Research Proposal for

Fabrication of Nanostructured Strain Sensor

Submitted to:

CiSTUP
Indian Institute of Science
Bangalore 560 012

Investigator(s) from IISc: S.Venugopal, Kesava K Rao

From: Name: S. Venugopal

Department: Chemical Engineering
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Centre for infrastructure, Sustainable Transportation and Urban Planning
Indian Institute of Science

APPLICATION FOR GRANT OF RESEARCH / DEVELOPMENT PROJECT

PART –A

1	Title of research/ development Proposal	Fabrication of Nanostructured Strain Sensor
2	Name of the Principal Investigator Designation and Address	S, Venugopal, Assistant Professor, Department of Chemical Engineering, IISc. Ph: 2293 3113 venu@chemeng.iisc.ernet.in
	Name of the Co- Investigator (s) from IISc Designation and Address, Phone, Fax, Email, Mobile Numbers	Kesava K Rao, Professor, Department of Chemical Engineering, IISc. Ph: 2293 2341 kesava@chemeng.iisc.ernet.in
	Name of the Co-Investigator(s) from other connected Agency Designation and Address, Phone, Fax, Email, Mobile Numbers	**NA**
3	Proposed duration of the research/development proposal	2 Years
	Proposed date of commencement of project	April 1, 2013.
4	Amount of grant proposed for	Rs. 5,17,500/- (See Appendix – A for details)
5	Department of the institution where R & D project will be carried out	Chemical Engineering
	Other department if any, which will co-operate in this study	CeNSE facilities will be used for microstructural characterization
	Details of financial support sought/obtained from other agencies	
6	Specific Aim of the Project	Appendix B
	Summary of Proposed research/facilities and objectives (brief statement about the proposed investigation, its conduct and the anticipated results in not more than 300	Appendix B

	words)	
	Key words	Appendix B
	Classification of the project	
7	Background and justification	
	(Basis for the proposal with a brief review of the state of the art in the subject, followed by an outline of the relevance and importance of the project, in particular, towards research/development/design related to CiSTUP programs	Appendix C
8	Approach (details of the actual approach indicating how each of the objective listed in item 6 (a) will be achieved); deliverables, Task schedule and bar chart	Appendix C
9	Previous work done in this or related fields Describe briefly any work done that is particularly pertinent to the proposal & list: (I) your personal publications in this & related areas	Appendix C
10	Expected Contributions from other collaborators	Appendix C

I certify that a detailed technical report describing the research work/ procedure and its findings will be submitted before the closure of the project.

Date: Signature of the Principal Investigator

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APPENDIX – A

Project Title: **Fabrication of Nanostructured Strain Sensor**

Amount of Grant Proposed: **Rs 5,17,500**

Grants (In Lakhs of Rupees)	I Year	II Year	Total
(a) Salary#			
(b) Equipment⊗			
(c) Working Expenses*	2,50,000	2,00,000	4,50,000
Sub-Total	2,50,000	2,00,000	4,50,000
(d) IISc Overheads ≈@15%	37,500	30,000	67,500
Total	2,87,500	2,30,000	5,17,500
Grand Total			**5,17,500**

List of important consumable/components with approximate cost:-
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1. Photolithography related consumables: Photoresist & developer, smooth and flexible plastic substrates etc. 2,00,000
2. Gold salt for synthesizing nanoparticles: 1,00,000

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APPENDIX – B

Project Title: **Fabrication of Nanostructured Strain Sensor**

1. SPECIFIC AIM/ OBJECTIVE OF THE PROJECT:

1) To fabricate strain sensor elements consisting of mono/multilayer ordered films of gold nanoparticles
2) To evaluate the response characteristics of the strain sensor and optimization of array parameters such as nanoparticle diameter and interparticle spacing.

2. SUMMARY OF PROPOSED RESEARCH:

We propose to fabricate a strain sensor using arrays of ordered gold nanoparticles on a flexible substrate. Changes in applied strain lead to reversible changes (over a large dynamic range) in interparticle spacing within arrays of nanoparticles, and the electrical conductivity of ordered assemblies of nanoparticles are strongly influenced by the interparticle spacing. We propose to harness these two features to form strain sensors with high gauge factors by fabricating devices, wherein an array of nanoparticles is used to transduce an applied strain into an electrical signal.

Keywords:

Strain sensor, Gold nanoparticles, 2D array, Gauge factor.

