THREE DIMENSIONAL ASSEMBLY OF SILVER NANOPARTICLES USING DIELECTROPHORESIS

RET Participants: Erica Wilson (The Engineering School), Pakamas Tongcharoensirikul (Quincy High School)
Faculty Mentor: Dr. Mehmet Dokmeci, Electical and Computer Engineering
Research Team: Chia-Ling Chen, Shih-Hsieh Chao, Electical and Computer Engineering

ABSTRACT

A novel technological approach for three-dimensional (3D) assembly of silver nanoparticles using dielectrophoresis (DEP). A micromachined platform is fabricated which is applicable for assembling conductive nanostructures. The assembly process is achieved at room temperature and is compatible with conventional semiconductor manufacturing and batch fabrication. Potential applications include making high density 3D interconnects, vertically integrated nanosensors, and for in-line testing of manufactured conductive nanoelements.

INTRODUCTION

Nanoscience, or developing and fabricating materials at a very small scale (<100nm), is seeing unprecedented growth.[1-2] Nanoscale materials have a wide range of attractive properties such as large surface to volume ratio, high packaging density, and long-range order, which are very promising for novel technological applications.

Nanoparticles are used in the creation of novel systems such as nanosensors[3], nanoresonators[4], nanoactuators[5], nanoreactors[6], single electron tunneling devices[7], plasmonics[8] and nanowire based devices[9]. Recently, Kreuple et al[10]. have utilized a bottom-up approach to grow vertical carbon nanotubes to be used as integrated circuit interconnects, yet this approach required elevated temperatures (>500ºC) and was not IC compatible. The controlled assembly and manipulation of nanoparticles into 3D structures represents the first step towards the realization of high density microsystems. There have been several approaches for controlled manipulation of nanoparticles such as template-directed synthesis[11], atomic[12] and scanning force microscopy[13], nanotube nanotweezers[14], and nanorobotic manipulations[15]. Careful manipulation techniques have been used by the authors to obtain devices with nanoscale materials integrated on them via technologies such as optical lithography, e-beam lithography, CVD etc. However, most of these approaches have several drawbacks which limit their use on a large scale. Furthermore, all of these approaches are achieved on a planar 2D surface. It is fairly clear that a 3D approach will address the emerging needs of high density devices and miniaturization. Accordingly, utilizing a two mask process, we have developed a versatile micromachined platform (Figure 1) for the integration of nanomaterials into microdevices in a three-dimensional manner. Our approach is demonstrated for Au and Ag nanoparticles, and has potential applications for assembling other conductive nanostructures and in the development of 3D interconnects, 3D nano-electromechanical systems, and for the characterization of manufactured nanomaterials.

DIELECTROPHORETIC ASSEMBLY

Dielectrophoresis has become a powerful method for manipulation, trapping, and separation of micro- and nanoparticles. An electric field is used to set up a dielectrophoretic force which attracts the nanostructures in gaps where the gradient of the electric field is maximum or minimum. A polarizable object placed in this nonuniform electric field, due to its interaction with the field, exhibits a translation motion which forms the basis of dielectrophoretic assembly[16]. Dielectrophoresis occurs in both AD and DC electric fields, however AC fields are preferred since they allow manipulation and assembly of the nanocomponents while minimizing and/or suppressing the electrochemical and particle migration effects present using DC fields.[17]

The dielectrophoretic force can be expressed as[18]:

$$F_{DEP} \, \alpha \, \varepsilon_m \left((\varepsilon_p - \varepsilon_m) / (\varepsilon_p + 2\,\varepsilon_m) \right) \nabla E^2_{rms}$$

where εp and εm are the dielectric constants of the nanostructures and the solvent medium, respectively and *E*rms is the average field strength. Li and co-workers[19] have demonstrated the use of DEP for manipulation of carbon nanotubes for nanosensing applications while Washizu[20] and Burke[21] have shown that DNA and proteins can also be manipulated using AC electric fields. Amlani[22] and Fritzsche[23] have demonstrated DEP assembly of gold nanoparticles over a 2D structure, and we extend this method for assembling Ag nanoparticles on our 3D novel microfabricated platform (as illustrated in Figure 2). This approach overcomes most of the drawbacks of the other methods and is a versatile and widely applicable method which has direct applications in the realization of 3D interconnects, 3D nano-electromechanical systems, and for characterizing manufactured nanoelements.

