Contact-less handling of metal sub-micron and nanowires for microelectronic packaging applications

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ABSTRACT

Individual sub-micron particles produced by non-lithographic techniques are promising for future microelectronic applications. Being too small to be handled by traditional Pick & Place, they require a contact-less manipulation. We propose a combination of dielectrophoretic and acoustic trapping for the separation and oriented positioning of metal and semiconductor wires on microelectronic substrates. Chiplets, rods, and spheres of different materials can be manipulated in microfluidic channels by dielectrophoresis and ultrasonic standing waves, covering object sizes from the micro- to the nanoscale. Technical principles developed for the biotechnological manipulation of single live cells and other microparticles are adapted to the integration of miniaturized components into a microelectronic periphery. Developing these handling techniques for tiny and delicate individual components in microelectronic packaging ultimately requires the use of carrier liquids that facilitate employing self-assembly strategies.

Keywords: self assembly, dielectrophoresis, acoustic trapping, field cage, particle sorting

1 MOTIVATION

In current microengineering, continuously shrinking sizes of functional elements open up further enhancement of functional density. At the same time, however, they face traditional techniques for microelectronic packaging or MEMS applications. The well-established Pick & Place approaches are limited to a certain size scale. Even with classic SMD, sequential error-free placement of chip components requires sophisticated automata and, hence, rising costs and efforts. In view of the stringent future goals outlined in the ITRS roadmap, the only possible solution lies in the search for alternative and completely new approaches in future component handling, i. e. advanced packaging. Besides miniaturization, the availability of promising materials applicable to information processing diversifies. In order of decreasing organizational level these comprise: neuronal cellular networks; single living cells, like microorganisms, animal cells or valuable plant cells; isolated organelles (e. g. chloroplasts, forisomes [1]); functional biomacromolecular assemblies (e. g. two-dimensional bacteriorhodopsin lipid crystals, i. e. purple membrane [2]), s-layer proteins [3], and different substance-specific channel-forming proteins [4, 5]; molecular motor proteins or gene-engineered variants of the same, and so forth. The inorganic class of materials is made up of different types of micro- and nanotubes, synthetic organic and inorganic particles. Multilayer, i. e. core shell, nanoparticles are thought to become important for future coupling between microelectronics and photonics, exploring evanescent fields generated at resonator-entrapped NPs [6] or even atoms [7]. Not only semiconductor nanowires but also metal nanowires are considered essential elements in future microelectronic packaging [8]. However different these functional materials might be, they all have in common to be not touchable. Therefore, techniques have to be developed that prevent mechanical damage during handling or processing. Another crucial influence on NPs to be avoided is the adsorption of different contaminants, passivating layers, or other unwanted substances from the surrounding atmosphere or carrier liquid. The presence of liquid carrier and shielding media additionally helps to prevent unwanted contamination through electrostatic attraction (ESA), as it is observed in microfabricated silicon microparts.

Where are suitable manipulation techniques to be found? In the biosciences, especially in medical and biotechnological single-cell technologies, a whole range of methods has been developed over the last decades for research and even commercial single-cell applications. Manipulated objects include microorganisms, plant or animal cells [9]. Often, a combination of various physical principles and microfluidics is sufficient to deal with the delicate objects. Such objects are: gene-engineered microorganisms, living single cells, artificially generated cell hybrids, stem cells, progenitor cells, or even somatic stem cells. These cells are either isolated from diluted samples or from complex fluids (e. g. blood or biofermenter broth). These micron-scaled objects are always suspended in a liquid medium which shields against the surroundings and fulfills the function of a nutrient and a buffer. Individual cells are the object of single-cell-based branches in biotechnology, food industry, cellular medicine and comparable fields [10, 11]. Strangely enough, intense related R & D activities remained almost unnoticed by classic microengineering. Since semiconductor technologies have always been open for new materials and inspirations from different disciplines, the observed technological convergence at the sub-micron and nanoscale will doubtlessly facilitate progress in all engaged fields and disciplines.

2 PHYSICAL FORCES AND MANIPULATION PRINCIPLES

What are the general requirements for the massively parallel component processing and assembly necessary in any modern high-throughput screening (HTPS) or future high-throughput assembly (HTPA) scenario? Objects, i. e. components, have to be isolated, sorted, aligned, vectorially oriented, moved, and placed. Technical components (future microelectronic components) have to be joined at their final location for being connected electrically or for being optically addressable. Biotechnical components at the end of the virtual conveyor are placed to give clonal growth (cells, microorganisms) or to be brought into contact with others (cells, macromolecules, or biochemically functionalized microparticles, polymer beads, or NPs). This is a striking technological convergence from a process engineer's point of view.