APPENDIX – C

Project Title: **Fabrication of Nanostructured Strain Sensor**

Background and justification

Strain sensors find applications in human and robotic motion detection and monitoring structural health in buildings. Nanomaterials like metal nanoparticles (NPs), graphene, carbon nanotubes (CNTs) are the new class of materials that are currently being considered for fabricating low-cost, strain sensors. In a typical device made from CNTs or graphene, the CNT or graphene solution is sprayed onto a substrate and then their strain sensing capability is studied [1-3]. In case of nanoparticles, either a solution is drop cast on the electrode or wires are fashioned out of colloidal solution using convective self-assembly [4-6]. The electron transport through nanoparticle assemblies is either governed by the mechanism of electron tunneling or electron hopping. For a given system of nanoparticle and ligand, the tunneling process is only dependent on the interparticle distance; whereas, the hopping process is further dependent on the size of the nanoparticles and temperature also. Hermann et al. [5] have modeled the sensitivity of a strain sensor made of nanoparticle film by using a simple model as depicted in Fig.1.

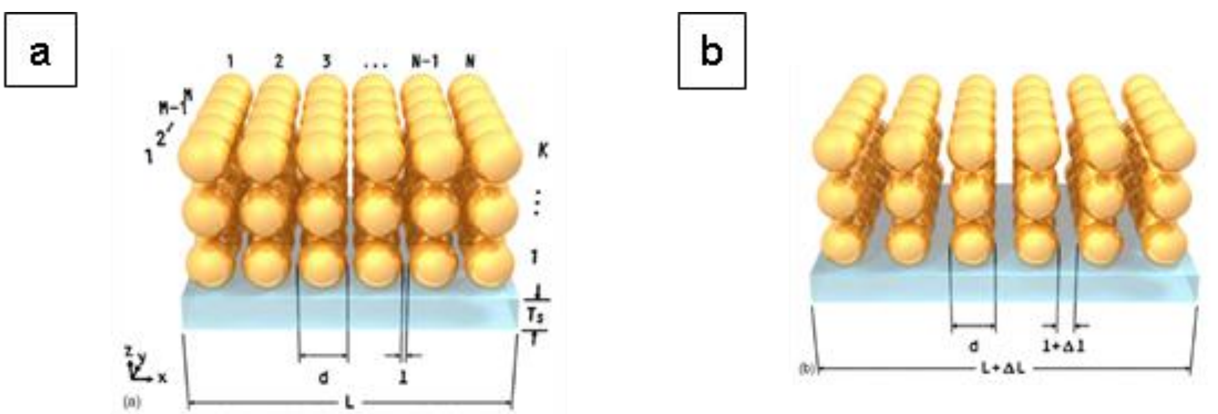


Figure 1: (a) Schematic representation of the NP film in unstrained geometry (b) When the film is subjected to strain in the x direction, and the length changes from L to ΔL, in the model the strain is represented as a change in the interparticle distance l to Δl. (Reproduced from [5])

The sensitivity of the film when modeled as above, is calculated as

$$\frac{\Delta R / R}{\epsilon} = \beta \left(d + l \right) \quad \ldots (1)$$

Where β is tunneling coefficient

Since typical values for $\beta \cong 10$ nm-1 and if (d+l) is 10 nm, the gauge factor of such a device would be $\cong 100$. This value is comparable with the state of the art semiconductor strain gauges that are manufactured using microelectronic fabrication techniques. The gauge factors obtained using gold nanoparticles are found to be about one to two orders of magnitude greater than a simple metal foil. This also shows that sensitivity of a strain gauge can be increased by modifying the particle diameter and ligand. Farcau et al. [6] studied the strain sensing characteristics of sensors made out of wires fabricated using convective self-assembly. They found that as the height of the wire decreases their sensitivity increases, but at the cost of increased resistivity. A drawback of the convective self-assembly process is the inability to form nanowires at desired locations on the substrate, i.e. one has to search and locate areas where nanowires have formed, rendering this approach non-scalable. Siffalovic et al. [7] studied a monolayer film of nanoparticles on a membrane using SAXS. They observed that the interparticle distance changed linearly with the strain only in the direction of the stress. There was no change in the interparticle distance, in the orthogonal direction of the applied stress. This implies that the monolayer remains intact, and the primary effect of the applied stress is the change in the interparticle distance.

