation of ZnO nanowires in general cases to provide useful guidance in real applications.

DEP is the electric field force that a dielectric particle receives when it is placed in a non-uniform electric field. ZnO nanowires can be treated as a cylindrical shaped particle with much longer length and relative small diameter. Morgan made significant contributions to the research on the DEP force on cylindrical particles [5]. Assuming a nanowire with radius r and length l inside a non-uniform electric field is placed along the direction of the electric field, the DEP force it receives can be expressed as [5]:

$$\mathbf{F}_{\mathrm{DEP}} = \frac{\pi r^2 l}{6}\varepsilon_m \,\mathrm{Re}\{\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_m^*}\}\underline{\nabla}\mathbf{E}^2 \qquad (1)$$

where $\mathbf{E}$ is the electric field, and ε_m^* and ε_p^* are the complex permittivities of the medium and particles, respectively. The complex permittivity can be defined as:

$$\varepsilon^* = \varepsilon - i\frac{\sigma}{\omega}$$

where σ is the electric conductivity, and ω is the angular frequency.

However, Equation (1) is only correct when the direction of the electric field is along the axis of the nanowire. When the electric field is perpendicular to the length of the cylinder [6, 7], the DEP force becomes:

$$\mathbf{F}_{\mathrm{DEP}} = \pi r^2 l\,\mathrm{Re}\{\frac{\widetilde{\varepsilon}_m(\varepsilon_p^* - \varepsilon_m^*)}{\varepsilon_p^* + \varepsilon_m^*}\}\underline{\nabla}\mathbf{E}^2 \qquad (2)$$

where $\widetilde{\varepsilon}_m$ is the complex conjugate of ε_m^*, defined as $\widetilde{\varepsilon}_m = \varepsilon_m + i\frac{\sigma_m}{\omega}$.

Most time, however, the electric field is neither along nor perpendicular to the axis of the nanowire. Moreover, it is assumed in Equation (1) and (2) that the electric field around the whole nanowire is nearly uniform. In the research on ZnO nanowire manipulation, this assumption is not reasonable, since the size of the nanowire is often near the size of the gap between electrodes and non-uniformity is unavoidable. Therefore, the exact DEP force applied on nanowires is much complicated and deserves further investigation.

Noticing the limitations of directly following Morgan and Pohl's work to analyze the DEP force on ZnO nanowires, in this paper, we study a more general case and propose a comprehensive modeling method to calculate the exact force on ZnO nanowires. Detailed simulation is provided to verify the theoretical analysis. Through the simulation study, we found that the DEP force is determined by the dielectric properties of the suspension medium and the nanowire, the position and orientation of the nanowire, and also the magnitude and frequency of the applied electric field. Moreover, by controlling the frequency of the electric

field, the ZnO nanowires with different conductivities can be selectively aligned to the electrodes.

II. MODELING

The analytical expression proposed by Morgan has been widely used in the analysis of DEP force on cylindrical particles like ZnO nanowires. However, Equation (1) is limited to the situations when (i) the rod is small enough that the electric field in the vicinity could be treated as uniform one; (ii) the length of the rod is parallel to the direction of the electric field. These situations are seldom true in real applications. Therefore, a more comprehensive DEP force expression is needed for more general cases.

In order to calculate the force on the cylinder inside a non-uniform electric field, a handy method is to divide the whole rod into a lot of small cylinders such that the electric field around each small cylinder is considered to be uniform. A composition of the net forces on each small cylinder gives the total DEP force on the whole rod.

Assuming the acute angle between the axis of a small cylinder and the direction of the electric field in the vicinity is θ, as shown in **Fig. 1**. The electric field **E** can be decomposed into two parts $\mathbf{E_1}$ and $\mathbf{E_2}$, which are parallel to and perpendicular to the length, respectively. Obviously, this orthogonal decomposition implies $|\mathbf{E_1}| = \mathbf{E}\cos\theta$, and $|\mathbf{E_2}| = \mathbf{E}\sin\theta$. The DEP force induced by the total electric field **E** is equivalent to the composition of the two forces produced by $\mathbf{E_1}$ and $\mathbf{E_2}$, respectively.

