Simple model for dielectrophoretic alignment of gallium nitride nanowires

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A model describing the dielectrophoretic alignment of gallium nitride nanowires suspended in a solvent is presented here. The variations in the dielectrophoretic forces experienced by nanowires in different dispersing solvents have been calculated. It is shown that the relative sizes of the nanowires with respect to the spherical microparticles play a major role in the dielectrophoretic forces experienced by them. © *2007 American Vacuum Society.* [DOI: 10.1116/1.2429673]

I. INTRODUCTION

Semiconducting nanowires and carbon nanotubes have been utilized to form novel electronic and optoelectronic devices and to study fundamental transport properties in mesoscopic systems.[1–5] Nanowires of group IIIA nitrides (binary and ternary alloys of AlN, GaN, and InN) with unique material properties, such as direct wide band gaps, high saturation velocities, and high breakdown electric fields, are particularly important as they have great potential for realizing next generation efficient nanoscale ultraviolet/visible light emitters, detectors, and gas sensors. Reproducibly assembling these nanowires at predetermined positions on a substrate is the key to achieve functional nanosystems. To this date, assembly of nanowires without individual registration has been attempted mainly using electric field assisted aligning,[3,6] chemical patterning, microfluidic aligning,[7] Langmuir-Blodgett technique,[8] and optical traps.[9]

In the electric field assisted alignment technique, nanowires suspended in a solvent are dispersed on a substrate (e.g., SiO_2 coated Si) with voltage applied between two prepatterned metal pads. The divergent electric field interacts with the induced electric dipole moment of the nanowire, resulting in a net time averaged downward force, ultimately causing the nanowires to bridge the pads. In this article we have investigated the electric field assisted aligning technique of GaN nanowires using a simple model and numerical calculations to gain an insight into the alignment process.

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II. THEORETICAL BACKGROUND

A neutral particle placed in a nonuniform electric field experiences a force due to the interaction of the induced dipole moment with the divergent electric field. This force is called the dielectrophoretic (DEP) force, and the translational motion of the neutral particle caused by this force is termed as dielectrophoresis.[10] Aligning or manipulating particles using the dielectrophoretic force relies on the difference in the polarizability of the particle and the medium used for suspending the particles. Most often the suspending medium is an organic solvent such as isopropanol alcohol (IPA), ethanol, acetone, etc. The force experienced by a neutral particle in such a solution due to the nonuniform electric field is given by the relationship

$$\mathbf{F}_{\mathrm{DEP}}(t) = (\mathbf{p}(t) \cdot \nabla)\mathbf{E}(t), \tag{1}$$

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

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

where V is the total volume of the particle and α is the polarizability tensor for the particle. It can be shown that the time averaged DEP force is given by the equation[11,12]

$$\langle \mathbf{F}_{\mathrm{DEP}} \rangle = \Gamma \varepsilon_m \, \mathrm{Re}\{k_f\} \nabla |\mathbf{E}_{\mathrm{rms}}|^2, \tag{3}$$

where Γ is the particle geometrical factor, $\mathrm{Re}\{k_f\}$ is the real part of the Clausius-Mossotti factor which depends on the shape of the particle, ε_m is the real part of the complex permittivity of the medium, and $\mathbf{E}_{\mathrm{rms}}$ is the root mean square value of the electrical field. The complex permittivity is given by

$$\varepsilon^* = \varepsilon - i\frac{\sigma}{\omega}. \tag{4}$$

ε is the real permittivity, σ is the conductivity, and ω is the angular frequency of the applied electric field. For a cylindrical particle with $l \gg 2r$, k_f and Γ are given by

$$k_f = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_m^*}, \tag{5}$$

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

where ε_p^* and ε_m^* are the complex permittivities of the particle and the medium, respectively. For a cylindrical particle, length is given by l, and r represents the radius for both the cylindrical and spherical particles.