These studies indicate that a change in conductance, which is sensitive to the change in the interparticle distance of nanoparticle arrays, can be harnessed to manufacture strain sensors; provided a nanoparticle monolayer arrays can be fabricated in a reliable and scalable process. Another challenge in using the processes reported in the literature for fabricating nanostructured strain sensors is their relatively large baseline resistance (Table 1), which necessitates the use of sophisticated current measuring circuitry and renders such processes less cost-effective. **The objective of this proposal is to address these two issues by developing a scalable process for fabricating robust strain sensors based on monolayers of gold nanoparticles.**

Table 1 - A summary of the strain gauge characteristic values reported in literature

Nanomaterial	Initial Resistance	Strain	Gauge factors
CNT	kΩ	0.6 - 280%	0 - 6
Graphene	kΩ – GΩ	0 - 2%	15 – 150
Metal nanoparticles	MΩ	0 - 5%	50 - 200

Approach

Our approach to tackle the two issues outlined above is as follows. Fig. 2 depicts the proposed steps involved in the fabrication of a strain gauge. We will utilize a RF plasma process, recently developed by our group [8], to fabricate robust, "bare" nanoparticle arrays starting from self-assembled, large-scale arrays of ligand-coated gold nanoparticles. The ligands are needed during the self-assembly step from an organosol, but limit the physical and chemical robustness of the nanoparticle array, post-assembly. The 'plasma-treated' arrays can withstand the chemical and physical treatments required for fabrication of electrodes using photolithography; thereby enabling the fabrication of metal nanoparticle based strain sensors in a scalable manner. We will tune the array parameters (i.e. particle size and spacing), as well as the number of layers to maximize the baseline signal as well as their sensitivities.

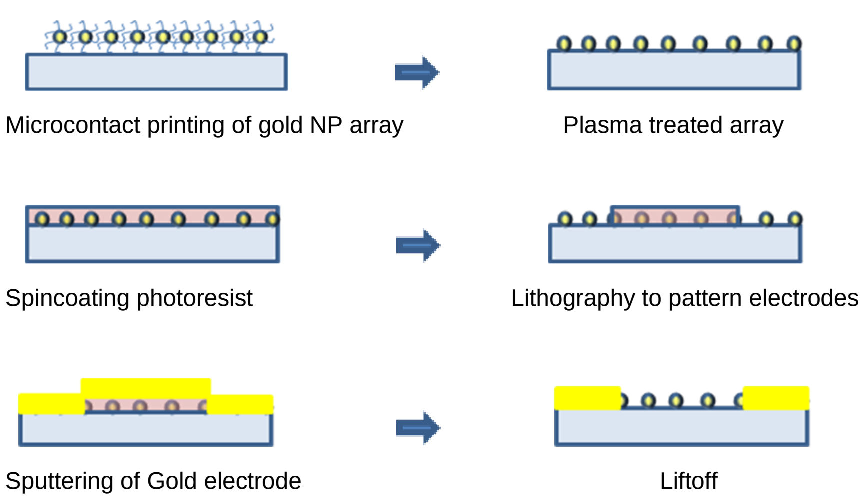
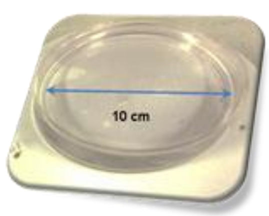


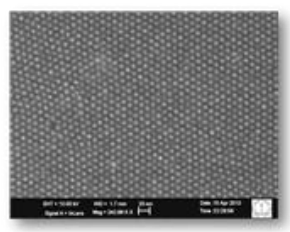
Figure 2: Steps involved in fabrication of strain sensor

Previous work done in this area

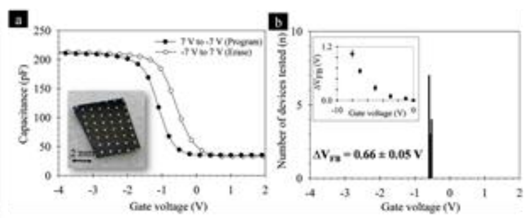
Our group has been working in the area of nanoparticle engineering and device fabrication for the last eight years at IISc. Over these years, we have developed processes for synthesizing monodisperse, ligand-coated, gold nanoparticles and forming large-scale ordered arrays of ligand-coated gold nanoparticles, by harnessing self-assembly from colloidal solution [8]. Recently, we have also developed a novel process for fabricating robust metal nanoparticle arrays by removing the ligands coating the nanoparticles [9]. As an example of device fabrication, such regular and ordered nanoparticle arrays were used to fabricate floating gate memory devices. These devices show reproducible memory windows in a MOS capacitor structure, attesting to their uniformity at the wafer-scale [10].



