MAX PLANCK INSTITUTE
OF MICROSTRUCTURE PHYSICS

Materials Systems #2

Workshop

29.11.2024

10:00–16:30

LECTURE HALL
B.1.11,
BUILDING B

SPEAKERS

Kerem Çamsari, University of California
Ilia Valov, Peter-Grünberg Institute
Stefan Filipp, Technical University of Munich
Katharina Franke, Freie Universität Berlin

MAX PLANCK INSTITUTE
OF MICROSTRUCTURE PHYSICS

Materials Systems #2

WORKSHOP | 29.11.2024 | 10:00–16:30

10:00–11:00
Kerem Çamsari
University of California,
Department of Electrical and Computer Engineering
Probabilistic Computing with p-bits: Optimization, Machine Learning and Quantum Simulation

11:00-11:30 Coffee break

11:30–12:30
Ilia Valov
Peter-Grünberg Institute, Electronic Materials
Nanoionic-enhanced electronics – the evolution of information and data processing technologies

12:30-14:00 Lunch break

14:00-15:00
Stefan Filipp
Technical University of Munich
Fabrication and operation of superconducting quantum circuits for QIP

15:00-15:30 Coffee break

15:30-16:30
Katharina Franke
Freie Universität Berlin
Atomic-scale spectroscopy and transport

Probabilistic Computing with p-bits: Optimization, Machine Learning and Quantum Simulation

29.11.2024 | 10:00—11:00 | LECTURE HALL

Abstract

The slowing down of Moore's era has coincided with escalating computational demands from Machine Learning and Artificial Intelligence. An emerging trend in computing involves building physics-inspired computers that use intrinsic properties of physical systems for domain-specific applications. Probabilistic computing with p-bits, or probabilistic bits, has emerged as a promising candidate in this area, offering an energy-efficient approach to probabilistic algorithms and applications [1-5].

Several implementations of p-bits, ranging from standard CMOS technology to magnetic tunnel junctions have been demonstrated. Among these, the most promising p-bits appear to be based on stochastic magnetic tunnel junctions (sMTJ) [2]. sMTJs harness the natural randomness observed in low-barrier nanomagnets to create energy-efficient and fast fluctuations, up to GHz frequencies without requiring external clock circuitry for resetting or CMOS periphery [4]. In this talk, we will discuss how magnetic p-bits can be combined with conventional CMOS to create hybrid probabilistic-classical computers for various applications. We will provide recent examples of how p-bits are naturally applicable to combinatorial optimization, such as solving the Boolean satisfiability problem [3], energy-based generative machine learning models like deep Boltzmann machines [4-5], and quantum simulation for investigating many-body quantum systems [1].

Through experimentally informed projections for scaled p-computers using sMTJs, we will demonstrate how physics-inspired probabilistic computing can lead to GPU-like success stories for a sustainable future in computing.

[1] S. Chowdhury, A. Grimaldi, N. A. Aadit, S. Niazi, M. Mohseni, S. Kanai, H. Ohno, S. Fukami, L. Theogarajan, G. Finocchio, S. Datta, K. Y. Camsari, A full-stack view of probabilistic computing with p-bits: devices, architectures and algorithms, IEEE Journal on Exploratory Solid-State Computational Devices and Circuits, (2023)

[2] W. A. Borders, A. Z. Pervaiz, S. Fukami, K. Y. Camsari, H. Ohno, S. Datta, Integer Factorization Using Stochastic Magnetic Tunnel Junctions, Nature, 573, 390-393 (2019)

[3] N. A. Aadit, A. Grimaldi, M. Carpentieri, L. Theogarajan, J. M. Martinis, G. Finocchio, K. Y. Camsari, Massively Parallel Probabilistic Computing with Sparse Ising Machines, Nature Electronics (2022)

[4] CMOS + stochastic nanomagnets: heterogeneous computers for probabilistic inference and learning, K. Kobayashi, N. Singh, Q. Cao, K. Selcuk, T. Hu, S. Niazi, N. A. Aadit, S. Kanai, H. Ohno, S. Fukami, K. Y. Camsari, Nature Communications (2024)