Following previous analysis, the DEP force produced by the electric field $\mathbf{E_1}$ can be written as:

$$\begin{aligned}\mathbf{F}_1 &= \frac{\pi r^2 l}{6}\varepsilon_m \,\mathrm{Re}\{\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_m^*}\}\underline{\nabla}\mathbf{E}_1{}^2 \\ &= \frac{\pi r^2 l}{6}\varepsilon_m \,\mathrm{Re}\{\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_m^*}\}\underline{\nabla}|\mathbf{E}_1|^2 \\ &= \frac{\pi r^2 l}{6}\varepsilon_m \,\mathrm{Re}\{\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_m^*}\}\underline{\nabla}\left(|\mathbf{E}|\cos\theta\right)^2. \end{aligned} \quad (3)$$

Since θ does not depend on the location vector, cosθ is able to be taken out of the gradient $\underline{\nabla}$ operator, simplifying the above equation to:

$$\mathbf{F}_1 = \frac{\pi r^2 l}{6}\varepsilon_m \cos^2\theta \,\mathrm{Re}\{\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_m^*}\}\underline{\nabla}\mathbf{E}^2. \quad (4)$$

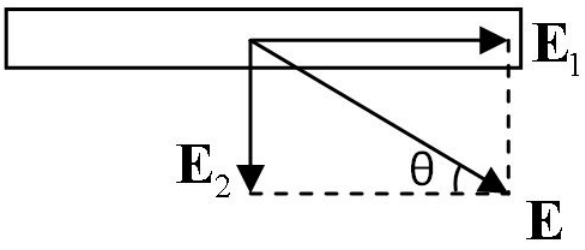

Fig. 1. The decomposition of the electric field.

Similarly, the DEP force generated by the electric field $\mathbf{E_2}$ has a form:

$$\mathbf{F}_2 = \pi r^2 l \sin^2\theta \,\mathrm{Re}\{\frac{\tilde{\varepsilon}_m(\varepsilon_p^* - \varepsilon_m^*)}{\varepsilon_p^* + \varepsilon_m^*}\}\underline{\nabla}\mathbf{E}^2. \quad (5)$$

The directions of both $\mathbf{F_1}$ and $\mathbf{F_2}$ are determined by the direction of $\underline{\nabla}\mathbf{E}^2$. Thus, the composition of $\mathbf{F_1}$ and $\mathbf{F_2}$ gives the net force on the small cylinder:

$$\mathbf{F} = \pi r^2 l \underline{\nabla}\mathbf{E}^2\left[\frac{\varepsilon_m}{6}\cos^2\theta \,\mathrm{Re}\{\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_m^*}\} + \sin^2\theta \,\mathrm{Re}\{\frac{\tilde{\varepsilon}_m(\varepsilon_p^* - \varepsilon_m^*)}{\varepsilon_p^* + \varepsilon_m^*}\}\right] \quad (6)$$

The vector summation of the forces on each small cylinder produces the net force on the whole rod.

