Optical manipulation of silicon microparticles in biological environments

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ABSTRACT

Manipulation of micron-scale silicon particles has been investigated with optical tweezers implemented using a two-dimensional scanning trap driven with acousto-optic modulators. Spheres of latex, Poly(methyl methacrylate) (PMMA), silica, and silver-coated PMMA have been utilized to calibrate transverse trapping forces. The goal of this work is to non-invasively manipulate 10-20μm silicon-based devices in and around cells.

Keywords: optical trapping, optical tweezers, silicon, integrated circuits

1. INTRODUCTION

It is now technologically possible to produce micron-scale integrated circuits (μICs) incorporating thousands of Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) with nanometer-scale gate lengths. Integrating μICs together with silicon-based sensors would provide a powerful new tool for biotelemetry, where measurements could be acquired at the cellular level. However, for biotelemetry applications, a nondestructive means for manipulating these devices is required.

Optical trapping (or optical tweezers) is a non-invasive and non-destructive means of manipulating small particles within biological tissues and cells.[1] Two forces are associated with optical trapping, the scattering force and the gradient force. The scattering force is proportional to the light intensity and acts in the direction of light propagation. The gradient force is proportional to the spatial gradient of the light intensity and acts in the direction of the gradient. Trapping is stable whenever the gradient force is larger than the scattering force, predominantly when microscope objectives with the highest possible numerical apertures are used. Power levels necessary for optical trapping have proved harmless, allowing repositioning of cell organelles within living cells.

The challenges inherent to the optical manipulation of silicon are expected to be similar to metallic particles, due to its highly reflective and absorptive properties. One of the

Manipulation and Analysis of Biomolecules, Cells, and Tissues,
Dan V. Nicolau, Jörg Enderlein, Robert C. Leif, Daniel L. Farkas, Editors,
Proceedings of SPIE Vol. 4962 (2003) © 2003 SPIE · 1605-7422/03/$15.00

early strategies for the manipulation of high refractive index particles[2] uses the TEM_{01} donut laser mode, which has an intensity distribution of the form $I(r)=I_o(2r/w_o)\exp(-2r^2/w_o^2)$. For a metallic particle trapped at the dark center, the absorption is minimized. Optical trapping of metallic Mie particles ($d >> \lambda$) has been demonstrated[3,4] in two dimensions using a standard Gaussian-type focal volume. Trapping forces in the transverse plane are enhanced with higher-NA objectives,[5] which is an opposite behavior than for more refractive, non-absorbing particles. However, these previous experiments reveal that trapping of metallic Mie particles cannot be achieved axially due to the large amount of optical momentum delivered in the propagation direction of the laser from surface reflections.

Alternative trap beam geometries are an extensive area of study. Computer-controlled holographic techniques[6] and the generalized phase-contrast method[7] have been used to create multibeam tweezers for trapping multiple refractive, non-absorbing particles. The use of axicon lenses to produce Laguerre-Gaussian beams[8] is another technique for generating an optical trap with a hollow center. Scanning techniques using galvanometer mirrors[9], a piezo-driven mirror[10], and acousto-optic and electro-optic deflectors[11,12] have been extensively used to produce arbitrary two-dimensional traps. For example, a "laser cage" was created specifically for metal particle manipulation by drawing a ring using two galvo mirrors.[13] The reflective metallic particle is repelled from the higher-intensity region of the trap, keeping it within the dark center in the transverse plane. It may also trap axially if the confocal parameter is sufficiently small. The use of an optical trap which holds the particle at an intensity minimum may be desirable if it minimizes the absorption and subsequent local heating. (For a given incident laser power, one would expect absorption to be minimized at oblique angles.) In biological environments heating effects are of primary concern to cell viability. Also of concern is the photoactivity of the near-infrared laser light within a cell. Recent reports[14,15] indicate that cell viability is highly wavelength-dependent and can be affected after exposure to as little as 20J of near-infrared light.

We report here a preliminary study of trapping using two acousto-optic modulators (AOMs) to produce a ring with a central dark spot in order to trap silicon and other high index microparticles. This type of trap has the potential for axially trapping large metallic particles, and we anticipate that the configurability will be especially useful for non-spherical particles such as μICs.

