Research Plan at Texas Tech University

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As an experimental condensed matter physicist interested in low dimensional electronic systems, my research vision is to utilize charge and spin degrees of freedom in nano-devices for technological advancement of our society. Keeping application as the ultimate goal, I enjoy investigating physical phenomenon in quest to understand the fundamental laws governing our reality.

My mid-long term research vision is to establish a center of excellence to probe and utilize mesoscopic physics in nano-devices. The proposed Hybrid Electronics And Mesoscopic Systems (**HEAMS**) laboratory at Texas Tech University will house unique organic-inorganic hybrid cluster deposition system. The proposed fundamental and applied projects are briefly discussed ahead.

In later sections, I have briefly summarized my research background before discussing specific research plans at HEAMS Laboratory, Texas Tech University.

Brief Research Background

Presently as Principal Investigator I am working on Marsden FastStart grant (NZD 300,000) from Royal Society of New Zealand on project titled '*Brain inspired on-chip computation using self-assembled nanoparticles*'. With unique nano-cluster deposition system, the metal- metal-oxide nano-clusters are self-assembled into complex atomic-switch network. The electronic transport studies shows that the electric field induced conductance switching[1] in this randomly connected clusters can be utilized as biological synapses,[2] for on-chip brain-inspired Neuromorphic computation. The preliminary results have been published[3,4] and the fabrication procedure submitted for patent application.[5] The central aim is to understand the complex network dynamics of associated atomic-switches and utilize the dynamics for neuromorphic on-chip pattern recognition.

The motivation to investigate Neuromorphic architectures originated at my former Postdoctoral position in the NanoElectronics (NE) group at the University of Twente, where I was working on reprogrammable Single-Electron Transistor networks as part of *NAnoSCale Engineering for Novel Computation using Evolution* (NASCENCE) consortium project. The Bose *et al.* report published in *Nature Nanotechnology* 2015,[6] is the first experimental demonstration of fully reconfigurable logic based on randomly distributed nanoscale components, using self-learning algorithms. The project involved extensive nano-fabrication in MESA+ clean room, low-temperature electronic transport measurements, and associated data-analysis. During 2011-2012, I was involved in projects related to molecular magnetic doping of metals and the resulting effects on (coherent) electronic transport (*Nature Nanotechnology* 2012),[7] ultra-sensitive magnetization measurements, and graphene electronics.

Prior to that, my doctoral research at I.I.T. Kanpur was based on the exciting issues of mesoscale physics, where I had self-assembled and studied nearly-perfect square nanoislands of Fe on MgO[100], grown via pulsed laser deposition technique. Spin-dependent charge transport with normal metal Ag as spacer between the islands lead to system transition from the Coulomb blockade regime to the infinitely connected network, showing dynamic resistance as the coverage area of Ag is increased. I further assembled distributed NbN-Fe-NbN Josephson junction array and explored the magnetic-flux-closure domain pattern via anisotropic angular magnetoresistance measurements.

Future plan at Texas Tech Univ.

With my research background as summarized above, the short-term and long-term research plan at HEAMS Laboratory, Texas Tech Univ., are summarized in the Fig. 1. The central workhorse at the proposed laboratory will be customized nanocluster facility. The idea is to establish a facility for metal and ceramic nanocluster deposition with in-situ size-selection and characterization. This will support the following principal thrust areas arranged according to the priority timeline:

(1) Nature-inspired architectures: What would be the future replacement of current Von Neumann architecture[8] and associated Moore's law of transistor miniaturization? Nature-inspired Neuromorphic architecture are a strong candidate for complex computation[9,10] and on-chip pattern recognition.

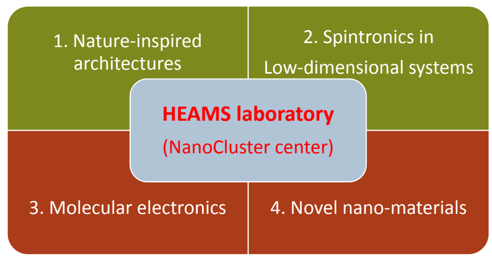

Fig. 1: Key focus areas of proposed Hybrid Electronics And Mesoscopic Systems (**HEAMS**) Laboratory.

(2) Spintronics in low-dimensional systems: Organic-inorganic hybrid geometries with metal-nanoclusters to explore spin-transport phenomenon in 2-dimensional hybrid systems.

(3) Molecular electronics: As outlined ahead the pre- and post-deposition functionalization of clusters with custom organic molecules will enable fabrication and utilization of molecular devices.

(4) Novel nano-materials: The facility will serve as nucleating center for experimentally probing and validating the electronic and magnetic properties of interesting materials when one or more dimensions are reduced to nanoscale.

Nature-inspired architectures:

The astounding success of Von Neumann architecture for computers,[8] with complementary complementary metal-oxide semiconductor (CMOS) transistors, will not sustain forever due to minimum transistor dimensions approaching the quantum size-limit and uneconomical and unsustainable increase in research and development costs for new process-lines. On the other hand, the organic mammalian brain can perform highly complex computational tasks like navigation, recognition, and decision-making with remarkable ease, as millions of years of Darwinian evolution focussed on optimizing pattern-recognition for species survival. The brain gathers a multitude of sensory information with the useful parts (patterns) being processed and stored. This pattern recognition by a set of interconnected biological neurons, e.g. of a particular voice/face in a crowd, is immediate and cannot even be matched by the most-advanced supercomputers.[11,12]