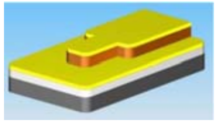

Figure 1: Micromachined platform for 3D assembly

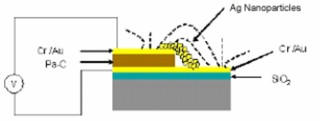

Figure 2: 3D Dielectrophoretic Assembly of silver nanoparticles

FABRICATION

The micromachined platform is fabricated utilizing a two mask self-aligned process. A schematic of the fabrication process is illustrated in Figure 3. A 1µm thick isolation oxide is first thermally grown on 3” silicon wafers. A Cr/Au (200Å/1500Å) layer is then deposited and patterned using liftoff process to serve as the first metal electrode layer (Figure 3 (i)). Next, a thin (0.7µm), pin-hole free parylene-C dielectric layer is deposited on to the wafer at room temperature. The second metal layer (Cr/Au-200Å/1500Å) is then deposited and patterned using lift-off process (Figure 3 (ii)). The two metal layers serve as the electrodes to assemble the nanostructures. By utilizing the second metal layer as a hard mask (in a self-aligned manner), the parylene-C layer is etched in an inductively coupled plasma (Plasmatherm 790) using O_2 (Figure 3 (iii)). In these experiments, commercially available Ag nanoparticles (BBInternational, Cardiff, UK) suspended in H_2O are utilized. The mean diameter of the Ag nanoparticles is 50nm. After applying an AC voltage of 8 Vp-p (peak to peak) at 1MHz[22] using a function generator (Agilent 33220A) to the microelectrodes, a droplet (2-3µl) of the solution containing the nanoparticles is dispensed on top of the electrodes with a pipette. After 1 minute of assembly at room temperature, the sample is blow dried with nitrogen and the power is turned off, resulting in the 3D assembled nanoparticle bridge (Figure 3 (iv)).

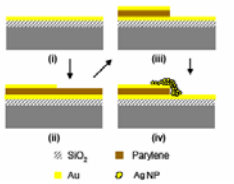

Figure 3: Fabrication Process for the 3D microplatform

NanoAssembly Electrodes
For these assembly experiments, we have designed platforms with single and multiple (8) fingers (an optical image is illustrated in Figure 4). A fabricated 3D platform before assembly is displayed in Figure 5. The width of a finger is selected as 2µm (limited by photolithography) and has an overlap of 3µm with the first metal layer. The assembly gap was designed as 0.7µm (thickness of the parylene-C layer) for these experiments, yet can be adjusted for other nanostructures. Fritzsche et al[24] state that the dimensions of the nanoparticles that can be assembled depends on the spacing between the electrodes, hence for our designs, a spacing of 0.7µm worked fairly well with particles of average size 50nm, yet for smaller size particles smaller gaps are recommended. Since the gap spacing is in vertical dimension, by utilizing thinner films, one can readily vary this spacing while assembling smaller nanostructures without the need for expensive tools (electron beam lithography).

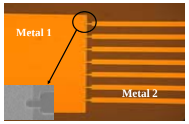

Figure 4: Multi-finger electrode structures for 3D assembly

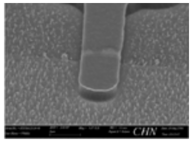

Figure 5: SEM micrograph of 3D platform before assembly

TEST RESULTS

Figure 6 shows Scanning Electron Microscope (SEM) micrographs of the 3D assembled nanostructures. Figure 7 shows a side-view of the assembled bridge. The observed large globular structures are possibly due to the melting of the particles due to current heating after a path is formed between the two electrodes[23]. A possible solution to limit the current damage would be to reduce the applied voltage required for assembly, however this approach significantly prolongs the assembly time. Another alternative is to use a nanofuse[24] which also minimizes the damage after a bridge is formed between the two electrodes. In this case, a 5.6 kOhms resistor was utilized in series with the 2 metal electrodes.[23]