[5] Niazi, Shaila, Shuvro Chowdhury, Navid Anjum Aadit, Masoud Mohseni, Yao Qin, and Kerem Y. Camsari. "Training deep Boltzmann networks with sparse Ising machines." Nature Electronics (2024)

Bio

Kerem Çamsarı is an Assistant Professor at the Department of Electrical and Computer Engineering at the University of California, Santa Barbara. His Ph.D. work established a modular approach to connect a growing set of emerging materials and phenomena to circuits and systems, a framework adopted by others. In later work, he used this approach to establish the concept of p-bits and p-circuits as a bridge between classical and quantum circuits to design efficient, domain-specific hardware accelerators for the beyond-Moore era of electronics. He is a founding member of the Technical Committee on Quantum, Neuromorphic, and Unconventional Computing within the IEEE Nanotechnology Council where he currently leads the Unconventional Computing section. For his work on probabilistic computing, he has received the IEEE Magnetics Society Early Career Award, a Bell Labs Prize, the ONR Young Investigator Award, and the NSF CAREER award. He has been named one of the Distinguished Lecturers of IEEE Magnetics Society for 2024 and he is a senior member of the IEEE.

Kerem Çamsari,

University of California,
Department of Electrical and Computer Engineering

Nanoionic-enhanced electronics – the evolution of information and data processing technologies

29.11.2024 | 11:30—12:30 | LECTURE HALL

Abstract

Since the dawn of mankind, recording, saving, and transferring knowledge was an essential part of the civilisation. Within thousands of years the ways and procedures of writing, reading and developing different types of information carriers has continuously developed to reach unprecedently high intensities and densities of storing and processing information in the modern time.

Last decades were entirely dominated by the semiconductor (nano)electronics and related applications. However, the demand on increasing the number of transistors on a chip and the inevitable decrease of the size of the devices pushes this technology approaches towards its physical limits. In same time the request for low-power electronics and energy saving technologies becomes more and more social relevance. A way to solve these issues is to introduce a qualitatively new technology approach, being able to address the industrial challenges.

Nanoionic-enhanced electronic devices are providing this unique chance and opportunity. The recent years of research have clearly demonstrated the importance of nanoscale physicochemical/electrochemical effects in materials used in typically engineering fields of applications By inducing redox reactions at the interfaces, charge transport, incorporation (or depletion) of ions (donors or acceptors) in nanophases/ nanovolumes or using discrete/quantum effects one can control fundamental materials properties and tune reversible their electronic, magnetic, optical, catalytic and thermal properties and resulting functionalities. The latter in turn allows for a spectrum of (new) functionalities to be implemented in next generation bio-inspired artificial neurons and synapses, data/information processing and security, space, harsh-environment and medical applications, energy conversion and storage technologies, (electro)catalysis, sensors, nanoactuators, bioelectronic interfaces, and high-frequency applications.

An example for such nanoionic-enhanced device is the memristor. Predicted in 1971 by Leon Chua as forth missing electronic circuit element, memristors were identified as nanoionic memories 2008 by the group of Stan Williams at the HP Labs. Since that time memristive technologies have enormously developed finding applications as non-volatile memories, sensors, selectors, and elements of FPGA. Most important, their properties and behaviour make them ideal as artificial neurons and synapses, being an essential building blocks in neuromorphic, bio-inspired hardware.

The present lecture will explain in an accessible manner the fundamentals of nanionic-based memristors, highlighting the essential advantages of using these nanoionic technologies. The common fundamentals of biological and artificial memristive neurons and synapses will be explained and the examples for operation principles and applications will be provided.

Bio

Head of Group Nanoelectrochemistry, Forschungszentrum Jülich. Professor in Electrochemistry at the Institute of Electrochemistry and Electrochemical Systems, Bulgarian Academy of Sciences. Editor: Scientific Reports (Nature PG), Materials MDPI (section Nanomaterials). Member of the Editorial Board of Nature Unconventional Computing (NPG). Member of the International Advisory Board for Advanced Electronic Materials (Wiley). Member of the Editorial Advisory Board of APL Machine Learning. Member of the Scientific Advisory Board of Leibnitz Institute for Surface Modifications (IOM), Leipzig. Listed among top 2% world-leading scientists (Stanford University). Erskine Fellow (New Zealand) awarded for 2024.