2. EXPERIMENT

2.1 Setup and Methods

As shown in Figure 1, the experimental setup consists of a CW Ti:Sapphire laser tunable from 950-1100nm pumped by 15W from a multi-line argon ion laser. The output of the tunable laser (typically 1 Watt) is launched into a 980nm single-mode fiber to ensure high mode quality in the optical trap, as well as isolating the effects of laser steering fluctuations. The output of the fiber is collected by a 10X objective that can be adjusted to optimize the convergence of the beam for the experiment of interest. For trapping of lower index particles such as latex and SiO_2, the beam is typically gradually focused (>f/100) to slightly overfill the entrance aperture of the desired objective (10-100X). For trapping of reflective particles the beam convergence was adjusted to focus (f/20) the beam halfway between the closely-spaced AOMs (Isomet Model 1206C).

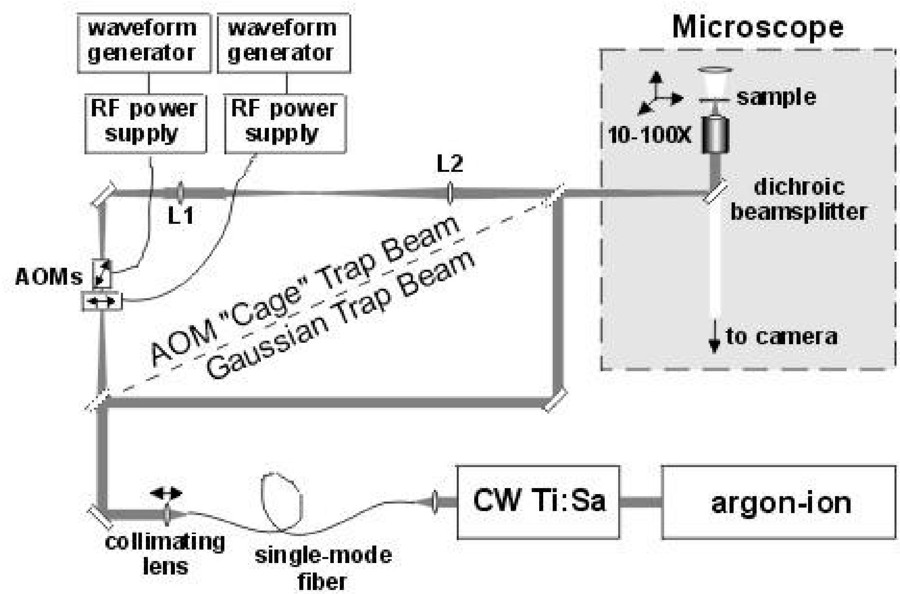

Figure 1: Schematic of the optical trapping setup (not to scale). The Gaussian trap can be accessed by inserting two mirrors on flipper mounts. The lenses L1 and L2 have focal lengths 250mm and 300mm, respectively.

A system composed of two lenses (L1 and L2 in Figure 1) ensured that the objective entrance aperture was in a conjugate plane with the AOMs, so that the deflection produced by the AOMs did not displace the beam on the objective aperture. Efficient deflection (>50% through both AOMs) in the wavelength range of interest was achieved with angular displacements ≤0.5°. In practice, using the system of lenses described above with a magnification of 1.2 corresponded to a maximum laser ring diameter of 18μm through a 63X objective. Keeping the deflection angle constant, the spot diameter and confocal parameter for these settings were measured in air at 1000nm, using a scanning razor edge and large area photodiode with hemispherical collection lens to capture the transmitted light. The measured waist diameter of 3.6μm and confocal parameter of 38μm are a factor of two larger than the values obtained when optimally overfilling the objective entrance aperture. Etendue, a conserved quantity $=\iint dSdQ$, where S is the surface area and Q the solid angle of a light source, limits the maximum spot size incident on the objective entrance aperture for a given deflection angle. Since we are interested in primarily trapping large particles (i.e. ICs >10μm on edge), however, we chose to underfill the objective entrance aperture in exchange for larger deflection angles.

