

Next-generation Integrated Sensors & MEMS

Industry Co-Development Center (ICC) with Industry Consortium for Next Gen Research and Workforce



Bhaskar Mitra
IIT Delhi



Venkatesh KP Rao
BITS Pilani



Jyotirmoy Roy
WIPRO

Global Faculty Collaborators



Prof. Ravinder Dhaiya
NorthEastern



Prof. Sunil Bhawe
Purdue

Ministry Partners



Harsha S



Nagahanumaiah



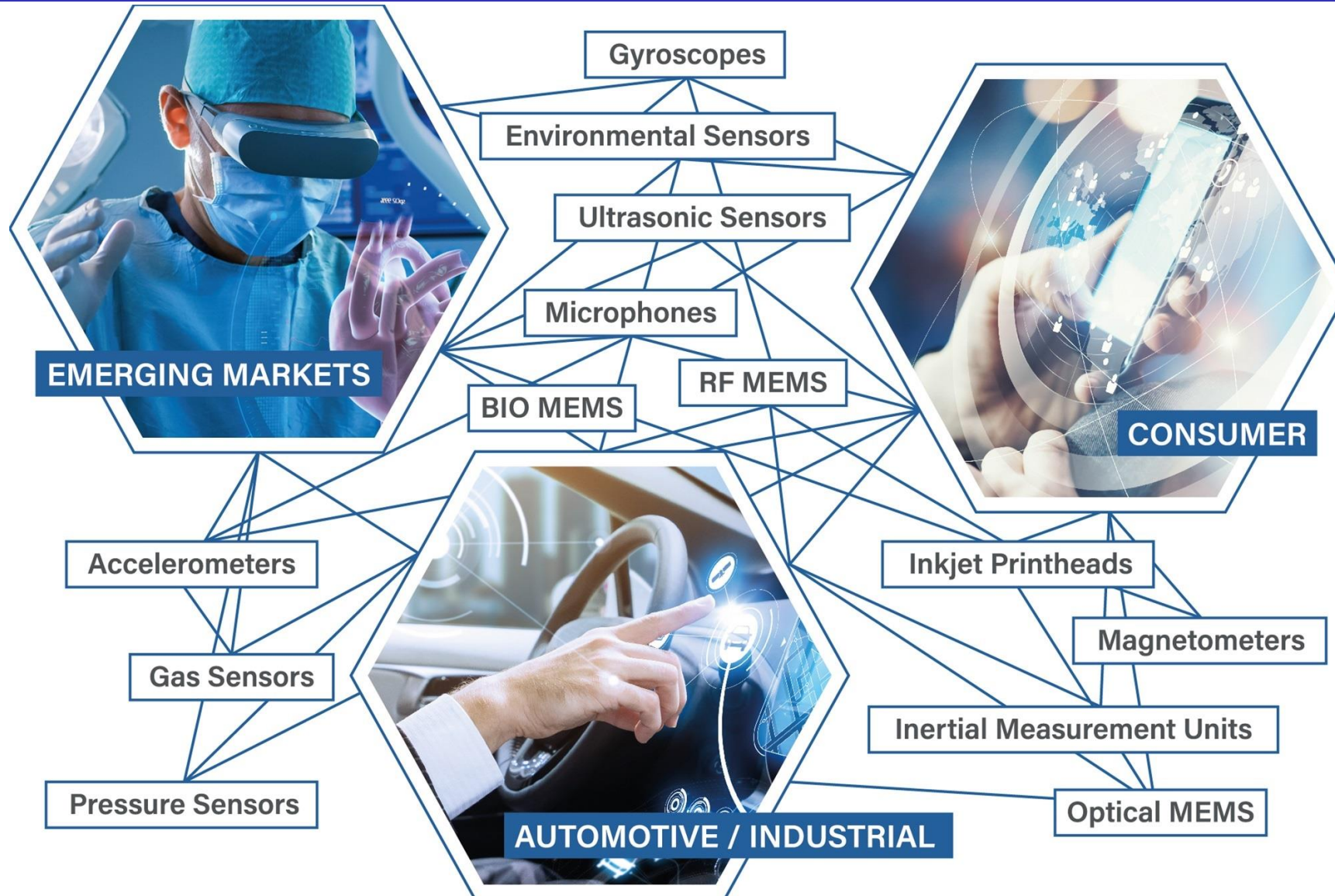
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India Semiconductor Mission

Indian DSPS R&D Team: Together, We Can.

ICC Research Areas



Faculty Team



Prof. Bhaskar Mitra
IITD
Inertial Sensors and Packaging



Prof. Sanket Goel
BITS Pilani
LIG Sensors



Prof. Subho Dasgupta
IISc.
Printed Electronics, Sensors



Prof. Satish Dubey
BITS Pilani
Microfluidics



Prof. R N Ponnalagu
BITS Pilani
System on chip



Prof. Venkatesh KP Rao
BITS Pilani
Electronic Skin, Packaging



Prof. Madhusudan Singh
IITD
Chemical Sensors, Printed Sensors
and Displays



Prof. Karabi Biswas
IIT KGP
Sensors Triboelectric Energy
Harvesters



Prof. Debanjan Das
IIT KGP
Triboelectric Energy
Harvesters



Prof. Ribu Mathew
MAHE
Mutiphysics Simulation

Next Generation Sensors and MEMS

Industry needs addressed:

- ❖ Closed loop sensors by use of piezoelectrics
- ❖ CMOS-MEMS Integration with low inductance interconnects
- ❖ Reducing dependence on submicron air-gaps for high performance devices
- ❖ Thin film encapsulation and high performance packaging with hybrid bonding
- ❖ In-device test and calibration
- ❖ IOT Stack development: Printed batteries, Energy harvesters, Printed Circuits and Sensors
- ❖ Biomedical and Wearables: Post Moore's law era: New Sensors for new markets
- ❖ Any others as per member requirements

Potential Industry and Government Agency Partners



Objectives in 3 categories — Research, Education and Industry partnership

1. Set up the research and education infrastructure for one or more India-wide Industry-centric for Research, education and industry collaborations.
2. Define **multi-disciplinary** research Program consistent with **industry needs involving industry engineers**.
3. Set up **industry consortium** in this ICC for industry collaboration and technology transfer.
4. Train UG & PG students on topics related to next-gen Integrated MEMS and Sensors. Develop hands-on educational labs in 10 or more institutions in the country.
5. Train industry professionals by conducting regular PDCs.
6. Incorporate this domain in regular curriculum through regular courses, electives and hands-on instructional laboratories.