For a spherical particle, k_f and Γ are given by

$$k_f = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*}, \tag{7}$$

$$\Gamma = 2\pi r^3. \tag{8}$$

The DEP force experienced by the nanowire is normal to the sample surface. In the case of a positive dielectrophoretic force (determined by the difference in the dielectric permittivities of the nanowire and the dispersing medium) the nanowires will be attracted towards the pads and will eventually settle down on the pads with the complete evaporation of the solvent.

III. NUMERICAL CALCULATIONS AND RESULTS

GaN nanowires grown using direct reaction of NH_3 and metal Ga results in the formation of a dense network of GaN nanowires emerging from a thin layer of randomly oriented GaN microplatelets,[13] which is sonicated in a solvent to form a nanowire suspension.[14] This suspension contains both the nanowires and the GaN microplatelets or fragments.[14] The physical situation can be modeled by assuming that the nanowires are perfectly cylindrical particles (with $l \gg 2r$) and the fragments are spherical in nature. Using Eqs. (3)–(6), the relative DEP forces experienced by a GaN nanowire in the presence of different dispersing media can be calculated. The real part of the Clausius-Mossotti factor for a cylindrical particle from Eq. (5) is given by

$$\mathrm{Re}\{k_f\} = \frac{\omega^2 \varepsilon_m (\varepsilon_p - \varepsilon_m) - \sigma_m (\sigma_m - \sigma_p)}{\omega^2 \varepsilon_m^2 + \sigma_m^2}. \tag{9}$$

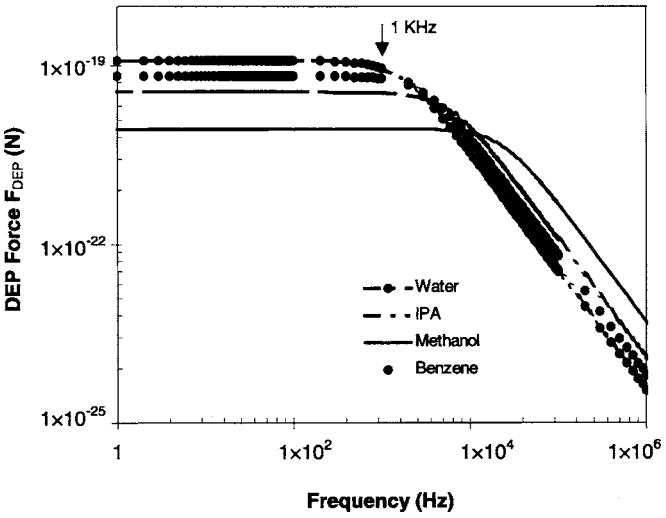

FIG. 1. Calculated DEP force experienced by a nanowire (100 nm diameter and 50 μm in length) in different dispersing media as a function of the alignment voltage. The drop in the DEP force for different solvents starts around 1 kHz.

Figure 1 shows the relative dielectrophoretic force variations for a 100 nm radius and 50 μm long nanowire in water, isopropanol, ethanol, and benzene, respectively, as a function of the bias frequency. Table I lists all the parameters used for calculating the relative dielectrophoretic forces for a nanowire in different solvents. For comparison purposes all the calculations were performed for unit $\nabla|\mathbf{E}_{\mathrm{rms}}|^2$. The conductivity of the GaN nanowires used for the calculations ($2.0 \times 10^4\ \Omega^{-1}\,\mathrm{m}^{-1}$) was experimentally obtained by depositing Pt contacts in a four terminal configuration on individual GaN nanowires utilizing focused ion beam induced metal deposition.[14] The relative dielectric permittivity for GaN used for the calculation was 9.7. From Fig. 1 it is clear that at low frequencies, between 1 Hz and 1 kHz, the DEP force is constant with the frequency for different dispersions. From Eq. (9) it can be seen that at low frequencies the DEP force is determined by the difference in the conductivities of the particle and the dispersing medium, whereas at high frequencies the DEP force is proportional to the difference in their permittivities. Water, although having the largest DEP force factors out of the four dispersing media, is not a good choice for DEP alignment, as maintaining high resistivities and low

TABLE I. Physical parameters used for the calculations of DEP forces for a nanowire in different solvents. (ε_0 denotes the dielectric permittivity of vacuum$=8.854\times10^{-12}\ \mathrm{F\,m^{-1}}$.)