Two digital waveform generators are used to tune the RF modulation frequencies driving each acousto-optic modulator, effectively tuning the angular displacement. In this way, a circle with an inner annulus can be generated using two sine waves with a $\pi/2$ phase offset. Typically a tuning frequency of 1kHz was applied, which is sufficiently fast to outpace the Brownian motion inherent to micron-scale particles.

The trap laser was subsequently directed into the excitation port of a Zeiss Axiovert 200M inverted microscope. The laser beam travels directly onto a dichroic beamsplitter where it was reflected onto the objective entrance aperture. Visible light is transmitted through the beamsplitter to allow viewing with a video camera, which was also typically able to detect scattering of the near-infrared laser for simultaneous visible and IR light viewing while performing optical manipulations. The microscope is also equipped with an incubator stage for extended cell studies.

A mechanical stage was programmed to travel at fixed velocities in a given direction for calibrations of the optical trap using the Stokes force law. For transverse force measurements, trapped spheres were scanned for 3 seconds at each velocity setting. The escape forces ($F=6\pi\eta vR$, where η is the viscosity of the fluid and R the sphere diameter) were estimated from the maximum velocity that could hold the sphere for this duration. In some cases, the escape forces were estimated from recorded video in which the particle was manipulated via a joystick controller of the stage until it escaped from the trap. In many cases these measuments reflect a lower bound on the actual trapping forces achievable, due to friction experienced between the particle and the coverslip or microscope slide.

2.2 AOM "Cage" Trapping

Trapping of refractive, non-absorbing microspheres such as PMMA, SiO_2, and latex using the Gaussian trap was used to test performance of the system. Typically, when suspended in water, trapping in the axial direction was only achievable with the NA=1.4 100X oil-immersion objective. Transverse trap forces for 5μm PMMA spheres in water were 16±5pN for a power of 120mW at 970nm when using the 100X objective. The forces obtained were the same in the ±X and ±Y directions.

Prior to the use of the AOM-based optical trap, experiments using a simpler, intensity masking technique were executed to test the feasibility of the concept. A 2mm-diameter circular mask was positioned in the 5mm diameter collimated laser beam immediately in front of the microscope. Under these conditions, without the use of the AOMs, irregularly-shaped Si particles typically between 1-5μm diameter exhibited transverse trapping in water with 40mW of laser power transmitted through a 40X objective at

1000nm. An escape velocity of 35µm/s was observed when trapping a silicon particle with average dimensions of 3µm.

Currently the AOM-based system is capable of keeping 1-5µm silicon particles within the central annulus for tens of seconds. Irregular silicon particles appear to be pushed in discrete events toward the center, except that in some cases the push will impart torque to the particle, causing it to spin and eventually resulting in escape from the trap. It is believed that more well-defined Si dimensions in conjunction with a trap geometry designed for the particle shape will yield better results.

Other evidence that the AOM trap may be suitable for Si lies in its ability to trap metallic particles in the beam annulus. As a model, 5µm diameter silver-coated PMMA spheres were studied. These microspheres were batch-processed from PMMA spheres which were cleaned, surface-treated, then coated with silver to a thickness >200nm. Their conductance was verified by measuring the contact resistance of a thin layer of microspheres.