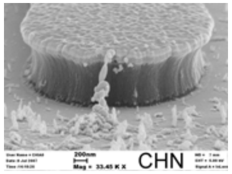

Figure 6. SEM micrograph of 3D assembly of 40nm Ag particles

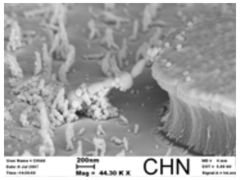

Figure 7. SEM side-view of Ag particle nanobridge

CONCLUSION

We have designed and fabricated a novel 2 mask platform for nanoassembly. Using dielectrophoresis, we have incorporated Ag nanoparticles of diameter ~50nm in a 3D bridge structure with had a two-terminal resistance between ~26-118Ω. This approach is quite versatile and can be extended to the integration of other conductive nanomaterials including nanowires, nanobelts and nanorods into devices and systems. Furthermore, due to its 3D orientation, it could potentially be used in making of high density stacked systems, high rate nanomanufacturing, and in-line characterization of nanoparticles.

REFERENCES

[1] K. Keren, R. S. Berman, E. Buchstab, U. Sivan, and E. Braun, “DNATemplated Carbon Nanotube Field-Effect Transistor,” *Science*, vol. 302, pp. 1380-1382, 2003.
[2] L. Sun, F. Banhart, A. V. Krasheninnikov, J. A. Rodriguez-Manzo, M. Terrones, and P. M. Ajayan, “Carbon Nanotubes as High-Pressure Cylinders and Nanoextruders,” *Science*, vol. 312, pp. 1199-1202, 2006.
[3] O. D. Velev and E. W. Kaler, “In Situ Assembly of Colloidal Particles into Miniaturized Biosensors,” *Langmuir*, vol. 15, pp. 3693-3698, 1999.
[4] K. L. Ekinci, X. M. H. Huang, and M. L. Roukes, “Ultrasensitive Nanoelectromechanical Mass Detection,” *Appl. Phys. Lett.*, vol. 84, pp. 4469-4471, 2004.
[5] W. C. Lee and Y.-H. Cho, “Bio-inspired Digital Nanoactuators for Photon and Biomaterial Manipulation,” *Current Appl. Phys.*, vol. 7, pp. 139-146, 2007.
[6] C. Roos, M. Schmidt, J. Ebenhoch, F. Baumann, B. Deubzer, and J. Weis, “ Design and Synthesis of Molecular Reactors for the Preparation of Topologically Trapped Gold Clusters,” *Adv. Mat.*, vol. 11, pp. 761-766, 1999.
[7] S. H. Hong, H. K. Kim, K. H. Cho, S. W. Hwang, J. S. Hwang, and D. Ahn, “Fabrication of Single Electron Transistors with Molecular Tunnel Barriers using AC Dielectrophoresis Technique,” *Jour. of Vac. Sci. Technol. B*, vol. 24, pp. 136-138, 2006.
[8] J. R. Krenn, J. C. Weeber, A. Dereux, E. Bourillot, J. P. Goudonnet, G. Schider, A. Leitner, and F. R. Aussenegg, “Direct Observation of Localized Surface Plasmon Coupling,” *Phys. Rev. B*, vol. 60, pp. 5029-5033, 1999.
[9] Y. Huang, X. Duan, Q. Wei, and C. M. Lieber, “Directed Assembly of One-Dimensional Nanostructures into Functional Networks,” *Science*, vol. 291, pp. 630-33, 2001.
[10] F. Kreupl, A. P. Graham, G. S. Duesberg, W. Steinhogl, M. Liebau, E. Unger, and W. Honlein, “Carbon Nanotubes in Interconnect Applications,” *Microelectron. Engg.*, vol. 64, pp. 399-408, 2002.
[11] P. Yang, A. Rizvi, B. Messer, B. F. Chmelka, G. M. Whitesides, and G. D. Stucky, “Patterning Porous Oxides within Microchannel Networks,” *Adv. Mater.*, vol. 13, pp. 427-431, 2001.
[12] W. R. Bowen, R. W. Lovitt, and C. J. Wright, “Application of Atomic Force Microscopy to the Study of Micromechanical Properties of Biological Materials,” *Biotechnol. Lett.*, vol. 22, pp. 893-903, 2000.