Ilia Valov,

Peter-Grünberg Institute, Electronic Materials

Fabrication and operation of superconducting quantum circuits for QIP

29.11.2024 | 14:00—15:00 | LECTURE HALL

Abstract

Quantum computers have the potential to solve complex problems efficiently. However, to unleash their full potential, complex quantum systems have to be manufactured, manipulated and measured with unprecedented accuracy and precision. In this presentation I will focus on superconducting qubits as one of the most promising platforms for quantum computing. To enhance their quantum processing capabilities we have systematically optimised the material parameters and reached several hundred microseconds coherence times. Moreover, we have built tunable couplers between two or more quantum circuits that mediate simultaneous local interactions. These can be harnessed to generate multi-qubit operations and efficient creation of many-body entanglement. I will conclude with an outlook on scaling up and discuss the performance of a 17-qubit quantum processor.

Bio

Dr. Stefan Filipp has been Professor in Technical Physics at the Technical University of Munich and Director of the Walther Meißner Institute of the Bavarian Academy of Sciences since 2020. Previously, he led the quantum computing team with superconducting qubits at the IBM Research Lab in Zurich. His current research focuses on improving superconducting quantum circuits, with an emphasis on control, materials, and fabrication processes, to develop concepts for scalable quantum processors. In 2020, he served as co-spokesperson for the expert group convened by the German government to implement the Quantum Computing Roadmap. He currently coordinates several collaborative projects aimed at realizing quantum computers in close cooperation between research and industry.

Stefan Filipp,

Technical University of Munich

Atomic-scale spectroscopy and transport

29.11.2024 | 15:30—16:30 | LECTURE HALL

Abstract

In addition to being an ideal tool for imaging and manipulating atoms and molecules on surfaces, the potential of the scanning tunneling microscope (STM) for high-resolution spectroscopy has been recognized in the fields of single-molecule physics, magnetism, and superconductivity. Recently, optical and terahertz pulses coupled into the STM junction have added ultrafast time resolution to this versatile experimental technique.

Here, we use the STM to resolve the interplay of magnetic atoms and molecules with superconducting substrates. The magnetic adsorbates induce bound states - known as Yu-Shiba-Rusinov (YSR) states - within the superconducting energy gap. These states remain isolated from the bulk, and, thus, provide a wide range of possibilities for engineering hybridized states, band formation, and topology. We exploit flexible molecular structures, molecular self-assembly and atomic manipulation to showcase the exquisite control over the corresponding quantum states.

Adding to this versatile platform, magnetic adatoms can be incorporated into Josephson junctions formed by approaching the atom with a superconducting STM tip. Remarkably, the presence of YSR states induces diode-like behavior of the Josephson junction. This means that the junction allows a nondissipative supercurrent to flow in one direction, while the current in the other direction is subject to dissipation.

Bio

Katharina Franke is a professor for experimental physics at Freie Universität Berlin. Her group investigates electronic and magnetic properties of single atoms, molecules and nanostructures at surfaces by scanning tunneling microscopy and spectroscopy at low temperatures. One of the major goals is to understand the interplay of magnetic adsorbates with superconducting substrates, more recently also adding the ultrafast time domain to the atomic scale investigations.

Katharina studied physics at the university of Kiel and at PennState, before carrying out her PhD at Freie Universität Berlin under the supervision of Prof. Karl-Heinz Rieder. At that time, she investigated quasicrystals using different diffraction techniques. She then got intrigued by scanning tunneling microscopy and moved to Lausanne for a PostDoc with Prof. Harald Brune. She returned to Berlin to work as a PostDoc with Prof. Jose I. Pascual and became a junior professor in 2009 at FU Berlin. After external offers, she got appointed to associated and full professor.

Katharina received the Karl-Scheel Preis of the Physikalische Gesellschaft zu Berlin, the Hertha-Sponer Preis of the Deutsche Physikalische Gesellschaft and a Consolidator Grant from the European Research Council.

Katharina Franke,

Freie Universität Berlin