Photovoltaic Tweezers as a flexible tool for micro- and nano-particle trapping and patterning

M. Carrascosa, J. Matarrubia, H. Burgos, M. Jubera, F. Agullo-López and A. García-Cabañes

Universidad Autónoma de Madrid, Dept. Física de Materiales, Madrid, 28049, Spain

m.carrascosa@uam.es

Trapping and manipulation of micro- and nano-objects is a fundamental issue for many applications in nano- and bio-technology. A number of different approaches have been proposed and explored. One method, recently described, uses the dielectrophoretic (DEP) and/or electrophoretic (EP) forces associated to the evanescent electric fields generated by the photovoltaic (PV) effect on the surface of certain ferroelectrics [1-3]. These fields can reach values as high as 10^4-10^5 V/cm for Fe doped $LiNbO_3$ [4] and depend on the doping level and light exposure. The method, that may be considered as a type of photoelectric tweezers, often called photovoltaic tweezers [5], presents a great potential and its capabilities and limits are now under investigation. In this contribution we present an overview of the work recently developed by our group including the description of the method, and the main achievements in the theoretical description and experimental demonstration. Finally, some insights on the possible applications are also discussed.

The photorefractive and patterning experiments have been mostly performed on 1-mm thick x-cut plates of congruent $LiNbO_3$ highly doped with iron (0.1 % wt) in order to assure a strong photovoltaic effect. The samples were illuminated with light patterns at λ=532 nm to develop the photovoltaic field patterns. Different particle deposition methods (in air and from a hexane suspension, with and without simultaneous illumination…) have been investigated to determine the best procedure. In fig 1 we show two illustrative examples of 1D and 2D particle patterns. Pattern 1a is obtained by illumination with a sinusoidal high contrast light pattern with spatial period Λ=17 μm. Al nano-particles with average diameter $d\sim$ 70 nm are deposited immersing the sample in a hexane suspension. In turn, for pattern 1b we use $CaCO_3$ micro-particles ($d\sim$1-3 μm) under a 2D light pattern of concentric circular fringes. So far we have obtained spatial resolutions up to a few micrometers. Nevertheless, using smaller particles smaller periodicities should be reachable up to the limit imposed by the shortest light period, i.e., about 100 nm.

In order to show the suitability to combine the technique with integrated devices we have also demonstrated particle deposition on $LiNbO_3$:Fe optical waveguides. This configuration has some advantages, namely, the high light intensities reached and so, the short photovoltaic response times, the high tolerance to mechanical vibrations during recording of PV fields and the geometrical separation between the light propagation channel and the particle deposition area. A representative result using a $LiNbO_3$:Fe planar optical waveguide is shown in figure 2a. The corresponding setup used to generate the PV field with two beams interfering inside the waveguide is schematically drawn in figure 2b.

The theoretical description of the physics involved in the operation of PV tweezers includes two steps: i) to calculate the edge photovoltaic field pattern generated in the proximity of the PV surface by a particular light pattern, ii) to obtain the DEP force associated to this pattern. Using a simple approach [5,6] we have developed useful expressions of the final DEP force acting on neutral particles that can explain our experiments. In particular the influence of some parameters such as light contrast and period, or anisotropy of particles is analysed. For instance, the theory predicts different behaviour for isotropic Al spherical nano-particles and anisotropic graphite micro-particles, so that the later ones can show a double periodicity that is absent when using the former ones. These differences are illustrated in figure 3.

The methodology presented in this work offers a large span of possibilities for application. Just to mention a few ones, we can consider its use for fabrication of particle decorated surface structures. Another relevant and quite feasible application consists in the fabrication of masks and diffractive optical elements that can be reconfigurable, such as Fresnel lenses and Bragg reflectors for laser technologies. Moreover, the feasibility to apply the technique combined with waveguide configuration opens the door to applications in integrated photonics. The possible use in microfluidics has been also reported [3,7]. Finally, in biology and biomedicine one might organize cells in predetermined patterns, for instance, to stimulate or control the growth of living tissues. In fact, the possibility to kill cancer cells using PV fields has been recently demonstrated [8].

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Figures

Figure 1.(a) Al nano-particle pattern with period Λ=17 μm obtained after sinusoidal illumination with a high contrast light pattern. The particles are deposited from an hexane suspension (b) $CaCO_3$ micro-particle (*d*=1-3 μm) pattern deposited in air under a 2D light pattern of concentric circular fringes

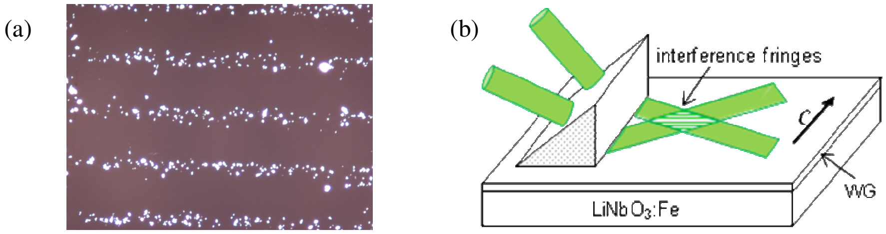

Figure 2. (a) Microphotograph of CO_3Ca particle patterns (diameter d ~ 1-3 μm) deposited from hexane on the surface of a $LiNbO_3$:Fe optical waveguide after sinusoidal light illumination (Λ=55 μm) during 3 s. (b) Schematic of the two beam interferometrical configuration used to generate the photovoltaic fields with guided beams

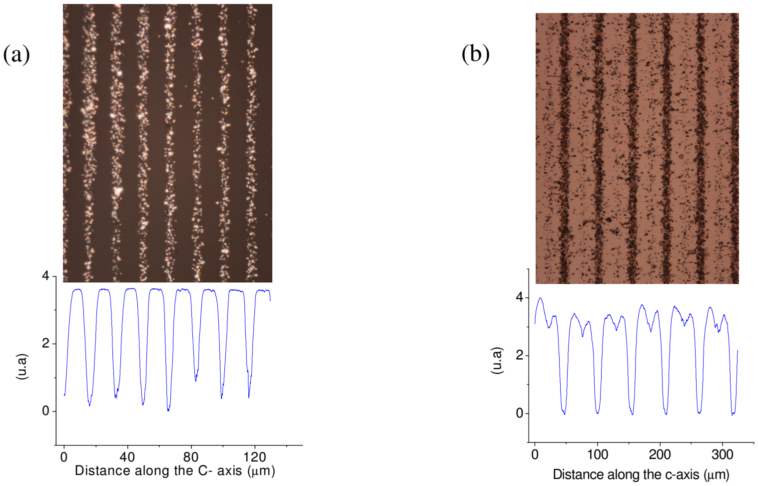

Figure 3. Optical microscope images of particle patterns for sinusoidal illumination with Λ=17 μm for (a) isotropic Al particles and (b) anisotropic graphite particles. In the bottom of each image the corresponding averaged particle concentration profile along c-axis direction is shown. This profile has been obtained from the microscope images