

# Dielectrophoretic assembly of ZnO nanowires

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The synthesis of zinc oxide (ZnO) nanowires is achieved by vapor phase transportation (VPT) method. The designed quartz tube, whose both ends are narrow and the middle is wider, is used to control the growth of ZnO nanowires. Dielectrophoresis (DEP) method is employed to align and manipulate ZnO nanowires which are ultrasonic dispersed and suspended in ethanol solution. Under the dielectrophoretic force, the nanowires are trapped on the pre-patterned electrodes, and further aligned along the electric field and bridge the electrode gap. The dependence of the alignment yield on the applied voltage and frequency is investigated.

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In recent years, one-dimensional (1D) nanostructure such as nanowires<sup>[1,2]</sup>, nanorods<sup>[3,4]</sup>, and nanobelts<sup>[5]</sup> have been intensively investigated for nanodevice applications due to their fascinating distinctive features. It is a challenge to manipulate and align these semiconductor nanostructures effectively and further construct nanodevices with low price. Stable connection to the nanostructures is essential to achieve such nanoscale devices, and thus several methods have been developed to assemble nanostructures onto electrodes<sup>[6–8]</sup>. Among them, dielectrophoretic assembly<sup>[9,10]</sup> in a fluid offers the possibility of convenient and effective alignment of nanostructures across opposing electrodes. Dielectrophoresis (DEP) method offers the room-temperature fabrication with rapid assembly of nanowires. DEP has been used to manipulate nanostructures such as carbon nanotubes<sup>[11]</sup>, Ni nanowires<sup>[12]</sup>, CdS nanowires<sup>[13]</sup>, GaN nanowires<sup>[14]</sup>, and ZnO nanowires<sup>[15]</sup>.

Among the wide range of 1D semiconductor materials, the 1D nanostructure of semiconductor ZnO nanowires<sup>[16]</sup> has aroused great interests because of its unique properties including direct wide band gap (3.37 eV) and large exciton-binding energy (60 meV) at room temperature. In this letter, DEP manipulation of ZnO nanowires, which are synthesized by vapor phase transportation (VPT) method, is demonstrated. The DEP-trapped ZnO nanowires are aligned along the electric field line and bridge the electrode gap. The dependence of the alignment yield on the applied alternating current (AC) voltage and frequency is investigated by varying the frequency.

When the ZnO nanowire is placed in an AC electric field, the large dipole moment is induced in the nanowire due to its high aspect ratio and the ZnO nanowire experiences the DEP force, which directs the ZnO nanowires to align, assuming damping or viscous forces on ZnO nanowire to be negligible compared with the dielectrophoretic force. The DEP force equation for long cylindrical nanowires can be written as

$$\mathbf{F}_{\text{DEP}}(t) = [\mathbf{p}(t) \cdot \nabla] \mathbf{E}(t), \quad (1)$$

where  $\mathbf{F}_{\text{DEP}}(t)$  is the time dependent dielectrophoretic

force experienced by the particle,  $\mathbf{p}(t)$  is the induced dielectric moment vector, and  $\mathbf{E}(t)$  is the time-varying applied electric field. The dipole moment vector, for simple case where the body is isotropically, linearly, and homogeneously polarizable, depends on the applied electric field as

$$\mathbf{p}(t) = \alpha V \mathbf{E}(t), \quad (2)$$

where  $\alpha$  is the polarizability tensor for the particle and  $V$  is the total volume of the particle. It can be shown that the time-averaged DEP force is given by<sup>[17,18]</sup>

$$\mathbf{F}_{\text{DEP}} = \Gamma \epsilon_m \text{Re} \{ K(\epsilon_{\text{ZnO}}^*, \epsilon_m^*) \} \nabla \mathbf{E}^2, \quad (3)$$

where  $\Gamma$  is a geometrical factor;  $\epsilon_{\text{ZnO}}^*$  and  $\epsilon_m^*$  are complex dielectric permittivities of the ZnO nanowire and the solvent medium, respectively;  $K(\epsilon_{\text{ZnO}}^*, \epsilon_m^*)$  represents the complex polarization factor (for spherical objects, this is known as Clausius-Mossotti function);  $\mathbf{E}$  denotes the applied AC field. For a nanowire of length  $l$  and radius  $r$ , the geometrical factor  $\Gamma$  is given by

$$\Gamma = \frac{\pi r^2 l}{6}.$$

For a cylindrical object, the complex polarization factor is given by

$$K(\epsilon_{\text{ZnO}}, \epsilon_m) = \frac{\epsilon_{\text{ZnO}}^* - \epsilon_m^*}{\epsilon_m^*}. \quad (4)$$