Strategic Research Areas



Emerging Devices: New Device concepts in Inertial Sensors, Resonators, Printed Sensors, Sensors for IOT and Wearables



New Materials and Processes: Sensors utilizing 2D materials grown on wafer scale; Materials for key technology challenges (MEMS die attach)

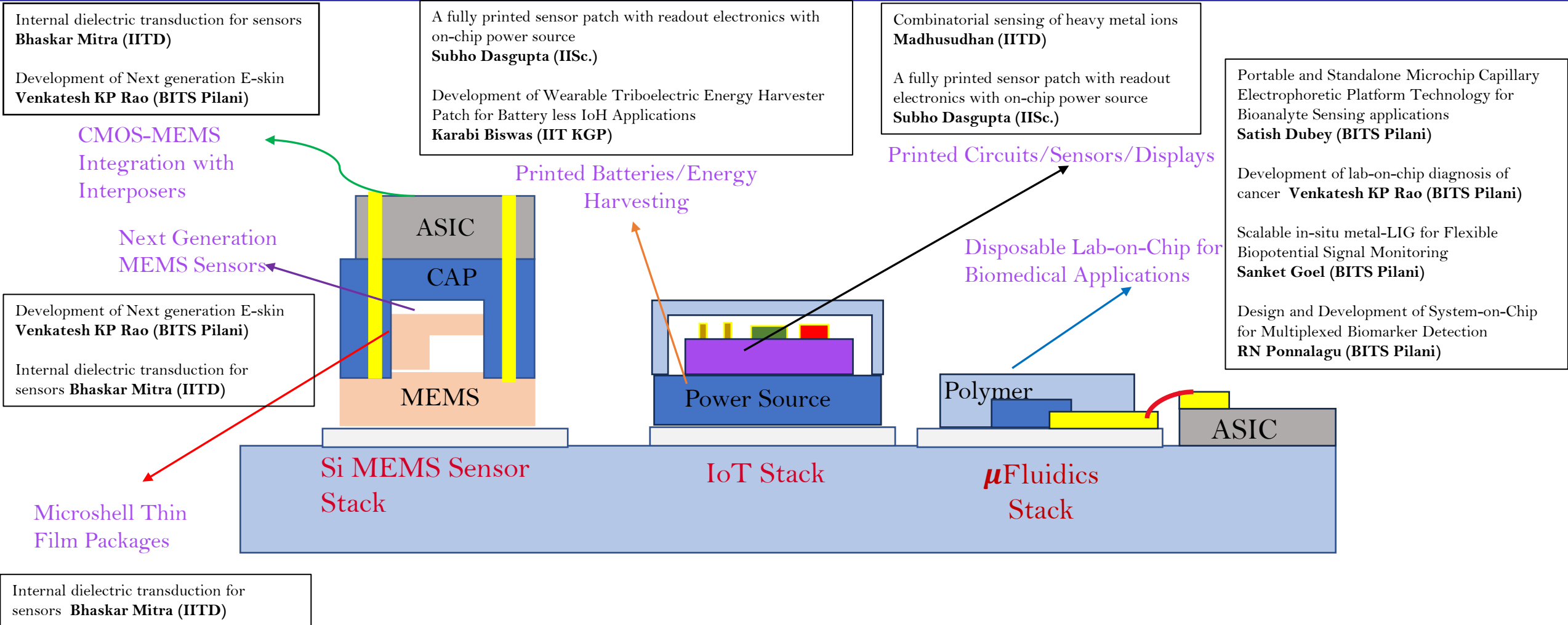


Sensor Fusion: Technologies for MEMS/CMOS integration, operation in harsh environments (higher temperature/waterproof/in-vivo) and application of chiplet concept to MEMS and Sensors

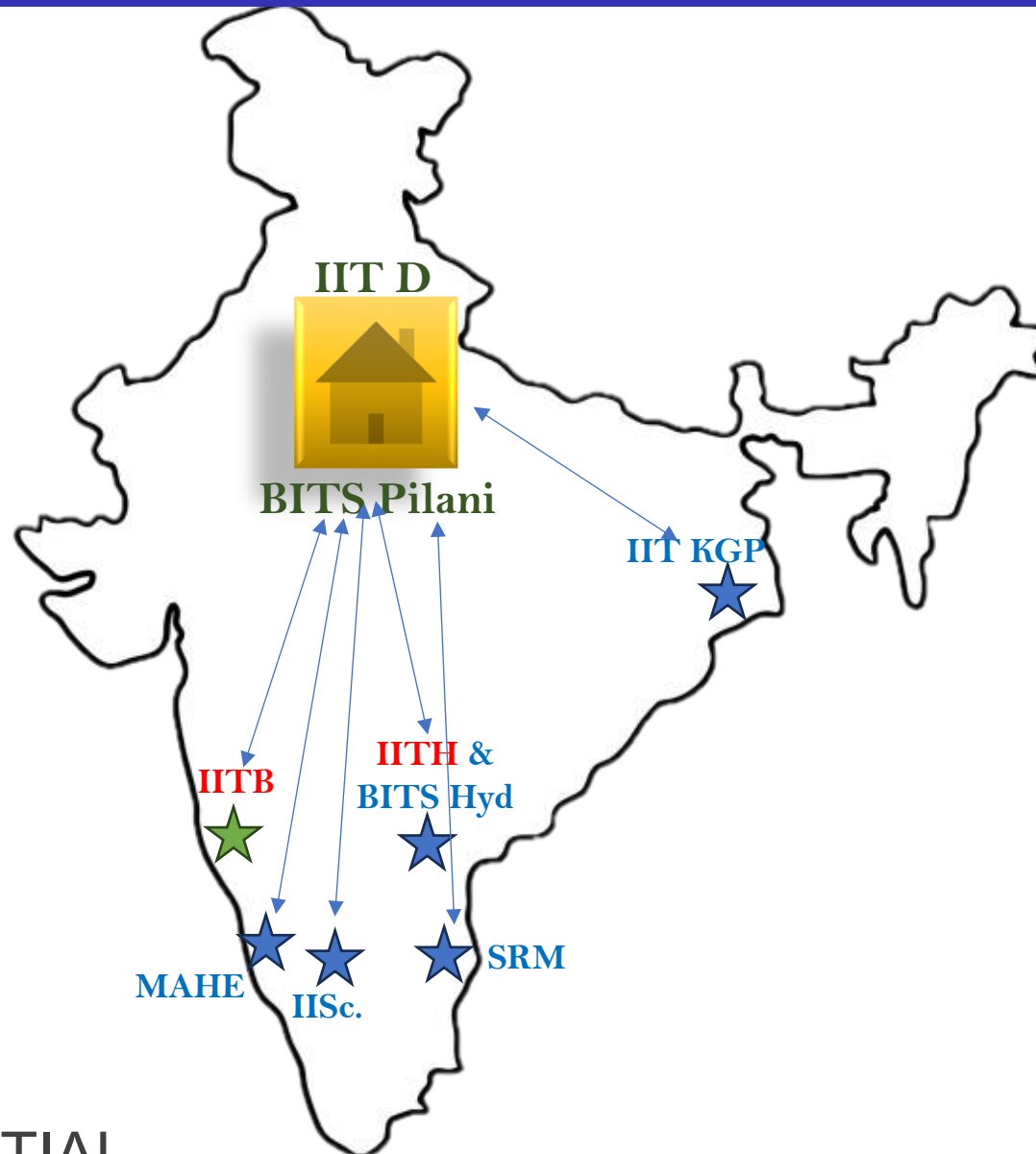


Testing and Reliability: Strategies for wafer level testing; protocols for evaluating and improving reliability of MEMS

Strategic Research Areas



ISM Hub & Spoke



Hub/Industry co-development Center



Core ICC Spokes



Cross ICC Spokes



Educational Programs at B.Tech, M.Tech and Ph.D and PDC levels.

