Diels-Planck-Lecture 2021

Priority Research Area KiNSIS »Kiel Nano Surface, and Interface Science«
Collaborative Research Center 1461 »Neurotronics: Bio-inspired Information Pathways«

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Nonlinear Dynamics in Nanoscale Electronic Devices for Brain-Inspired Computing

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With the near saturation of Moore's scaling of transistors, there has been a recent explosion in activity and creativity to find new modes of computation that will continue to advance exponentially with time even though transistor circuits only improve modestly. Much of the inspiration for new ways of computing comes from what little we understand about the brain. We actually don't know how the brain computes, but many different possibilities have been proposed, e.g. multinary logic, Neural Networks of all kinds, extensions of Hebbian learning via spike-timing dependent plasticity, Boltzmann/Ising machines, Hopfield networks, Bayesian inference and Markov chains, to name a few. These possibilities are not necessarily mutually exclusive – the brain may use some combination of several of them or even use a higher order generalization that contains most of them, since many share mathematical similarities. How to express these computational approaches efficiently in an electronic circuit is a significant challenge. Since the brain itself is a highly nonlinear dynamical system, an appropriate area to investigate is nonlinear dynamical circuit theory. This is the realm of the Principle of Local Activity, which provides a basis for inventing and building new generations of nanoscale memristor-based oscillators and amplifiers that emulate the integrate and fire dynamics of neurons to produce action potentials for signal processing, learning and computation. Combining such devices enables the design of 'neuromorphic' circuits that are biased at the Edge of Chaos, where the emergence of complex patterns and behavior in a homogeneous medium are found. Thus, the goal of my research is not to improve transistors but rather to create new analog electronic circuit elements that can replace hundreds to thousands of transistors in a brain-inspired computer. Can we emulate neural computation using new electrothermal devices that exhibit dynamical behavior? These could be based on properties such as negative differential resistance and/or capacitance that arise from thermally activated transport, Mott transitions, molecular redox chemistry, or even electro-mechanical response in soft matter. Can we intentionally design materials that will function in the Goldilocks zone of normal room temperature? Confining the active region of a device to nanoscale dimensions simultaneously provides three important properties for computation: the nonlinearity of the response of the material to an electrical or thermal stimulus is increased, which enables signal amplification and chaotic oscillations; the dynamics are much faster; and the energy required to activate the dynamics is much lower. This is a rapidly growing multi-disciplinary research field that requires coordinated efforts across a broad range of fields from neurophysiology, chemistry, materials, solid-state physics, electrical engineering and computer science. Early results are promising, with several experimental demonstrations of neuromorphic circuits outperforming digital CMOS and even a quantum computer by several orders of magnitude in terms of energy efficiency and time to solution for certain types of 'hard' problems.