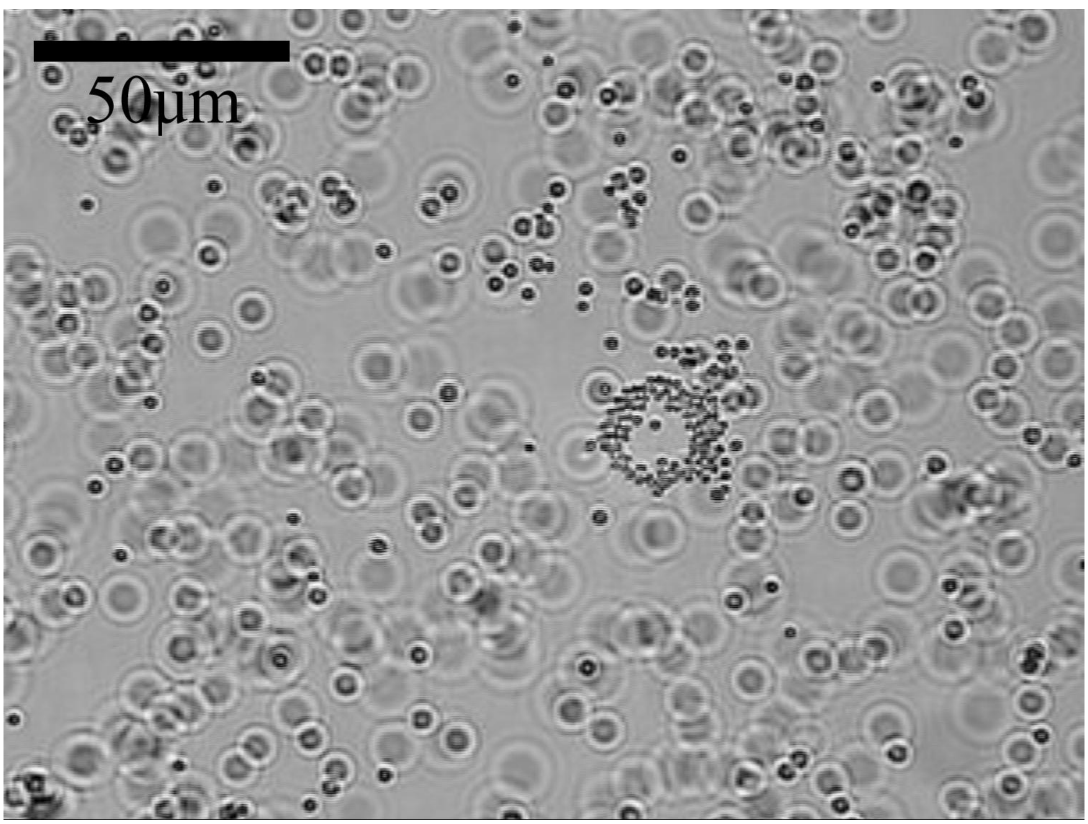

Figure 2: Intensity map of the AOM-based optical trap using 1µm latex beads as an indicator.

Ag-coated PMMA spheres were trapped transveresely in water using the AOM cage. Similar to the Gaussian trap, the spheres were initially moved in +Z until touching the microscope slide. The objective focus was then moved upward to compensate. The maximum trap efficiencies were obtained with a ring diameter of ~18μm. In general, when attempting to trap Si, the ideal ring diameter appeared to be ~4× the particle width. This allows for sufficient falloff of the light intensity in the center of the ring to allow stable trapping. With the 63X objective, the beam waist of the fixed laser was measured to be 3.6μm, however, there may be significant tails into the central region.

The highest trapping efficiencies of Ag-coated PMMA were obtained with a 63X objective. Powers ranging from 18-43mW were investigated at wavelengths of 950, 970, 990, and 1010nm. The trapping force as a function of laser power appears to be nonlinear: at 990nm, 4.0pN were obtained at 16mW but 18pN at 23mW of optical power. This latter measurement indicates a trapping efficiency ($Q=Fc/n_{water}p$, where n is the refractive index and p is the power) of 18%. The maximum velocity obtained was 460μm/s at 33mW of power at 970nm. In general, the trapping efficiency appeared to be insensitive to wavelength, but more data is necessary to make this determination to better than 50% precision. It is also important to note that the spheres were dragged along the microscope slide as part of these escape force measurements, which suggests that friction may be causing an underestimation of the actual trap force.

3. CONCLUSION

In summary, a configurable 2-D trap using AOMs was also investigated, and to date has demonstrated efficient (18%) trapping of silver-coated PMMA spheres. However, this trap is problematic for trapping randomly-shape silicon, and may produce better results with computer control to shape the beam for the particle of interest.

ACKNOWLEDGEMENTS

The authors would like to thank Kaethe Timp for her technical assistance. This work was supported by the Office of Naval Research.

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