Medium	Relative dielectric constant $\varepsilon_m/\varepsilon_0^*$	Conductivity σ ($\mathrm{S\,m^{-1}}$)
Water	80.0	7.6×10^{-6}
Methanol	32.9	4.4×10^{-5}
Isopropanol	18.6	6.0×10^{-5}
Benzene	2.3	4.0×10^{-7}

ionic conduction is challenging for water. Benzene appears (Fig. 1) to be a reasonable alternative to water with its DEP force factor comparable to that of water. Above 1 kHz, all the curves for different dispersing media experience a roll-off associated with the dielectric relaxation of the medium and the particle. This agrees well with experimentally observed results, where the highest yield is often observed at 1 kHz alignment frequency.[14]

The problem associated with the dispersion is the presence of the unwanted GaN microfragments in the dispersing medium, which are also subjected to the DEP force. In order to understand how these microparticles interact with the alignment field, we have calculated the DEP forces experienced by these GaN microfragments assuming they are perfectly spherical. Using Eq. (7) the real part of the Clausius-Mossotti factor for a spherical particle is calculated as

$$\mathrm{Re}\{k_f\} = \frac{\omega^2(\varepsilon_p + 2\varepsilon_m)(\varepsilon_p - \varepsilon_m)}{\omega^2\varepsilon_m^2 + \sigma_m^2} - \frac{\omega^2(\varepsilon_p + 2\varepsilon_m)(\varepsilon_p - \varepsilon_m)}{\omega^2\varepsilon_m^2 + \sigma_m^2}. \tag{10}$$