Figure 1 schematically explains the working principle of the dielectrophoretic alignment of the nanowires. When the ZnO nanowire suspension is dispersed on a sample with a voltage applied between two metal pads, the divergent electric field interacts with the induced electric dipole moment of the nanowire. The DEP force experienced by the nanowire is normal to the sample surface. In the case of a positive DEP force determined by the difference in the dielectric permittivities of the nanowire and the dispersing medium, the nanowire will be attracted towards the pads and eventually settle down

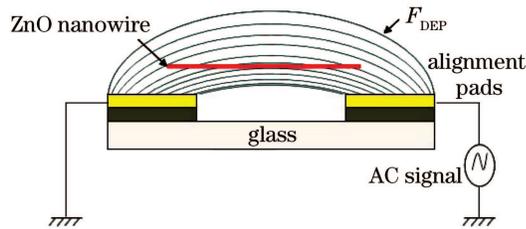


Fig. 1. Schematic representation of the dielectrophoretic alignment of ZnO nanowires.

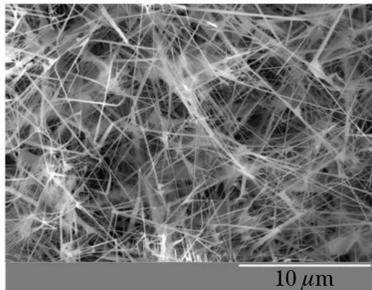


Fig. 2. SEM image of ZnO nanowires synthesized by VPT process.

on the pads with the complete evaporation of the solvent.

ZnO nanowires were synthesized in a traditional horizontal furnace by a simple VPT process<sup>[19]</sup>. The designed quartz tube, whose both ends are narrow and the middle is wider, was used to control the growth of ZnO nanowires. The Zn source was metal zinc powder (99.99%), which was loaded into a quartz boat. The quartz boat was put in one end of the inner quartz tube. A Si (100) substrate was laid in the other end of the inner quartz tube. The horizontal distance between the Si substrate and the Zn source was about 20 cm. The furnace was ramped to 710 °C under a constant flow of Ar and O<sub>2</sub> gas with the flow rates of 150 and 15 sccm, respectively. As shown by the scanning electron microscope (SEM) image in Fig. 2, this synthesis method could produce ZnO nanowires.

The model in Fig. 3 was designed to implement the assembly of process. Standard photolithography was carried out, following the metal deposition of Au/Cr (100 nm/50 nm) on the glass substrate. The final structure is shown in Fig. 4. Interdigitated electrodes were used to form high and low electric field regions periodically. These pads not only serve as alignment electrodes but also act as bottom contacts for the nanowires. Cr thin film was coated on the glass to enhance the adhesion between Au and glass. The gaps between electrodes vary from 5 to 10 μm, because the DEP force reaches a maximum when the ratio of gap size to nanowire length is in

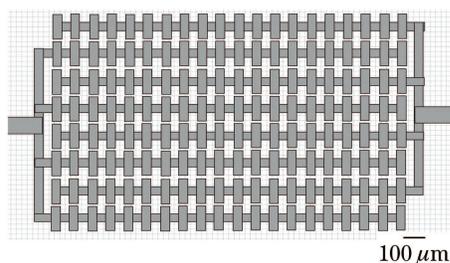


Fig. 3. Designed model consisting of interdigitated electrodes.

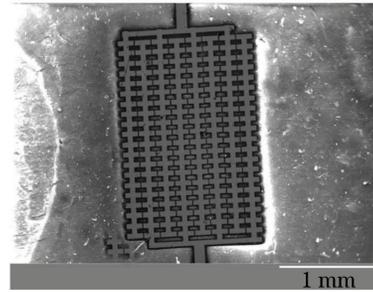


Fig. 4. SEM image of alignment Au pads on glass substrate.

the range of 0.85 – 1.0<sup>[20]</sup>.

The Si substrate, on which ZnO nanostructures were deposited by VPT, was immersed in ethanol and sonicated for 15 min using short ultrasound pulses. The ZnO nanowires peeled off from the substrate to disperse in ethanol, and then the large debris particles were removed by centrifuging to obtain the ZnO nanowire suspension. A drop of the ZnO nanowire suspension was dropped on the selected pattern using a micropipette while the electrical field was being applied across the electrodes. The electric field was continuously applied until the suspension completely dried out. The alignment was imaged by optical microscope and the yields of the aligned nanowires between the electrodes were observed. For the DEP experiment, four different AC electric fields (5, 10, 15, and 20 V, p-p') at two frequencies of 10 and 100 kHz were applied.