- **Development of hands-on instructional laboratories**

Existing framework provides very superficial introduction to clean room practice. We want to create instructional elements focused on state of the art in MEMS and Sensors. This will cover design, Fab and Test.

- **Incorporation into regular curriculum**

Senior UG and Masters level elective courses with both classroom and hands-on components (Already present at all Major IIT's, IISc and BITS Pilani)

- **Aggressive Outreach**

Short-term outreach courses (both online and offline) will be used to create trained manpower for the industry.

5 years milestones

- **Year 1:** Equipment Procurement, Set up Facility
- **Year 2:** New Processes: ScAlN, BEOL-CMOS MEMS, Printing for Combinatorial Sensing, Internal Dielectric Transduction
- **Year 3:** Products ready at TRL 5 : Sensor Characterized
- **Year 4:** System Integration with Circuitary and Packaging
- **Year 5:** System ready at TRL 7: Ready for Production (Connect with National Sensor Hub @SCL Mohali if needed)

Research projects with faculty leads and Institutions

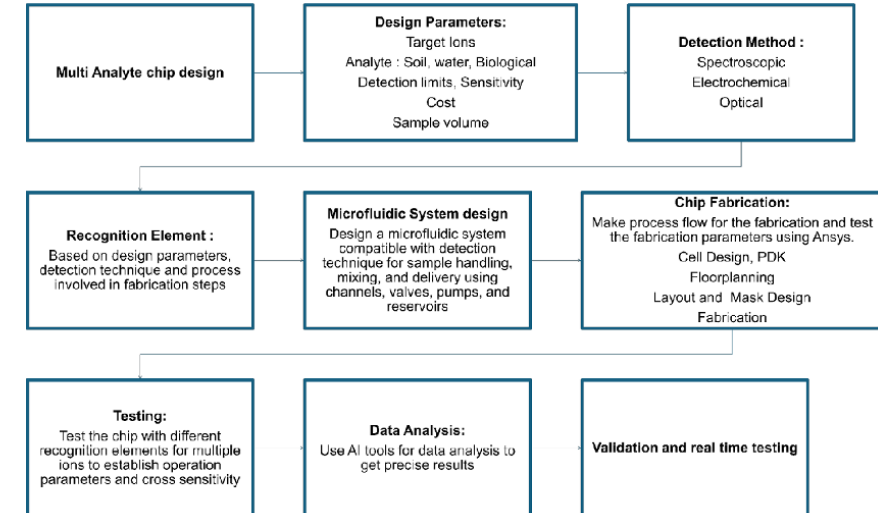
1. Combinatorial sensing of heavy metal ions
 - **Madhusudhan (IITD)**, Bhaskar Mitra (IITD), Jayadeva(IITD)
2. Internal dielectric transduction for sensors
 - **Bhaskar Mitra (IITD)**
3. A fully printed sensor patch with readout electronics with on-chip power source
 - **Subho Dasgupta (IISc)**
4. Development of Next generation E-skin
 - **Venkatesh KP Rao (BITS Pilani)**
5. Development of Wearable Triboelectric Energy Harvester Patch for Battery less IoH Applications
 - **Karabi Biswas (IIT KGP) and Debanjan Das (IIT KGP)**
6. Portable and Standalone Microchip Capillary Electrophoretic Platform Technology for Bioanalyte Sensing applications
 - **Satish Dubey(BITS Pilani)**
7. Development of lab-on-chip diagnosis of cancer
 - **Venkatesh KP Rao (BITS Pilani)**
8. Scalable in-situ metal-LIG for Flexible Biopotential Signal Monitoring
 - **Sanket Goel (BITS Pilani)**
9. Design and Development of System-on-Chip for Multiplexed Biomarker Detection
 - **RN Ponnalagu (BITS Pilani)**
10. Development of Next Generation NEMS Technology Piezoresistive Sensors with High Sensitivity & Reduced Non-linearity for Chemical/Gas Sensing Applications
 - **Ribu Mathew (MAHE)**

Project 1: Combinatorial Sensing of Heavy Metal Ions in Liquid Discards

PI: Madhusudan Singh (IITD) Co-PIs: Bhaskar Mitra (IIT Delhi), Jayadeva (IIT Delhi)

- Objective** –
- Designing sensors for multi-ion sensing is based on analyte's composition and application area.
 - The sensor design further needs an appropriate detection technique and stable recognition element that can be used for real-time monitoring of ions.
 - AI model developed for the specific site

	Current state*	Proposed
Cd LoD (ug/L)	40	11
Cu LoD (ug/L)	100	18



1. Vinayak, P.; Devi, H. S.; Mitra, B.; Singh, M. A Low-Cost Resilient Chalcogenide Ion-Sensitive Electrode for Copper Sensing With an LoD<20 ppb. *IEEE Sensors Letters* 2022, 6 (9), 1–4. <https://doi.org/10.1109/LSENS.2022.3197166>.
2. Mitra, B.; Singh, M.; Sapra, S.; Vinayak, P.; Hassan, Md. S. Nano Heterostructures of Transition Metal Dichalcogenide Sensing Film Based Extended Gate Field-Effect Transistor for the Sensing of Heavy Metals. *515585*, February 27, 2024.
3. Mitra, B.; Singh, M.; Vinayak, P.; Saha, S.; Devi, H. S. Low Cost Electrochemical Sensor. 363412, March 28, 2021.

Device fabrication

Device fabrication

Project 2: Internal Dielectric Transduction for Sensors

PI: Bhaskar Mitra (IITD)

Objectives

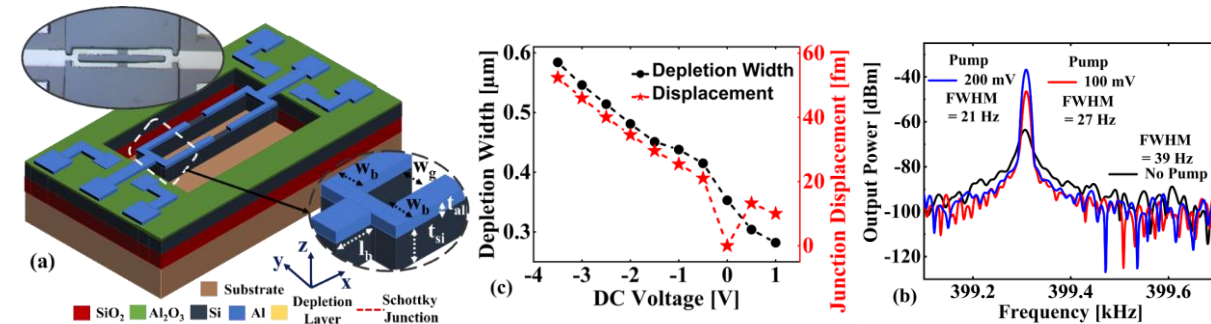
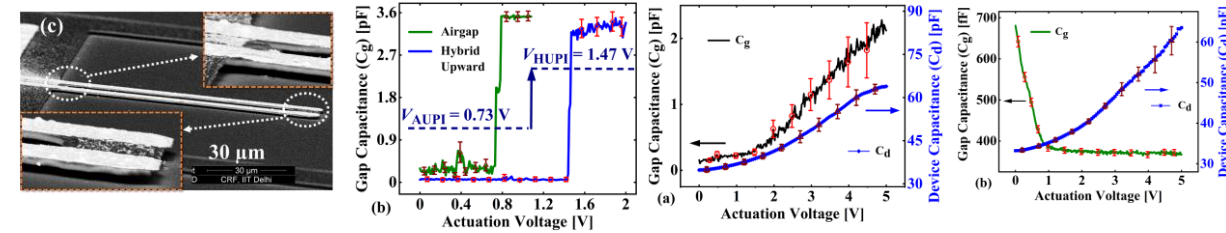
- To design and fabricate Silicon MEMS pressure sensors, flow sensors and accelerometers based on internal dielectric transduction.
- To achieve Integration with CMOS process
- To characterize the device over frequency and temperature corners