III. SIMULATION AND RESULTS

To obtain more insights on the DEP force theory, intuitive and convincible simulation is needed. The ZnO nanowires investigated herein have radius of 30 to 50 nm and length of 2 to 3 μm that is fabricated by chemical synthesis [8]. The permittivity ε_p of ZnO nanowires is about $2\varepsilon_0$ to $5\varepsilon_0$, where ε_0 is the vacuum permittivity. Since ZnO nanowires will degrade in water, organic solvents (isopropanol) are used as the suspending medium. Under room temperature, isopropanol has a conductivity of 3.5×10^{-4} *S/m* and a permittivity of $30\varepsilon_0$. We simulated the electric field based on Ansoft Maxwell software and calculated the DEP force in MATLAB. The non-uniform electric field is created by designing a pair of electrodes, as shown in **Fig. 2**. Two electrodes are symmetrically aligned on the X axis. The distance between the two electrodes is 1 μm. The AC voltage excitations are applied on both electrodes; while the phase difference between the two excitations is maintained to be 180° constantly. The effective value of the excitations is 5 V, and the frequency of the excitations can be set arbitrarily. Under this design, there should be a non-uniform electric field in space. Ansoft Maxwell enables us to export the data of both the electric field **E** and the gradient of the square of the electric field $\underline{\nabla}\mathbf{E}^2$ at each point in space. To simplify the problem, we equally divided the ZnO nanowire (radius: 30 to 50 nm, length: 2 to 3 μm, conductivity: 0.1 *S/m*) into 10 small cylinders along the length of the nanowire and assumed that the electric field around each small cylinder is almost uniform. Consequently, for the nanowire at any location and with any orientation, the DEP force can be calculated following the modeling in Section II.

Due to the symmetric property of this design, we only calculate the DEP force when the nanowire is placed in the bottom half of the plane as shown in **Fig. 2**. Moreover, to simplify the problem, we assumed that the core of the nanowire is on the Y axis. However, the location and orientation of the nanowire can be defined arbitrarily. We consider the two cases when the core of the nanowire is at the positions (0,-3 μm) and (0,-5 μm), respectively. The angles between the rod and positive X axis investigated are 0°, 30°, 45°, 60°, and 90°. The frequency of the electric field is set to be 1 MHz. The simulated result is shown in **Table I**.

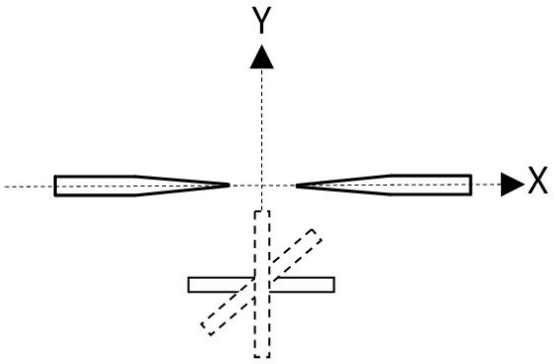

Fig. 2. The electrode design to generate a non-uniform electric field.

TABLE I: COMPARISON OF DEP FORCES

(1) FREQUENCY = 1MHZ, LOCATION (0,-5)

Angle (orientation of the rod)	F(pN)	Angle (orientation of the DEP force)
0°	0.542	91.2°
30°	0.613	98.5°
45°	0.631	94.3°
60°	0.651	96.2°
90°	0.675	89.6°

(2) FREQUENCY = 1MHZ, LOCATION (0,-3)

Angle (orientation of the rod)	F(pN)	Angle (orientation of the DEP force)
0°	2.43	93.9°
30°	3.06	100.8°
45°	3.20	98.4°
60°	3.28	102.2°
90°	3.56	87.2°

When the angle between the rod and the positive X axis changes from 0° to 90°, that is, the rod rotates from the horizontal position to the vertical orientation, the DEP force that the nanowire receives also increases. This is because when the rod is closer to the vertical orientation, the electric field in the vicinity tends to be more non-uniform, which gives larger value in $\underline{\nabla}\mathbf{E}^2$. However, this increment is not very significant, which implies that DEP force is not so sensitive to the orientation of the nanowire at a fixed position. When the angle between the rod and the positive X axis is 0° or 90°, that is, the nanowire is symmetrically placed across Y axis, the direction of the force on the nanowire is nearly parallel to the positive Y axis direction, which is reasonable because of the symmetric distribution of electric field around the nanowire. Therefore, the nanowire under these two cases tends to be attracted to the electrodes directly. For the nanowire with an orientation other than horizontal or vertical, it does not receive a straight vertical DEP force, which is supposed to generate rotations when the nanowire is attracted to the electrodes due to the torques introduced by the DEP force. Nonetheless, the orientation of DEP force is close to 90°. Hence, the nanowire receives positive DEP force and will be attracted to the electrodes. Moreover, the force that the nanowire receives at position (0,-3) is much larger than that at location (0,-5). The reason is the electric field at the position closer to the electrodes is stronger and more non-uniform.

