

# Study of the dipole-dipole interaction between metallic nanowires trapped using optoelectronic tweezers (OET)

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**Abstract:** We present a study of dipole-dipole interaction between silver nanowires trapped using optoelectronic tweezers. Measurement of the maximum repulsion force between nanowires and self-assembly of nanowires to achieve the lowest potential energy configuration are demonstrated.

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## 1. Introduction

Dielectrophoresis (DEP) [1] is a technique that uses the interaction between a non-uniform electric field and the induced dipole on the particles to attract or repel particles from areas with the highest electric field gradient. In the presence of a non-uniform electric field, an effective dipole moment ( $p$ ) is induced on the particles. The interaction of the induced dipole and the electric field creates a DEP force, which can be attractive or repulsive, depending on the AC bias frequency and the properties of the particles and the medium. In addition, the interaction of the induced dipoles typically produces two types of effects [2]. First, a chaining effect, where the electrical dipoles are aligned with each other in series, creating an attractive force and resulting in the formation of particle chains for polystyrene beads [1] and nanoparticles [3, 4]. Second, a repulsive effect, where the particle dipoles are aligned to each other in parallel, resulting in a repulsive force from the neighboring dipoles.

Optoelectronic tweezers (OET) is an optical manipulation technique that works based on the principle of optically-induced dielectrophoretic (DEP) force [5]. In addition to being an effective tool for large-scale, flexible, and low-optical power manipulation of microscale objects, such as polystyrene beads and cells [5], OET recently has been shown to be capable of manipulation of nanoscale particles such as single silicon nanowires [6]. In this paper, we study the dipole-dipole interaction between metallic nanowires that are trapped using OET.

## 2. Experimental results

To study the dipole-dipole interaction between nanowires, a 3- $\mu$ L solution of silver nanowires was introduced into the OET device chamber. The silver nanowires, grown using aqueous reduction of silver ions [7], are 15  $\mu$ m long and 50-80 nm in diameter and are dispersed in a 1:1 ethanol and KCl / deionized water solution. A 632-nm diode laser with a measured power of 100  $\mu$ W at the OET surface was used to trap the silver nanowires. AC voltages of 5 and 8 Vpp at 100 kHz were applied to the OET device. Observations were made using an Olympus BX51M microscope, and images were captured in the dark-field using a CCD camera. In the absence of an AC voltage the nanowires experienced Brownian motion, however, once the AC voltage was applied across the device, the nanowires aligned with the electric field and were trapped in the laser spot, demonstrating a positive (attractive) DEP force [4].

Figure 1b shows four silver nanowires trapped in the laser spot. The long-axis of the nanowires is aligned with the electric field lines, orienting the nanowires perpendicular to the image plane. As a result, the end cross-section of the nanowires is visible in the figures. The induced dipoles of each nanowire are in parallel, resulting in a net repulsive force ( $F_{dipole}$ ) on each wire from the aligned dipoles. This net force repels the nanowires from each other and pushes them away from the laser trap. However, the attractive DEP force ( $F_{DEP}$ ) created by the OET trap pulls the four nanowires towards the laser spot (Fig. 1a). Therefore, once the trapping laser source is removed (Fig. 1c), the nanowires are no longer held together by the DEP force ( $F_{DEP}=0$ ), and are pushed away from the trap by the dipole-dipole repulsion force (Figs. 1d and 1e). Since the dipole-dipole force falls off rapidly with the distance between the nanowires, the maximum net repulsive force on one wire can be calculated by measuring the maximum nanowire displacement per unit of time, immediately after the trapping source is removed. The analysis for nanowire 1 in Fig. 1b results in a maximum repulsive speed of 10.9  $\mu$ m/s. Approximating the nanowire with an elongated ellipsoid moving perpendicular to its axis, the formula for the drag force acting on the nanowire is given by [8]:

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$F_{\text{Drag}} = 8\pi\eta l v_{\text{drag}} / (2 \ln(l/r) - 1)$ , where  $r$  is the nanowire radius ( $\sim 25$  to  $40$  nm),  $l$  is nanowire length ( $\sim 15$   $\mu\text{m}$ ),  $\eta$  is dynamic viscosity of water, and  $v_{\text{drag}}$  is the drag velocity. Therefore, by equating the dipole-dipole interaction force ( $F_{\text{dipole}}$ ) to the drag force we can calculate the maximum  $F_{\text{dipole}}$  on nanowire 1 to be roughly  $0.28$  pN.