Like in real macrolife, gradients are the strongest cause for movement in micromanipulation. Since being well-understood, electromagnetic fields are the most important gradient sources in the micro-, sub-micro- and nanoworld. A simplified overview of available methods is summarized in the Table 1.

Force	Principles	Application variants
E-Field	Electrophoresis	Free Solution / Field Flow Fractionation Capillary electrophoresis
	Dielectrophoresis	Negative dielectrophoresis (nDEP) Positive dielectrophoresis (pDEP) Travelling wave DEP Travelling wave pumping
M-Field	Magnetophoresis	Mechanically driven, sliding magnets Electrically driven ferrofluid actors Magnetic tweezers
Optical pressure & Energy absorption	LASER	Laser tweezer / Photonic force microscopy Laser dissection
Acoustic pressure & Hydrodyn. Streaming	Interparticle interaction Acoustic energy	Different types of field flow fractionation (FFF) Acoust. Trapping / Ultrasonic standing waves

Table 1: Physical forces used for contact-free particle handling.

Not all the mentioned principles are helpful in the case of a suspension. It is important to notice that especially magnetic force fields and some variants of dielectrophoresis have to be combined with stringent space restrictions. Usually microfluidic channel networks or capillaries are applied to facilitate directed movement along a given track. The necessary guiding structures can also be provided by "wall-less tubes", i. e. suitably designed electrodes addressed by negative dielectrophoresis. Basic elements of dielectrophoretic guiding and sorting in liquid channel networks have been described earlier: particle enrichment by funnels, particle alignment by longitudinal quadrupole cages, particle trapping and holding inside closed field cages, and particle sorting by temporarily deflecting field barriers [12, 13].

Laser tweezers have also been combined with dielectrophoretic trapping to assemble particles and to measure bonding forces between them [14, 15]. Laser light has been used to engrave particles trapped contact-less in a three-dimensional cage [16] or to fix particle assemblies by initiating polymerization [17]. Some other technological principles important in the discussed context but beyond the table above entered pharmaceutical HTPS, combinatorial chemical analysis [18, 19], cell banking, and cryo-preservation. Prominent examples are:

- Segmented flow techniques based on structured mixtures of immiscible liquids [20];
- Picoliter spotting;
- Microcontact printing for the production of (bio-)chemically patterned substrates;
- Multi(-well) array and panel techniques.

The practically pre-dominant case in future microelectronics packaging will be heterogeneous integration, i. e. the assembly into functional units of discrete tiny components fabricated by different techniques and under different conditions. Beside the above-mentioned bioapplied techniques, self-organization phenomena can be explored. These size scale-independent entropy-driven processes came into the focus of modern microfabrication through artificial structures that occurred seemingly out of nowhere, like patterned films and interfaces [21]. The interest was strengthened by the high resolution power of different commercially available scanning probe microscopy techniques (AFM, AFAM, SEM, KPM) and sophisticated combinations thereof (e. g. crossbeam FIB-REM).

We aim at indicating prospective directions of future work. Our examples may vary in the development stage but are all transferable to broader microtechnical applications in the foreseeable future with a calculable effort. They show a concept for the contact-less manipulation over the important size scales. This concept of converging assembly strategies is developed based on the microtechnology toolbox for the need of both life sciences and future micro- and nanoelectronics.

3 DIELECTROPHORESIS AND ULTRASOUND FOR MANIPULATION AND SORTING OF SUB-MICRON PARTICLES

The dielectrophoretic particle manipulation in liquid carrier media offers wide possibilities for contact-less collection, assembly, sorting, and processing. This was previously shown for living entities, like mammalian cells, algae, pollen grains, yeast, bacteria, and even viruses [22]. By careful tuning of electric conductivity, dielectric constants, electric field (frequency and amplitude), and electrode shape, different tiny objects can be spatially confined, rotated, lifted, and assembled into sophisticated structures [17].