[13] R. Resch, C. Baur, A. Bugacov, B. E. Koel, A. Madhukar, A. A. G. Requicha, and P. Will, “Building and Manipulating 3-D and Linked 2-D Structures of Nanoparticles Using Scanning Force Microscopy,” *Langmuir*, vol. 14, pp. 6613-6616, 1998.
[14] P. Kim and C. M. Lieber, “Nanotube Nanotweezers,” *Science*, vol. 286, pp. 2148-2150, 1999.
[15] A. A. G. Requicha, C. Baur, A. Bugacov, B. C. Gazen, B. Koel, A. Madhukar, T. R. Ramachandran, R. Resch, and P. Will, “Nanorobotic Assembly of Two-Dimensional Structures,” *Proc. of IEEE Conf. on Robotics and Automation*, vol. 4, pp. 3368-3374, 1998.
[16] H. A. Pohl, “Dielectrophoresis: The Behavior of Neutral Matter in Nonuniform Electric Fields,” Cambridge Univ. Press, NY, USA, 1978.
[17] K. D. Hermanson, S. O. Lumsdon, J. P. Williams, E. W. Kaler, O. D. Velev, “Dielectrophoretic Assembly of Electrically Functional Microwires from Nanoparticle suspensions,” *Science*, vol. 294, pp. 1082-1086, 2001.
[18] R. Krupke, F. Hennrich, H. V. Lohneysen, and M. M. Kappes, “Separation of Metallic from Semiconducting Single-Walled Carbon Nanotubes,” *Science*, vol.301, pp.344-347, 2003.
[19] R. H. M. Chan, C. K. M. Fung, and W. J. Li, “Rapid Cssembly of Carbon Nanotubes for Nanosensiong by Dielectrophoretic Force,” *Nanotechnol.*, vol. 15, S672-S677, 2004.
[20] M. Washizu and O. Kurosawa, “Electrostatic Manipulation of DNA in Microfabricated Structures,” *IEEE Trans. on Industry Appl.*, vol. 26, pp. 1165-1172, 1990.
[21] L. Zheng, J. P. Brody, and P. J. Burke, “Electronic Manipulation of DNA, Proteins, and Nanoparticles for Potential Circuit Assembly,” *Biosensors and Bioelectron.*, vol. 20, pp. 606-619, 2004.
[22] I. Amlani, A. M. Rawlett, L. A. Nagahara, and R. K. Tsui, “An Approach to Transport Measurements of Electronic Molecules,” *Appl. Phys. Lett.*, vol. 80, pp. 2761-2763, 2002.
[23] J. J. Boote and S. D. Evans, “Dielectrophoretic Manipulation and Electrical Characterization of Gold Nanowires,” *Nanotechnol.*, vol. 16, 1500-1505, 2005.
[24] R. Kretschmer and W. Fritzsche, “Manipulation of Metal Nanoparticles in Micrometer Electrode Gaps by Dielectrophoresis,” *American Inst. of Phys. Conf. Proc.*, vol. 725, pp. 85-87, 2004.

CLASSROOM CONNECTION

Students will partake in a symposium on nanoethics, the goal of which is to engage students in discourse about significant topics in nanotechnology, and potential implications on individuals and society.

The strengths of the symposium are that students will be exposed to a new topic of which concepts are interesting, accessible, and relevant to the students. Discussions are grounded in scientific concepts, and students will be given the opportunity to acquire scientific values and attitudes such as curiosity, openness to new ideas, acceptance of ambiguity, the ability to work cooperatively, the willingness to modify explanations in light of new evidence, and taking intellectual risks.

Research Experiences for Teachers at Northeastern University
Claire Duggan, Program Director

This work was supported by the National Science Foundation
Grant #0227577,#9986821, #0425826