Digital photograph of wafer scale, ordered monolayer of gold nanoparticles formed by self-assembly on a water surface



FESEM image of an ordered monolayer of 7 nm gold nanoparticles, transferred onto a silicon substrate



Capacitance-Voltage characteristics of a floating gate capacitor fabricated using gold nanoparticles as the charge storage layer. The memory window (hysteresis) is reproducible and repeatable across several devices

Facilities Available:

In our laboratory we have the facility for synthesizing gold nanoparticles and their ordered assemblies, and characterizing these using Dynamic Light Scattering (DLS), Atomic Force Microscope (AFM), and Field Emission Scanning Electron Microscope (FESEM). We also have access to a maskless lithography system, e-beam evaporator and electrical probe station for fabricating interdigitated electrodes and electrical characterization of sensor response.

REFERENCES

1. Lipomi, D. J.; Vosgueritchian, M.; Tee, B. C. K.; Hellstrom, S. L.; Lee, J. A.; Fox, C. H.; Bao, Z., Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes. *Nat Nano* **2011,** *6* (12), 788-792.
2. Yamada, T.; Hayamizu, Y.; Yamamoto, Y.; Yomogida, Y.; Izadi-Najafabadi, A.; Futaba, D. N.; Hata, K., A stretchable carbon nanotube strain sensor for human-motion detection. *Nat Nano* **2011,** *6* (5), 296-301.
3. Hempel, M.; Nezich, D.; Kong, J.; Hofmann, M., A Novel Class of Strain Gauges Based on Layered Percolative Films of 2D Materials. *Nano Letters* **2012,** *12* (11), 5714-5718.
4. Farcau, C.; Sangeetha, N. M.; Moreira, H.; Viallet, B.; Grisolia, J.; Ciuculescu-Pradines, D.; Ressier, L., High-Sensitivity Strain Gauge Based on a Single Wire of Gold Nanoparticles Fabricated by Stop-and-Go Convective Self-Assembly. *ACS Nano* **2011,** *5* (9), 7137-7143.
5. Herrmann, J.; Muller, K. H.; Reda, T.; Baxter, G. R.; Raguse, B.; de Groot, G. J. J. B.; Chai, R.; Roberts, M.; Wieczorek, L., Nanoparticle films as sensitive strain gauges. *Applied Physics Letters* **2007,** *91* (18), 183105-3.
6. Farcau, C.; Moreira, H.; Viallet, B.; Grisolia, J.; Ciuculescu-Pradines, D.; Amiens, C.; Ressier, L., Monolayered Wires of Gold Colloidal Nanoparticles for High-Sensitivity Strain Sensing. *The Journal of Physical Chemistry C* **2011,** *115* (30), 14494-14499.
7. Siffalovic, P.; Chitu, L.; Vegso, K.; Majkova, E.; Jergel, M.; Weis, M.; Luby, S.; Capek, I.; Keckes, J.; Maier, G. A.; Satka, A.; Perlich, J.; Roth, S. V., Towards strain gauges based on a self-assembled nanoparticle monolayer—SAXS study. *Nanotechnology* **2010,** *21* (38), 385702.
8. Muralidharan, G.; Sivaraman, S. K.; Santhanam, V., Effect of substrate on particle arrangement in arrays formed by self-assembly of polymer grafted nanoparticles. *Nanoscale* **2011,** *3* (5), 2138-2141.
9. Sankar, K. S.; Venugopal, S., Realization of thermally durable close-packed 2D gold nanoparticle arrays using self-assembly and plasma etching. *Nanotechnology* **2012,** *23* (25), 255603.
10. Muralidharan, G.; Bhat, N.; Santhanam, V., Scalable processes for fabricating non-volatile memory devices using self-assembled 2D arrays of gold nanoparticles as charge storage nodes. *Nanoscale* **2011,** *3* (11), 4575-4579.

Task schedule (Important Milestones for research reviews/completion of tasks)

1st year: Developing a set-up for applying a known strain value on substrates
Optimization of protocols for fabricating interdigitated electrodes on flexible substrates for electrically contacting nanoparticle arrays
Electrical characterization of strain sensor response

2nd year: Fabrication of nanoparticle arrays with different particle sizes and interparticle spacings
Characterization of strain response as a function of array parameters (i.e. size and spacing)
Modification of sensor design to maximize response to strain, based on these results

Deliverables

1st year: Optimized protocols for forming electrically connected nanoparticle arrays on flexible substrates
Development of a set-up for applying a desired strain on a given substrate
Preliminary results on electrical characterization of the response of nanoparticle arrays to strain
Submission of interim technical report

2nd year: Optimization of nanoparticle array parameters to maximize the gauge factor of the nanostructured strain sensors
Submission of final technical report

Bar chart of Milestones for listed tasks