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Tin oxide nanosensor fabrication using AC dielectrophoretic manipulation of nanobelts

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Abstract

Nanobelts are a new class of semiconducting metal oxide nanowires. The ribbon-like nanobelts are chemically pure and structurally uniform single crystals, with clean, sharp, smooth surfaces, and rectangular cross-sections. Positive and negative dielectrophoresis (DEP) was demonstrated for the first time on semiconducting oxide nanobelts. This effect was then used for the fabrication of a nanodevice, which consisted of SnO_2 nanobelts attached to castellated gold electrodes defined on a glass substrate, and covered by a microchannel. The SnO_2 nanobelts (width ~ 100–300 nm, thickness ~ 30–40 nm) were suspended in ethanol and introduced into the microchannel. An alternating (AC) voltage of ~9.8 V peak to peak, with variable frequency, was applied between the electrodes (minimum electrode gap ~ 20 μm), which corresponds to an average electric field strength of less than 2.5×10^5 V/m. In the 10 Hz–1 kHz range, repulsion between the nanobelts and the electrodes occurred, while in the 1–10 MHz range, attraction was observed. Once the nanobelts touched the electrodes, those that were sufficiently long bridged the electrode gaps. The device was characterized and can potentially be used as a nanosensor.

Keywords: Nanobelt; Nanowire; AC dielectrophoresis; Nanosensor; SnO_2

1. Introduction

Dielectrophoresis (DEP) [1,2] is the force induced on a polarizable particle suspended in a fluid medium under the influence of non-uniform electric fields. In an electric field, a dielectric particle behaves as an effective dipole with induced dipole moment p, proportional to the electric field E [3], that is,

$$p \propto E \tag{1}$$

The constant of proportionality depends on the geometry of the dielectric particle. The force on a dipole, in the presence of electric field, is given by

$$F = (p \cdot \nabla)E \tag{2}$$

Combining the above two equations and using known results between p and E for a spherical particle, it has been shown that the dielectrophoresis force in an alternating (AC) field [1] is given by

$$F_{\mathrm{DEP}} = 2p\upsilon\varepsilon_{\mathrm{m}}\alpha_{\mathrm{r}}\nabla(E^2_{\mathrm{RMS}}) \tag{3}$$

where υ is the volume of the particle, ε_{m} the permittivity of the suspending medium, E_{RMS} the RMS value of the electric field, and a_{r} is the real part of the Claussius–Mossotti factor, $\mathrm{Re}[K(\omega)]$.

Homogeneous dielectric particles experience a Maxwell–Wagner interfacial polarization at a frequency determined by the relationship between the complex permittivities of the

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particle and the surrounding medium, which is expressed by the real part of the Claussius–Mossotti factor,

$$\mathrm{Re}[K(\omega)] = \alpha_r = \mathrm{Re}\left(\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*}\right) \quad (4)$$

where ε_m^* and ε_p^* are the complex permittivities of the medium and particle, respectively. The general complex permittivity is given by $\varepsilon^* = \varepsilon - j\sigma/\omega$, where ω is the angular frequency of the applied field, ε the permittivity, and σ is the conductivity. The surface conductivity is also included in the σ term [3]. Re[$K(\omega)$] is frequency dependent and determines both the magnitude and the sign of the dielectrophoretic force. The value of the a_r factor ranges from −0.5 to +1.0, and can be calculated from the properties of the medium and the particle. If the value of a_r is positive, the particle moves toward higher electric field regions, and is termed positive dielectrophoresis. If the value of a_r is negative, the particle moves toward lower electric field regions, and is termed negative dielectrophoresis. For a solid homogeneous particle undergoing a single interfacial relaxation process, the characteristic frequency at which the direction of the DEP force alternates is known as the crossover frequency. Analysis of the crossover frequency as a function of medium conductivity can be used to characterize the dielectric properties of a particle. This is at present the principal method of dielectrophoretic analysis of sub-micrometer particles such as latex beads [4,5] and viruses [6–8].