- ID transducers use the squeezing of an ultrathin dielectric film or depletion region in junctions to measure stress
- The established technique for Bulk Resonators and filters: we have applied it to switches and flexural resonators
- The transduction principle can be applied to pressure sensors, accelerometers, flow sensors, microphones, etc.
- Can address the Huge gap between consumer and navigation grade accelerometers.

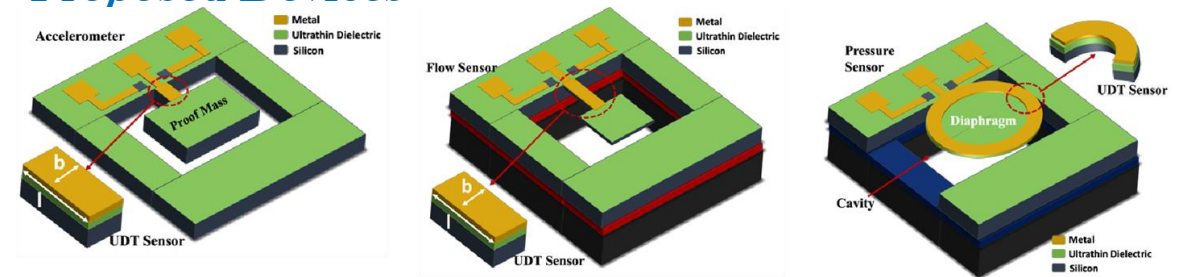
Parameter	Current state of the art	Proposed
Device Structure	3-Wafer stack with tunneling current readout	Single Wafer solution with internal dielectric.
Cost and scalability	Expensive and yield issues in bonding	Single wafer process likely to lower cost.

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ID Switches, Actuators, Resonators, Filters



Proposed Devices



Accelerometer, Flow Sensor and Pressure Sensor transduction using ID Resonators



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Project 3: A fully printed sensor patch with readout electronics with on-chip power source

PI: Subho Dasgupta (IISc)

Objectives

1. Printed batteries/supercapacitor-based power source
2. Realization of fully-printed sensor or anti-counterfeit tags on flexible substrates with printed ADC.
3. Study of the reliability/ scalability and life cycle analysis of the sensor or anti-counterfeit tag.
4. Study of the device performance in response to environmental variables.

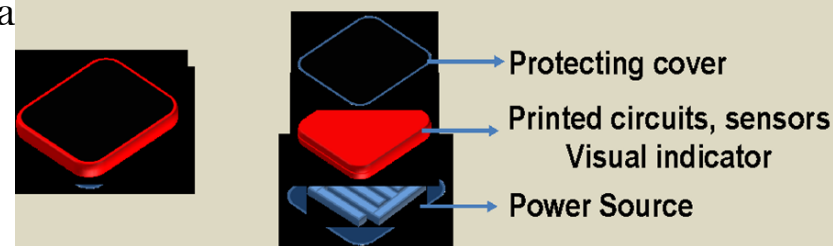
Parameters	Current state of the art	Proposed
Sensor patch with readout electronics and visual indicator	Si technology/ Oxide Fabrication: UHV techniques/ sputtering	Material: Oxides/ novel 2D materials Fabrication: Printing
Circuit complexity	High	Low
Cost	High	Extremely low (a small fraction of ₹)
Substrate flexibility	Low	High

INDUSTRY NEED AND APPLICATIONS

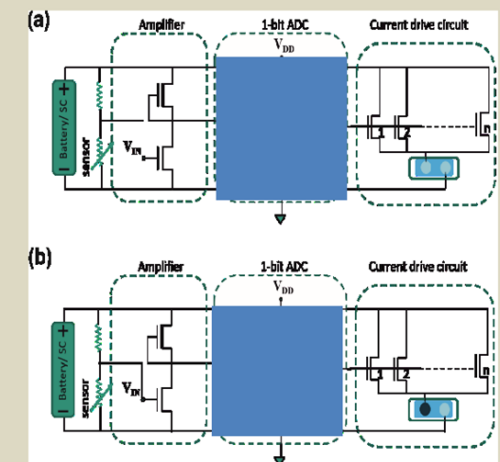
- Toxic gas sensors for industrial premises
- VOC sensor for food storage
- Temperature sensor for food and pharmaceutical safety and storage integrity
- UV sensor for pharmaceutical industry
- Pressure/ proximity sensor for wide applications
- Anti-counterfeit tag for product authenticity.

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Sensor chip design



* We own IP on ADC the design and the entire idea



Project 4: Development of Next-generation Electronic Skin

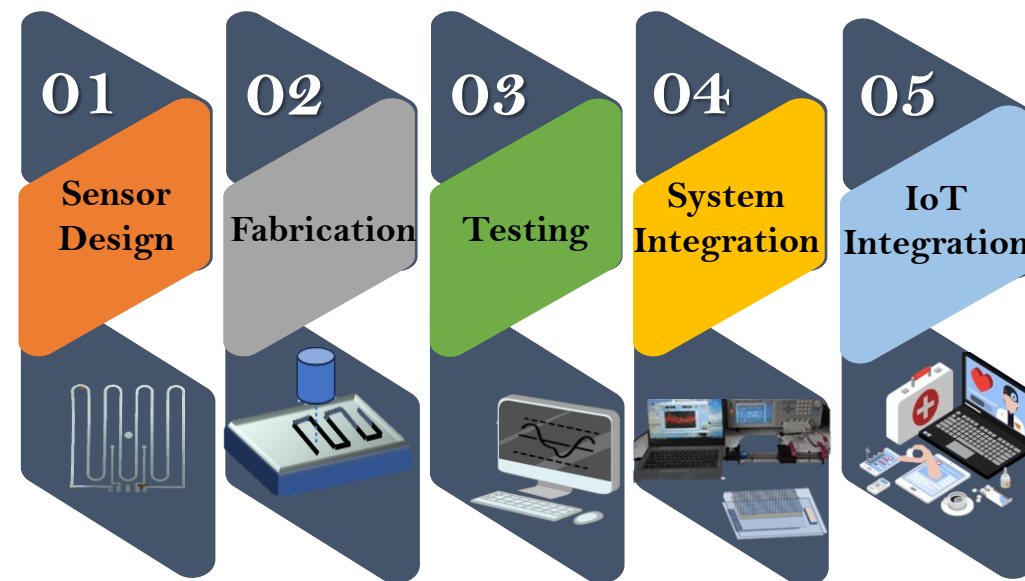
PI: Venkatesh KP Rao (BITS Pilani)

Objectives

1. Development of E-skin to mimic human skin's sensitivity for precise detection of pressure, temperature, humidity, and touch.
2. Integrate these sensors with IoT for real-time data collection and seamless communication

The project aims to develop electronic skin sensors with human-like sensitivity to pressure, temperature, humidity, and touch, enabling accurate environmental monitoring and real-time data sharing through IoT integration.