This is the motivation for the development of brain-inspired or neuromorphic architectures for computer chips[13] which promise fast, highly parallel information processing with lower energy consumption.[14] Efforts to emulate neuronal structures[9,15,16] have achieved tremendous successes, but these technologies still rely on silicon transistors, which have the same size and power dissipation limitations as all CMOS. A game-changing approach is therefore to build architectures that replicate the synapses and neurons in the brain.[17]

Our approach at HEAMS lab will be two-prong, first being percolating networks of nanoparticles that are much closer to the architecture of the brain and naturally incorporate the complexity and criticality that are essential for more complex functionality.[18] With electrode geometry compatible with nanocluster deposition facility at HEAMS lab, functionalized metal clusters devices with Ag-Ag_2S will be fabricated. The expertise and knowledge base gathered by PI Bose on Sn-cluster system[5] will be instrumental in this aspect. We will build a fundamental understanding of the key phenomena that underpin the functioning of this potential neuromorphic system.

The second approach will be self-assembled nanoparticle (NP) system with photo- and/or field-induced conductance switching linker molecules. Previous research by PI on such disordered nanoscale components (Bose *et al.* Nature Nanotech. 2015) showed completely reconfigurable logic being feasible. Utilizing the metal-clusters in conjugation with self-assembled NPs has tremendous potentials for advanced polymorphic computing, where every element can perform computation and also has serves as memory unit, eliminating the Von Neumann bottleneck. We will explore the potential of these nature-like networks for fault-tolerant computation and real-time on-chip pattern recognition. These proposed neuromorphic systems, should result in high-impact publications and patents.

Spintronics in low-dimensional systems:

The low-dimensional electronic systems where spin and charge degrees of freedom can be intertwined is an ideal system for spintronics applications. One such clean and ideal 2-dimensional electronic system is Graphene. With ballistic transport reported for length of the order of 10 μm,[19] and spin coherence lengths of few μm, multitude of device geometries are possible for studying spin-dynamics and proximity coupled transport. This is in line with the primary aim to explore magnetologic gate devices. The key question is whether selective anchor groups of tailored organic molecules can modify the local doping of Graphene to modulate spin-polarized transport?

For spin dopant in these devices, we can utilize our molecular-doping technique, where record concentrations of localized magnetic moments were introduced in metals via economical route of self-assembly.[7] The sample fabrication would be done in collaboration with international collaborators. Research groups at Exeter, United Kingdom and some commercial vendors will be able to supply the clean undoped Graphene samples for this purpose.

This has tremendous potential for active inter-university collaborations with organic chemists, physicists and computer engineers. The proposal will be submitted with associate investigators from relevant specialization at Texas Tech Univ.

Molecular electronics:

In the search for alternate routes of data storage and computation, one feasible approach is the organic-inorganic hybrid structures using molecules itself as basic element.[20] This combines the top-down technology, already refined in CMOS industry, and new bottom-up approaches linking desired molecules as active elements. Nano-clusters comprising of sub 10 nm diameter will be coated in-flight with active organic-molecules and subsequently deposited onto pre-fabricated electrodes. The independently tunable flow of nano-clusters and the molecules will be utilized to optimize the relative concentrations. Investigation of the electronic and spin transport via the molecules could answer some of the fundamental questions regarding the electronic coherence in molecular chains.

Novel Nano-materials:

Reduction of the dimensions e.g 2D (thin-flim), 1D (atomic-wires) or 0D (quantum-dots) of any material transforms the observed bulk properties of 3D. The unique nano-cluster center will be poised to produce and investigate in-situ the reduced dimensionality effects of new and novel materials. For example, self-assembly of magnetic nano-particles in presence of a pre-existing nano-structure on the substrate (magnetic or otherwise) can be utilized to design new and interesting magnetic structures.

HEAMS Laboratory:

To accomplish the research plan discussed above, my vision is to establish the low-dimensional systems research group Hybrid Electronics And Mesoscopic Systems (HEAMS) Laboratory at Texas Tech University. As indicated above, the focus of the group would be on spin- and electronic-transport in low dimensional systems, such as Neuromorphic systems and organic-inorganic hybrid structures. The proposed research activities has great potential for active inter-departmental collaborations with organic chemists, physicists and computer engineers. The research group thus will strive to impart spirit of collaborative research and encourage entrepreneurship. The next generation of engineers, scientists and researchers associated with the group would be trained as open-minded, ethical and hard-working researchers, who can then work towards overall development of the scientific community. The constructive project overlap between students will be encouraged, to ingrain the collaborative spirit in a harmonious and constructive research environment.

The proposed research lab will specialize in fabrication and measurements of mesoscopic devices. Therefore, as a foundation to future HEAMS laboratory, the initial line of action, with the seed-fund, will be to arrange and establish the following:

1. Nanocluster deposition system and off-the-shelf electronic transport measurement systems (Keithley).
2. Consumable chemicals for sample processing and measurements.

These measurement setups coupled with intra-institute and international collaborations, will be useful to startup the research activities on neuromorphic and hybrid-electronics thrust areas. The next line of research grants will be utilized to procure and setup:

1. Variable temperature close cycle system: A cost effective system for electronic transport measurements.
2. Four-point probe-station (Variable temperature attachment if funds permit).
3. In-situ attachment for cluster-thin-film composite fabrication, e.g. thermal vapor deposition.

These facilities will be procured and established with central govt. funding and will be utilized by any researcher at Texas Tech Univ. interested in collaborating for their sample fabrication and measurements. Although the proposed facilities may seem over-reaching, but I believe with focussed research results and dedicated efforts, this is achievable.

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