Besides the location and orientation of the nanowire, the DEP force also depends on the frequency of the electric field and the electric conductivity of ZnO nanowires. To better evaluate the effects of the frequency and the conductivity, the position and orientation of the nanowire is supposed to be fixed. Specifically, we consider ZnO nanowires locate at (0,-5) with an orientation of 0°.

As a semiconductor, the conductivity of ZnO nanowire is very small and variant depending on the temperature and its impurity. Hence, in order to recognize how the DEP force is affected by the conductivity of the ZnO nanowires, a series of value of ZnO conductivity are chosen for comparison. The DEP forces on ZnO nanowires with different conductivities are plotted versus the frequency ranging from 10 kHz to 10 GHz in **Fig. 3**. The inner plot is a zoom in view from 10 MHz to 1000 MHz, which shows the crossover effect. The DEP force can be either positive (attractive force) or negative (repulsive force). At low frequencies, the DEP force is positive and strong enough (at the order of $10^{-11}N$) to attract ZnO nanowires to the electrodes. As the frequency raises, the DEP force decreases and exhibits a crossover from positive to negative (repulsive), which is similar to the observation of Krupke on semiconducting single-walled carbon nanotubes [9]. Larger frequencies lead the DEP force converging to a negative value (at the order of $10^{-13}\ N$). Moreover, the DEP force is affected by the electric conductivity of the ZnO nanowires. ZnO nanowires with lower conductivity receive smaller attractive DEP force at low frequencies. Besides, it is much easier to repel ZnO nanowires with lower conductivity by increasing the frequency of the applied electric field.

Since the DEP force applied on ZnO nanowires changes with respect to their conductivity and the frequency of the electric field, it is able to manipulate and align ZnO nanowires according to their conductivity or to directly measure the conductivity according to the frequency turning point at which the DEP force changes from negative to positive. For example, an electric field at low frequency (10kHz) is sufficient to attract the mixture of nanowires with different conductivities to the electrodes. If we want to separate ZnO nanowires that have conductivities larger than 0.1 *S/m* from ZnO nanowires with conductivity smaller than 0.05 *S/m*, a non-uniform electric field with a threshold frequency can be used. ZnO nanowires that has conductivity less than 0.05 *S/m* will be repelled away, while those have conductivity larger than 0.1 *S/m* are supposed to be attracted to the electrodes. Moreover, multi-stage manipulation is able to select ZnO nanowires of specific conductivity. For instance, if we want to select nanowires with a conductivity of 0.3 *S/m* (black curve in the plot), an electric field with threshold frequency near 110MHz is able to only attract the nanowires with conductivity larger than 0.5 *S/m* and repel other nanowires. A second-stage electric field with another threshold frequency at 100MHz is supposed to attract nanowires with conductivity of 0.3 *S/m* to the electrodes. Furthermore, by starting at a high frequency, the turning

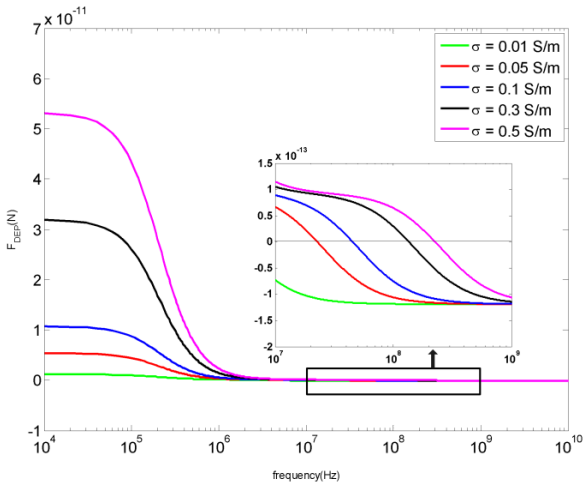

Fig. 3. The DEP force vs. frequency.