Approach



Outcome

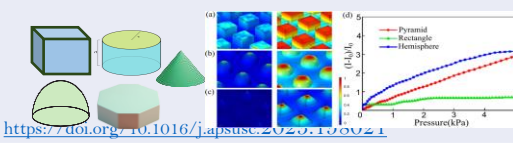
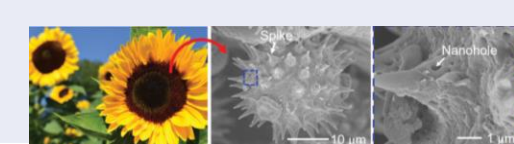
1. Developed a highly sensitive E-skin that accurately detects pressure, temperature, humidity, and touch, resembling human skin.
 2. Integration of E-skin in wearables provided real-time physiological feedback, enabling better health management and timely interventions.
1. Fei Li *et al.*, Flexible pressure sensors tuned by interface structure design – Numerical and experimental study, *Applied Surface Science*, **638**, (2023).
 2. Yanqin Yang *et al.* All-organic transparent plant e-skin for noninvasive phenotyping. *Sci. Adv.* **10**, (2024).



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Proposed vs. Prior Art

Parameter	Current state	Proposed
Sensing parameter	Mostly 2 parameters (Pressure and Temperature)	Pressure, Temperature, Touch, and Humidity simultaneously
Parameters	 https://doi.org/10.1016/j.apsusc.2020.105021	
Fabrication technique	Screen printing, thin film deposition, and lithography are used in sensor fabrication, and inkjet printing is less commonly reported.	Inkjet printing will be utilized to fabricate electrodes and essential components for sensors at a low-temperature process of approximately 150°C.
Sensitivity & Response time	Several structures, including pyramids, domes, rectangular, and hemispheres, were used to microstructure the flexible sensor. The hemisphere microstructure showed the highest sensitivity.	To utilize this unique combination of micro and nano needle-like spike structures to enhance the sensitivity and response time of sensors.

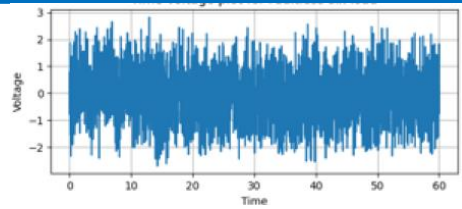
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Project 5: Development of Wearable Triboelectric Energy Harvester Patch for Battery less IoH Applications

PI: Karabi Biswas (IIT KGP) and Debanjan Das (IIT KGP)

Objective: Design and development of a high-performance wearable Triboelectric energy harvester cum sensing system for healthcare applications

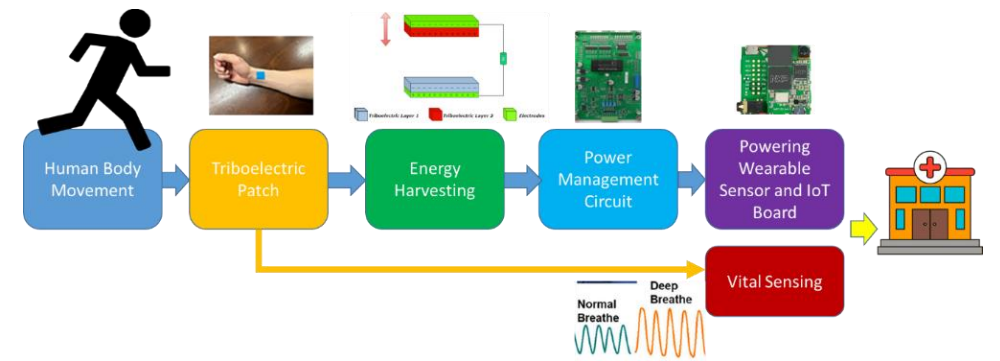
- ❑ Fabrication of high performance triboelectric nanogenerator (TENG)
- ❑ Self-powering the biomedical devices with TENG
- ❑ Wearable sensor integration and packaging



Parameters	Current state of the art	Proposed
Design and wearability	Bulky	Light-weight wearable TENG
Joint harvester and sensor	Either works as an energy harvester or sensor	TENG will work in duo-mode
Healthcare IoT integration	Mainly focus on ambient, wind, sea wave energy harvesting	Simple design to interface with wearable healthcare application with lower cost.

Approach

- Design, Analysis, Optimization and fabrication of Triboelectric Energy Harvester patch
- Integration of Power Management Circuit and Testing
- Deployment of the Integrated System and its Characterization and Demonstration for self-powered Internet of Health (IoH) applications



Outcome and Impact

- High performance TENG structure with interfacing power management circuit
- Design, and characterization of integrated self-powered sensing system for IoH application

1. Z. Gao, Y. Zhou, J. Zhang, J. Foroughi, S. Peng, R. H. Baughman, "Advanced Energy Harvesters and Energy Storage for Powering Wearable and Implantable Medical Devices. Advanced Materials," 2404492, 2024.
2. H. Wang, J. Cheng, Z. Wang, L. Ji, & Z. L. Wang, "Triboelectric nanogenerators for human-health care," Science Bulletin, 66(5), 490-511, 2021.

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Project 6: Portable and Standalone Microchip Capillary Electrophoretic Platform Technology for Bioanalyte Sensing applications

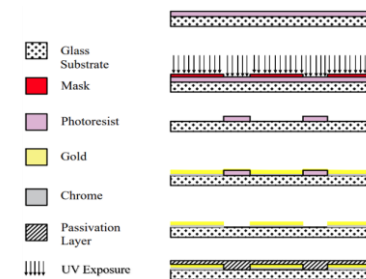
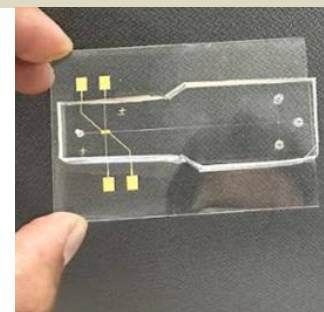
PI: Satish K Dubey (BITS Pilani)

Objective: To develop a standalone portable device based on microchip capillary electrophoresis (MCE). *Specific Objectives:*

- Develop microchip capillary electrophoretic (MCE) platform technology for on-chip sensing of bioanalytes
- Fabricate integrated miniaturized circuitry for signal generation, driving of charge particles and data acquisitions
- Validate MCE platform technology in the laboratory for hemoglobin and other bioanalyte sensing.