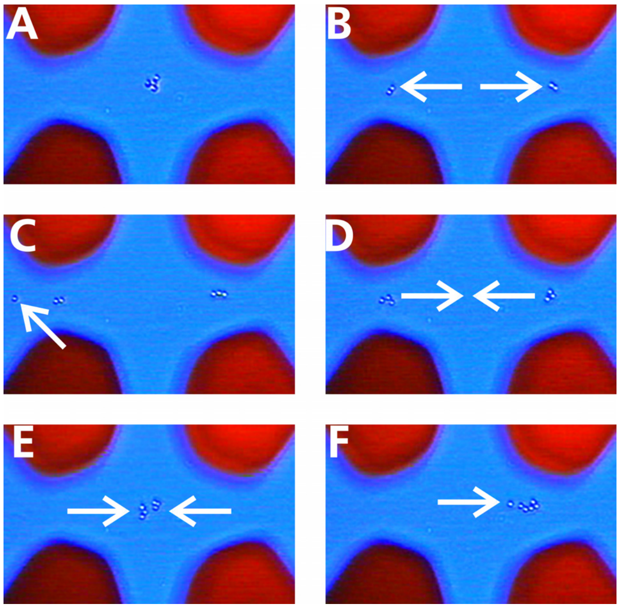

Figure 1: Contact-less assembly of nanoparticle aggregates through dielectrophoretic manipulation. (a) An ensemble of five polymer beads (r = 500 nm) is kept between eight microelectrodes (red) and (b) then separated into two groups by specific electric conditions. (c) Another particle is added from the left. (d) Both groups are joined into one (e) which is then positioned on one side (f).

Both negative dielectrophoresis, i. e. the manipulation at electric field minima, and positive dielectrophoresis have been applied to induce directed particle movement. In a recent research project, we are investigating possibilities to orient and to align metal sub-micron and nanowires (NW). These wires have to be handled with great care, since they are susceptible to mechanical damage which easily causes crystal defects, e. g. the prominent sliding along the <111> crystal plane in fcc metals like Au and Pd or twin formation. In principle, new contact-less assembly techniques must be developed to make the exciting properties of nanowires accessible to future microelectronics.

Nanowires can be produced non-disruptively at the very places where they are to be used. The well-described step edge deposition technique (STD) represents the technologically most conform approach. Since, however, only horizontally oriented edges on the wafer substrate are accessible, generated wires are oriented in plane as well. The carrier substrates encounter high temperatures due to CVD and PECVD deposition conditions. Therefore, we consider individually and externally generated single-crystalline metal wires an alternative for future NW applications. The ballistic electron transport (i. e. conductance) is improved along certain crystal planes and deflected at grain boundaries. Therefore, the electrical conductivity of NWs will be crucially influenced by the electrons' mean free path and, hence, by crystal defects [23]. Future electronic interconnects will require single-crystalline wire interconnects. Such predictable reliability-diminishing effects of electronic devices, like electromigration, might be reduced in the approach we follow.

Acoustic trapping by ultrasonic standing waves are another promising technique for microparticle handling. Different research groups are investigating methods to apply acoustic trapping to biotechnological applications. In essence, standing waves are generated at megahertz frequencies inside fluidic channels. At these frequencies, no cavitation and, hence, no damage to fragile objects occurs. Particles suspended in the coupling medium will be trapped and enriched in nodes and can be moved hydrodynamically in nodal planes or lines. Trapped objects are also accessible to contact-less manipulation through controlling the number, shape, and spatial extension of nodes by the coupling acoustic field and the resonance pattern. The combination of hydrodynamic streaming and dielectrophoresis together with ultrasound has already been shown to be suited for the handling of polymer beads [24]. We aim at extending this approach to the contact-free handling of inorganic particles important for future microelectronic packaging. During the already finished first evaluation phase of a related research project, the basic concept has been approved.

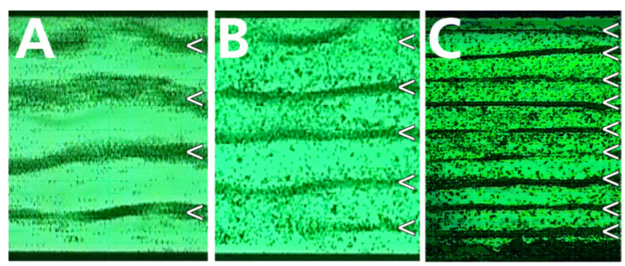

Figure 2: Ultrasonic standing wave trapping of spherical polymer beads (arrowheads) inside a microfluidic channel at increasing frequencies (a to c).

Basic manipulation principles, like aligning, sorting, and assembling are accessible. Their combination must be investigated in more detail in order to finally succeed in the assembly of fully functional nanodevices.

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