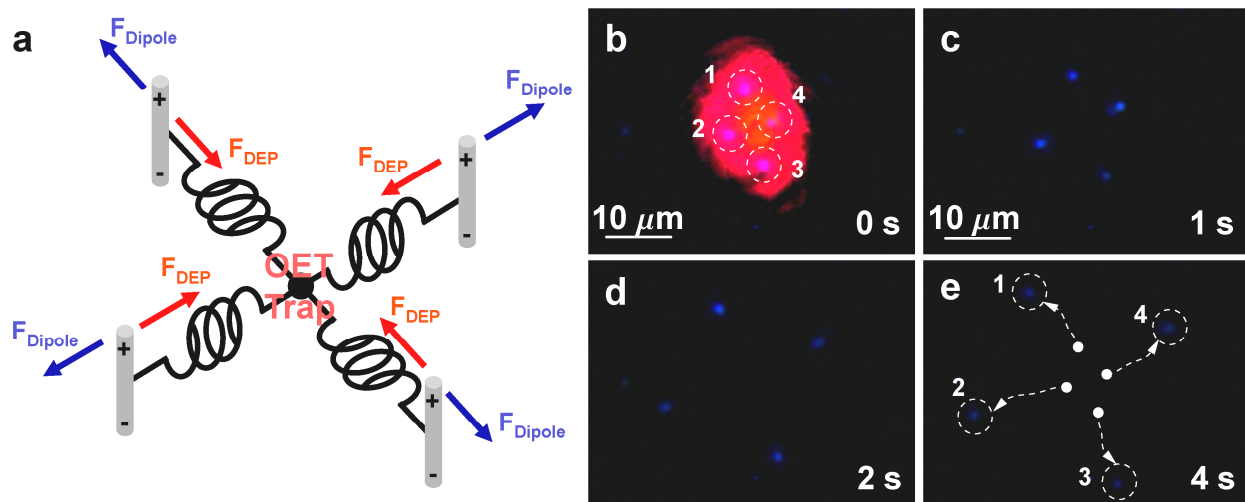


Fig. 1: Dipole-dipole interaction of four silver nanowires trapped using OET. (a) Schematic of four nanowires trapped in an OET trap. The nanowires are pulled towards the laser trap by the DEP force while pushed away from the trap by the dipole-dipole repulsion force. (b) Four silver nanowires trapped inside an OET trap. (c) Once the laser trap is removed, the nanowires are pushed away from the trap since the DEP force is no longer holding the nanowires together. (d) Nanowires continue to be repelled from each other, until, as in (e), the repulsive force cannot overcome the Brownian motion due to the large distance between the wires. The arrows indicate the approximate trajectory of the nanowires.

Multiple nanowires confined in the same OET trap will spontaneously assemble into patterns with the lowest potential energy. This is observed experimentally, where two nanowires trapped by OET form a line, three nanowires form an equilateral triangle, four nanowires form a square, and five nanowires form a pentagonal structure (Fig. 2). These regular nanowire patterns present stable arrangements with the lowest possible potential energy.

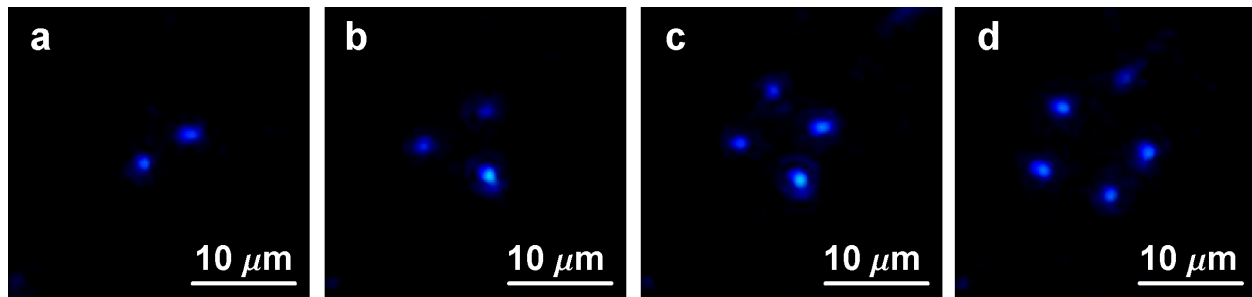


Fig. 2: Formation of smallest possible energy systems by nanowires trapped using OET. Formation of (a) a line for two nanowires trapped (b) an equilateral triangle for three nanowires trapped (c) a square for four nanowires trapped, and (d) a pentagonal structure for five nanowires trapped. The trapping laser source is filtered out in the images.

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