PROPOSED APPROACH

- Controlled SiO₂ deposition to achieve thin passivation layer with reduced porosity (≈ 500 nm).
- Microsecond precision in the high voltage switching to achieve high separation efficiency.
- Signal stabilization and enhancing signal to noise ratio.



Proposed vs. Prior Art

Parameters	Current state of the art	Proposed
Passivation layer	130- 500 μm	200 nm
Resolution	10 bits	24 bits
High voltage switching	Absent	Present
Label free sensing	Absent	Present

INDUSTRY NEED AND APPLICATIONS

- MCE offers label-free sensing for point-of-care applications, which is the current industry need for diagnostics.
- MCE provides label-free sensing of multiple ions simultaneously and is suitable especially for biological samples.
- Useful in Medical Diagnostics, and Agro-Tech

1. Xu, Z., Wang, X., Weber, R. J., Kumar, R., & Dong, L. (2017). Nutrient sensing using chip scale electrophoresis and in situ soil solution extraction. *IEEE sensors journal*, 17(14), 4330-4339.
2. Zhang, J., Wang, R., Jin, Z., Guo, H., Liu, Y., Chang, Y., ... & Chen, X. (2022). Development of on-site rapid detection device for soil macronutrients based on capillary electrophoresis and capacitively coupled contactless conductivity detection (C⁴D) method. *Chemosensors*, 10(2), 34.

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Project 7: Development of lab-on-chip diagnosis of cancer

PI: Venkatesh KP Rao (BITS Pilani)

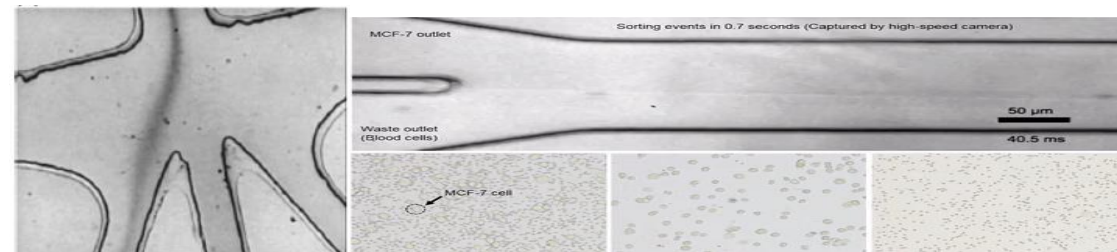
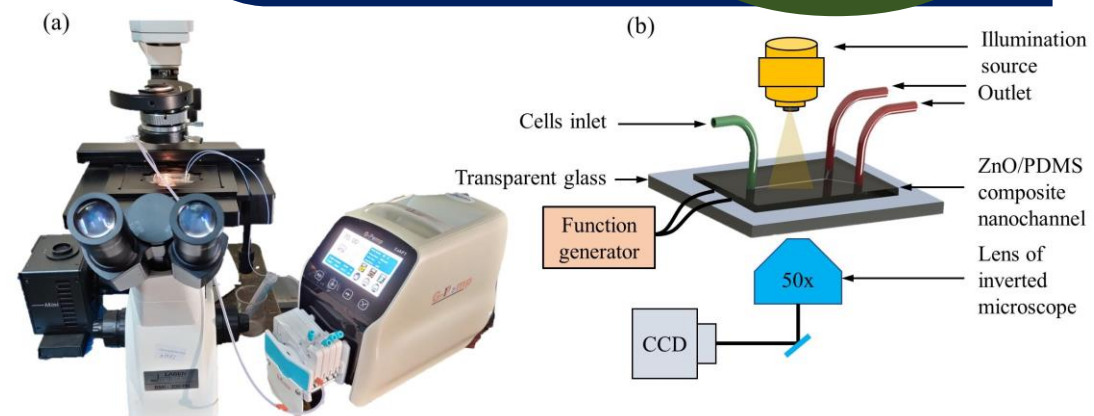
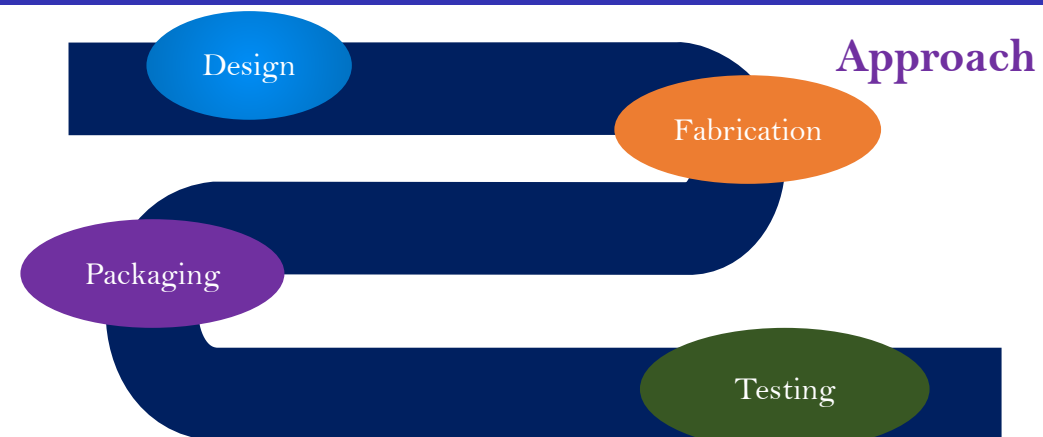
Objective -To develop a standalone microfluidic based on mechanodiagnosis of cancer.

- Measurement of alteration in cellular behavior of cancer cells.
- Mechanical diagnosis of invasive and noninvasive cell lines based on mechanical signature.
- Development of microfluidic platform for mechanodiagnosis

Parameter	Current state of the art	Proposed
Transduction	Electrical and Biochemical assays	Microfluidic based cancer diagnosis using mechanical assays
Label free diagnosis	Absent	Present

References

1. Diplesh Gautam, Abhilasha Srivastava, Rajdeep Chowdhury, Inamur R. Laskar, Venkatesh K. P. Rao, Sudeshna Mukherjee; Mechanical microscopy of cancer cells: TGF- β induced epithelial to mesenchymal transition corresponds to low intracellular viscosity in cancer cells. *J. Acoust. Soc. Am.* 154 (2023).
2. Mierke, Claudia Tanja. "Extracellular matrix cues regulate mechanosensing and mechanotransduction of cancer cells." *Cells* 13, (2024).



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Project 8: Scalable in-situ metal-LIG for Flexible Biopotential Signal Monitoring

PI: Sanket Goel (BITS Pilani)

Objective: To develop high-performance flexible biosensors leveraging metal-doped laser-induced graphene for cost-sensitive applications.