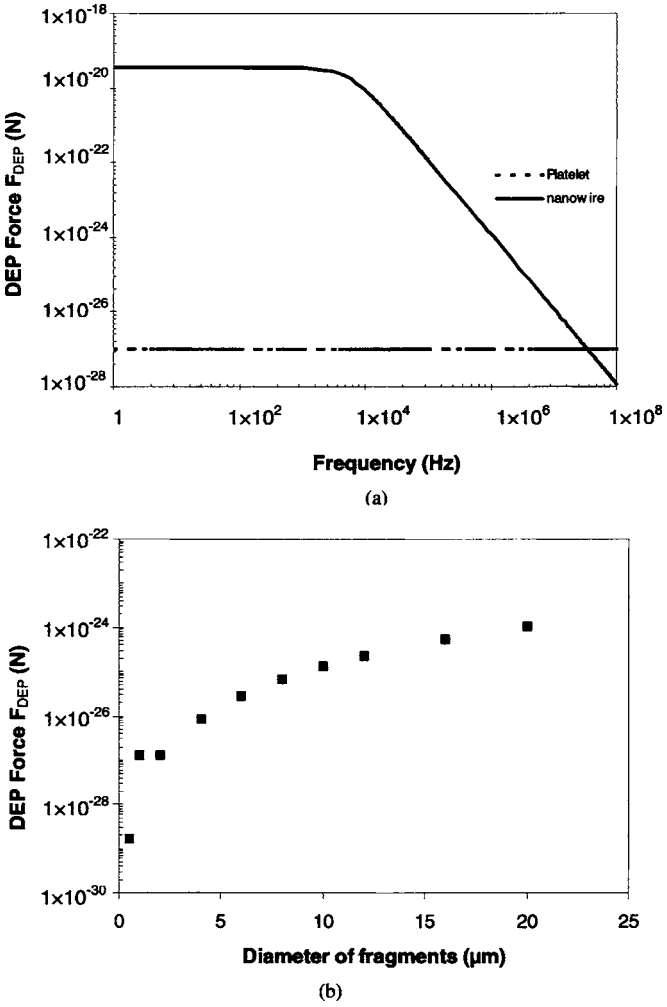

FIG. 2. (a) Calculated DEP force experienced by a nanowire (100 nm diameter and 50 μm in length) and a spherical fragment (2 μm diameter) in IPA with alignment frequency at 1 kHz. (b) Variations of the DEP force experienced by spherical GaN microfragments in IPA as a function of their diameters, with alignment frequency set to 1 kHz.

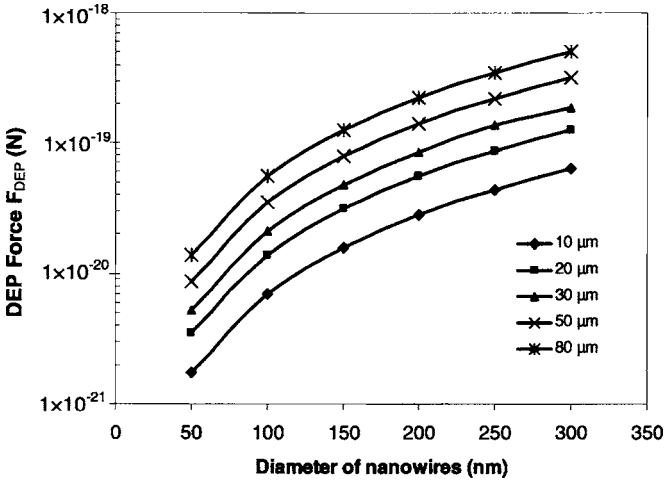

FIG. 3. Calculated DEP force variation as a function of nanowire diameter and length. The alignment frequency is set to 1 kHz and the dispersing medium is IPA.

Figure 2(a) is the plot of the variations of the DEP force experienced by a nanowire (100 nm diameter and 50 μm length) and a spherical GaN fragment (2 μm diameter) in IPA as a function of the frequency of the aligning field. It is interesting to note that in the low frequency range, a perfectly spherical particle experiences negligible DEP force compared to a nanowire. Due to their large conductances, the spherical GaN microfragments do not exhibit significant variations in DEP force with the frequency. This factor might be beneficial in selective alignment of nanowires over the fragments. We have not investigated the effects of the irregular shapes of these fragments on the DEP forces experienced by them, although Fig. 2(b) shows a plot of the DEP force experienced by spherical particles of different diameters. From the plot it is clear that the larger size fragments (15 μm) experience DEP forces comparable to those experienced by the nanowires. Although these simplified calculations show that the GaN fragments are less attracted by the alignment field, in experiments it is found that after alignment the nanowires had these fragments attached to them. We believe this is due to the fact that the nanowires, when bridged between two alignment pads, have a strong radial electric field surrounding them. Due to their small diameters, the electric field gradient normal to the surface of the nanowires is quite large and is capable of attracting these fragments on to the nanowire surface.

Figure 3 is a plot showing the DEP forces experienced by nanowires in IPA as a function of the diameter of the nanowire for different lengths of the nanowires. The alignment frequency is 1 kHz with peak to peak voltage of 20 V. It can be seen that thicker nanowires experience larger DEP force than thinner nanowires. Also there is about one order of magnitude increase of the DEP force with the increase in length of the nanowires from 10 to 80 μm. This variation in DEP forces experienced by nanowires of different dimensions can be utilized for selective alignment of nanowires.

IV. CONCLUSION

A simple model to analyze DEP alignment of nanowires in suspension is demonstrated. The present calculations are adaptable for nanowires of different material systems. Detailed numerical calculations taking into account the complex nature of the divergent electric field with spatial variations and other fluid properties must be carried out to better understand the alignment procedure.

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