It has to be noted that Eq. (3) is a classical calculation on bulk material. Hence, it may not be quantitatively accurate for nanostructures and molecules. Surface charge and quantum effects are likely to affect the quantitative predictions [3]. However, the equation does give an idea of the variables involved and the possible trends.

Another effect of AC electric fields on polarizable objects is to orient them with respect to an electric field. The induced dipole moment p of the object interacts with the electric field to produce a torque T, given by [3]

$$T = p \times E \quad (5)$$

This effect is responsible for the alignment of DNA, nanotubes, nanowires, nanobelts, and such thin, long objects in fluid medium [3].

The DEP effect is independent of the charge on the particle [1]. Neutral particles are subject to this effect, and therefore DEP is more versatile in its applications for manipulating live cells, macromolecules, nanostructures, etc. Dielectrophoresis has traditionally been used for manipulating cells and other objects on the micrometer range (1–1000 μm) [1,2]. Only recently has it been used to study, manipulate, and separate nanometer scale objects such as latex spheres [4,5], viruses [6–8], nanowires [9], carbon nanotubes [10–13], and macromolecules [14,15].

AC dielectrophoretic alignment and assembly of metallic (Au) nanowires (35–350 nm diameter and up to 8 μm long) was demonstrated [16] by using a combination of floating and electrically contacted electrodes, field strengths of up to 10^7 V/m, and frequencies from 20 Hz to 20 kHz. Positive trapping of the Au nanowires was found at the floating electrodes for frequencies above 200 Hz, with the effectiveness increasing with higher frequencies. Iso-propyl alcohol (IPA) was the dielectric medium during the DEP assembly process.

Yamamoto et al. [11] performed dielectrophoresis studies on multi-walled carbon nanotubes (MWCNTs) of lengths between 1 μm and 5 μm, using Al electrodes with 400 μm gaps, field strengths of 2×10^5 V/m and iso-propyl alcohol as the dielectric medium. They observed alignment and attraction of the nanotubes to the electrodes (positive dielectrophoresis) for AC frequencies between 10 Hz and 10 MHz. The degree of alignment of the nanotubes increased with increasing frequency and increasing nanotube lengths. They also found that the alignment was more effective with AC dielectrophoresis compared to DC dielectrophoresis [12]. Similar studies were carried out on single walled carbon nanotubes (SWNTs) by Chen et al. [13]. The SWCNTs were dispersed in ethanol and electric field of 5×10^6 V/m intensity in the frequency range 500 Hz–5 MHz was applied. The DEP was positive for all frequencies studied. The SWCNTs were found to be oriented more strongly at higher frequencies. They found no effect of DC electric field on alignment.

A multi-walled carbon nanotube (MWCNT) based gas sensor fabricated using dielectrophoresis has been reported in the literature [17]. MWCNTs dispersed in ethanol were trapped and concentrated at an interdigitated microelectrode gap under the action of a positive DEP force. After the DEP process, the ethanol was evaporated and the microelectrode retaining the MWCNTs was exposed to ammonia (NH_3) gas. The electrode impedance was monitored and was found to change with ppm-levels of ammonia at room temperature. The ammonia exposure decreased the sensor conductance, while the capacitance increased. The conductance change was proportional to ammonia concentration below 10 ppm and then gradually saturated at higher concentrations.

To the best of our knowledge, the only reported dielectrophoresis work on semiconducting nanowires has been done by Duan et al. [9]. However, it was DC dielectrophoresis, which was used to align and electrically contact InP nanowires of 30 nm diameter to Ni/In/Au contact electrodes. The electrode gap separation was about 25 μm and the electric field strength between the electrodes was $\sim 10^7$ V/m. Chlorobenzene was used as the solvent medium, so that electrolysis was not an issue, since high DC voltages (100 V) were used in the dielectrophoresis process. They were able to align InP nanowires into a cross-bar topology using a layer-by-layer application of dielectrophoresis. AC dielectrophoresis on semiconducting material nanowires has not been reported so far.

An excellent review of the applications of dielectrophoresis in nanotechnology and future possibilities has been presented by Burke [3]. To use dielectrophoresis in pre-