frequency can be obtained by monitoring the deposition of nanowires on the electrode when gradually reducing the frequency. The conductivity of the deposited nanowire can be derived from this turning frequency. Because the conductivity of ZnO nanowire is dictated by their doping levels, the DEP force can also be applied to separate ZnO nanowires with different doping levels, or to directly measure the doping concentration.

IV. Conclusion

In this paper, we investigated the method of using DEP force to manipulate ZnO nanowires and provided the theoretical analysis for this method. We started from the fundamentals of DEP and focused on Morgan's equation of the DEP force on a cylindrical shaped nanowire. This method has some limitations since it assumes the electric field in the vicinity is almost uniform and only considers the case when the direction of the electric field is parallel to the length of the cylinder. To apply the DEP force method to a more general case, we proposed a more comprehensive analysis by dividing the nanowire to a lot of small cylinders and orthogonally decomposing the electric field. Moreover, we calculated the DEP forces that ZnO nanowires receive in a non-uniform electric field produced by a pair of electrodes through simulation study. Guided by the simulation work, we also realized the significance of the frequency of the electric field and the conductivity of ZnO nanowires. By controlling the frequency of the electric field, we were able to selectively manipulate ZnO nanowires of different conductivities.

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References

[1] M. S. Arnold, P. Avouris, Z. W. Pan, and Z. L. Wang, "Field-effect transistors based on single semiconducting oxide nanobelts", *J. Phys. Chem. B*, 107, pp. 659-663, 2003 .

[2] C. S. Lao, J. Liu, P. Gao, L. Zhang, D. Davidovic, R. Tummala, and Z. L. Wang, "ZnO nanobelt/nanowire Schottky diodes formed by Dielectrophoresis alignment across Au electrodes", *Nano Letters,*0vol. 6, no.2, pp. 263-266, 2006.

[3] J. Suehiro, N. Nakagawa, S. Hidaka, M. Ueda, K. Imasaka, M. Higashihata, T. Okada, and M. Hara, "Dielectrophoretic fabrication and characterization of a ZnO nanowire-based UV photosensor", *IOPscienc, Nanotechnology 17*, pp. 2567-2573, 2006.

[4] Pohl, *Dielectrophoreis* (Cambridge University Press, London, 1978).

[5] H. Morgan, N. G. Green, "Dielectrophoretic manipulation of rod-shaped viral particles", *Journal of Electrostatics*, vol. 42, pp. 279-293, 1997.

[6] H. A. Pohl, K. Pollock, J. S. Crane, "Dielectrophoretic force: a comparison of theory and experiment", *Physical Biological Science*, vol. 6, pp. 133-159, 1978.

[7] H. A. Pohl, R. Pethig, "Dielectric measurements using non-uniform electric field (dielectrophoretic) effects", *Journal of Physics E: Scientific Instruments*, vol. 10, pp. 190-193, 1977.

[8] C. Xu, P. Shin, L. Cao, and D. Gao, "Preferential growth of long ZnO nanowire array and its application in dye-sensitized solar cells", *The Journal of Physical Chemistry C,* vol. 114, pp. 125-129, 2009.

[9] R. Krupke, F. Hennrich, M. M. Kappes, and H. V. Lohneysen, "Surface conductance induced dielectrophoresis of semiconducting single-walled carbon nanotubes", *Nano Letters*, vol. 4, no. 8, pp. 1395-1399, 2004.