ZnO nanowires were successfully synthesized by VPT process on the catalyst-free Si substrate. The ZnO nanowire had an average diameter less than 100 nm and length in the micrometer range. As seen in Fig. 5, a sharp and strong emission located at 380 nm and a very weak visible emission located at 475 nm in the room temperature photoluminescence (PL) spectra indicate that our synthesized ZnO nanowires have a good crystal quality with excellent optical properties. The designed quartz tube, whose both ends are narrow and the middle is wider, was used to control the growth of ZnO nanowires. The end of the tube where the Zn source is put is narrower than the middle, so Zn vapor is easy to get through the middle of the tube. When the Zn vapor gets to the other end where the substrate is put, the Zn vapor is apt to deposit on the substrate. If the amount of Zn powder is little, it is probable that the nanostructure is nanowire.

Images of the ZnO nanowires trapped onto the microelectrode are shown in Fig. 6. The ZnO nanowires

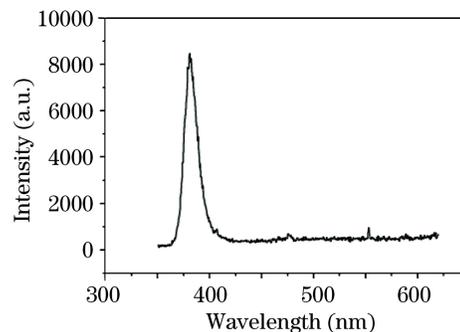


Fig. 5. Photoluminescence (PL) spectrum of the ZnO nanowires.

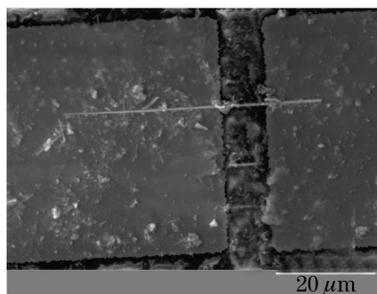


Fig. 6. SEM image of a pair of Au electrodes after DEP alignment.

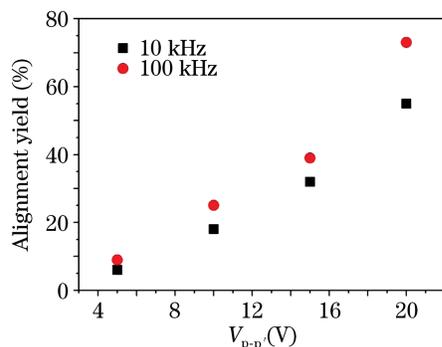


Fig. 7. Dependence of the alignment yield on the applied AC voltage.

were trapped around the electrode corner, where the electric field became higher, probably due to positive DEP<sup>[21]</sup>. The trapped ZnO nanowires were aligned along the electric field line and bridged the electrode gap. Although only a portion of the microelectrode is shown, ZnO nanowires were similarly trapped in the other electrode gaps. The number of trapped ZnO nanowires increased with the elapsed time. For the DEP experiment, the pattern was applied with different AC electric fields (5, 10, 15, and 20 V, p-p') at the frequency of 10 kHz. Nanowires in the pattern shown in Fig. 3 trend to bridge against the electrode so that it is fit to be used to connect circuits. Figure 7 shows the alignment yield of the ZnO nanowires in the gap when applying AC electric fields at the frequencies of 10 and 100 kHz. The results indicate that the alignment yield of the ZnO nanowires strongly depends on the AC electric field. Generally, it was observed that the yield rate increased with increasing the AC voltage. This can be simply explained by the AC DEP force with a high electric field as predicted in Eq. (3). The alignment yield for applying a frequency of 100 kHz is slightly higher than that for 10 kHz.

In summary, ZnO nanowires were successfully synthesized by VPT on Si substrate. The designed quartz tube, whose both ends are narrow and the middle is wider, was used to control the growth of ZnO nanowires. A sharp and strong emission located at 380 nm and a very weak visible emission located at 475 nm in the room temperature PL spectra indicate that our synthesized ZnO nanowires have a good crystal quality with excellent optical properties. Moreover, we also demonstrated a

novel and expedient approach, which was a powerful technique for extracting the electrical properties from many semiconductor nanowires, using AC DEP. The alignment yield of the ZnO nanowires strongly depends on the applied AC electric field and the yield rate increased with the increase of voltage.

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