INDUSTRY NEED AND APPLICATIONS

- Growing demand for portable & affordable biosensors for rapid disease detection and monitoring.
- Flexible polyimide biosensors & detection system based on metal-doped laser-induced graphene can provide enhanced signals compared to the conventional devices.
- Affordable real-time patient monitoring in healthcare.

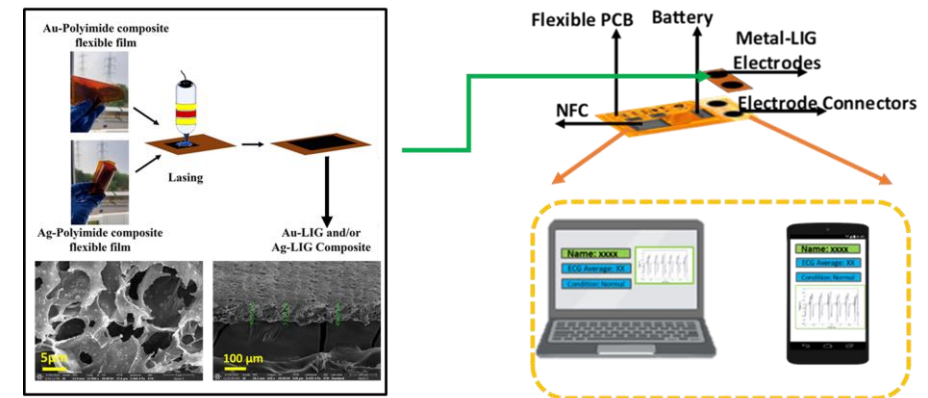
COMPARISION – PROPOSED vs EXISTING

Property	Proposed	Current state of art
Electrical Conductivity	1,000 - 10,000 S/m	500 - 2,000 S/m
Mechanical Strength	150 - 200 MPa	100 - 150 MPa
Bending Radius (Flexibility)	~1-2 mm	~3-5 mm
Uniformity of Metal Dispersion	High	Low

1. Edberg, Jesper, et al. "Laser-induced graphitization of a forest-based ink for use in flexible and printed electronics." *npj Flexible Electronics* 4.1 (2020): 17
2. Ebnalwaled, A. A., Ahmed H. Sadek, Sameh H. Ismail, and Gehad G. Mohamed. "Structural, optical, dielectric, and surface properties of polyimide hybrid nanoporous films embedded mesoporous silica nanoparticles synthesized from rice husk ash for optoelectronic applications." *Optical and Quantum Electronics* 54, no. 11 (2022): 696.

PROPOSED APPROACH

- Goal → Scalable & sustainable method for single-step rapid synthesis of densely structured metal doped-LIG
- Approach:
 - In-situ production of metal oxide or metal-LIG ink
 - Surface modifications for improved mechanical stability on metal-LIG ink
 - Use of low temperature solder options for smoother integration on the LIG-ink based printing on Polyimide
 - Deployment of required metal/semiconducting materials to significantly increase of scalability of electronic circuits by maskless dry process.



Project 9: Design and Development of System-on-Chip for Multiplexed Biomarker Detection

PI: Ponnalagu R N (BITS Pilani)

Objective: Design and development of multi parameter SoC sensing platform to detect disease biomarkers for PoC Healthcare application with easy integration, small form factor and ultra-low power operations suitable for mobile, IoT and wearable devices

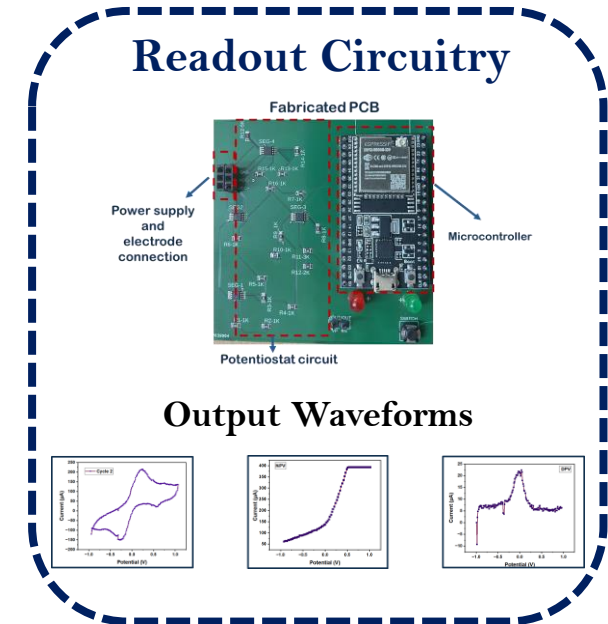
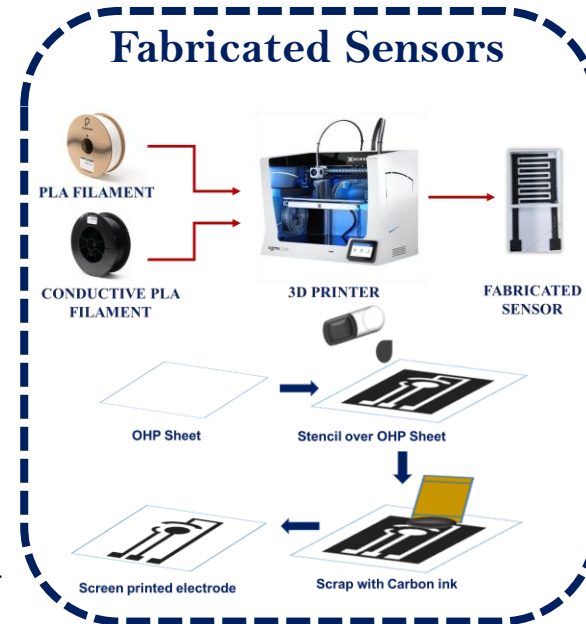
Industry need and applications

- Affordable devices for health monitoring through biomarker detection.
- Portable system for bedside point-of-care detection of biomarkers.
- Integrating IoT for remote monitoring.

Technical Challenges

- Sensitive and selectivity of the fabricated sensor towards particular biomarkers.
 - Stability concerns of the biosensors under various temperatures and pH.
 - Affordable, portable read-out circuitry development enabled with IoT
1. J. M. Mohan, K. Amreen, A. Javed, S. K. Dubey, and S. Goel, "Emerging trends in miniaturized and microfluidic electrochemical sensing platforms," Current Opinion in Electrochemistry, p. 100930, 2021.
 2. A. Taj, A. Rehman, and S. Z. Bajwa, "Biomarkers and their role in detection of biomolecules," Nanobiosensors: From design to applications, pp. 73–94, 2020.
 3. Hoilett, O.S., Walker, J.F., Balash, B.M., Jaras, N.J., Boppana, S. and Linnes, J.C., 2020. KickStat: A coin-sized potentiostat for high-resolution electrochemical analysis. Sensors, 20(8), p.2407.

Parameter	Current state	Proposed
Sensing Platform	Mostly sensing is done for individual biomarkers.	Multiplexed biomarker detection platform
Electrodes	Bulk electrodes are used in the conventional electrochemical detection setup.	Miniaturized test strips using techniques like screen printing, laser printing, 3D printing will be fabricated and utilized for detection.
Read-out Circuitry	Available readout circuitry are bulky and not cost effective	The circuitry developed will be portable and economical.



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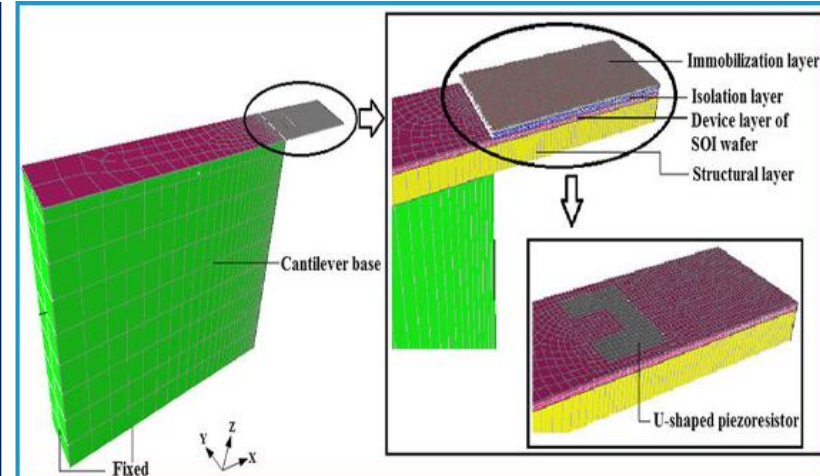
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Project 10: Development of Next Generation NEMS Technology Piezoresistive Sensors with High Sensitivity & Reduced Non-linearity for Chemical/Gas Sensing Applications

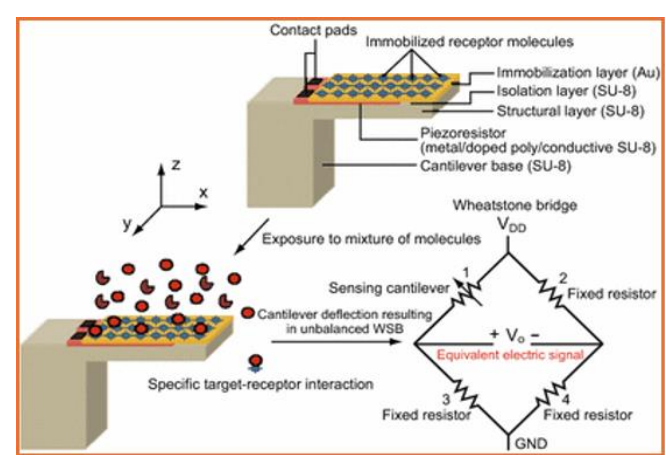
PI: Ribu Mathew (MAHE)

Objective:

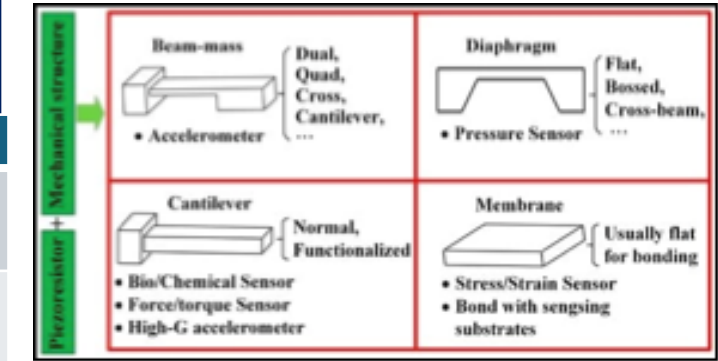
- NEMS piezoresistive (PZR) sensors can detect specific chemical/gas with high selectivity.
- PZR sensors are complex multilayered structure with their functionality and reliability depending on thermo-electro-mechanical sensor material and geometrical parameters.
- Two critical reliability issues of PZR sensors are structural non-linearity and temperature induced errors which induce inaccuracy in sensor detection.
- This project aims at developing next generation NEMS PZR chemical/gas sensors with rational material selection, mechanical platform selection & process dependency using optimization algorithms/FEAs and on-chip design strategies to reduce non-linearity, thereby improving sensor sensitivity & reliability.
- Sensor development includes integration of readout circuitry and tailored packaging technology.



Solid-state semiconductor sensor with piezoresistive readout



Entities	Prior art	Proposed
Design domain	Independent material, geometrical parameters	Considers the interdependence of material, geometrical & fab process
Modeling framework	Focused on performance improvement	Focusses on performance improvement, reliability, integration of readout circuit and packaging
Thermal Sensitivity	Not considered	Aims at reducing sensor's thermal sensitivity with on-chip solutions
Figure of Merit	Electrical sensitivity, SNR	Ratio of Electrical sensitivity to thermal sensitivity, on-chip solutions for thermal drift, material/process dependence
Project focus	Design and multi-physics modeling with focus on performance	Material selection, design-modeling, process dependence and validation, Focus on performance & reliability



Typical mechanical platforms of NEMS sensor

[1] Meena et al., 2022. Journal of Micromechanics and Microengineering, 32(9), p.095008.

[2] Mathew, R et al 2021. Microsystem Technologies, 27(7), pp.2647-2660.



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SRA Action Plan

- Two main hubs: IIT Delhi and BITS Pilani
- IIT Delhi Hub: MEMS Pilot line – Co-located with Devices SRA for Si/CMOS MEMS
- Include Basic Packaging Infra
- BITS Hub: Pilot Line for Non-Silicon Fabrication
- Some generic testing (Rate tables, Thermomechanical Testing)
- Spoke Entities: Access to Pilot Line either as visiting researchers or through Service requests
- Characterization equipment specific to projects
- Manpower/Consumables shared with all spoke entities

Critical Equipment MEMS and IOT

Design and Modelling



Fabrication and Integration



Characterization and Test

1. EDA software
2. GPU Workstations

1. Damascene Electroplating
2. Atomic Layer Deposition
3. Deep Reactive Ion Etching
4. LPCVD Furnaces
5. Aligned Wafer Bonder
6. Reactive Sputter System
7. PECVD (IMD, Nitride)
8. Fume Hood
9. Laser/Plasma Dicing
10. Pick and Place bonder

1. Laser Doppler Vibrometer with Vacuum Probe Station
2. Digital Holographic Microscope
3. MEMS Automated Tester
4. Optical Microscope
5. Rate Table
6. Environment Chamber

5 years Milestones

Deliverable	Year 1		Year 2		Year 3		Year 4		Year 5	
Formation of SRA Consortium with industry members	■	■								
Equipment Procurement and installation	■	■	■							
Definition of projects	■	■	■	■						
Set up primary research CoEs (2) in the country (hub)	■	■	■	■						
Technology Demonstration and Development			■	■	■	■				
Design and demonstration prototypes				■	■	■	■	■		
Technology licensing framework							■	■	■	
Educate Graduate students PhD : 30+, MTech: 50+ within Institute		■	■	■	■	■	■	■	■	■
Set up 10 + 2 instructional facilities		■	■	■	■					
Train 2000 students, researchers, engineers and technicians through the educational outreach programmes			■	■	■	■	■	■	■	■

Thank you