The concept of creating a 'brain-on-a-chip' revealed

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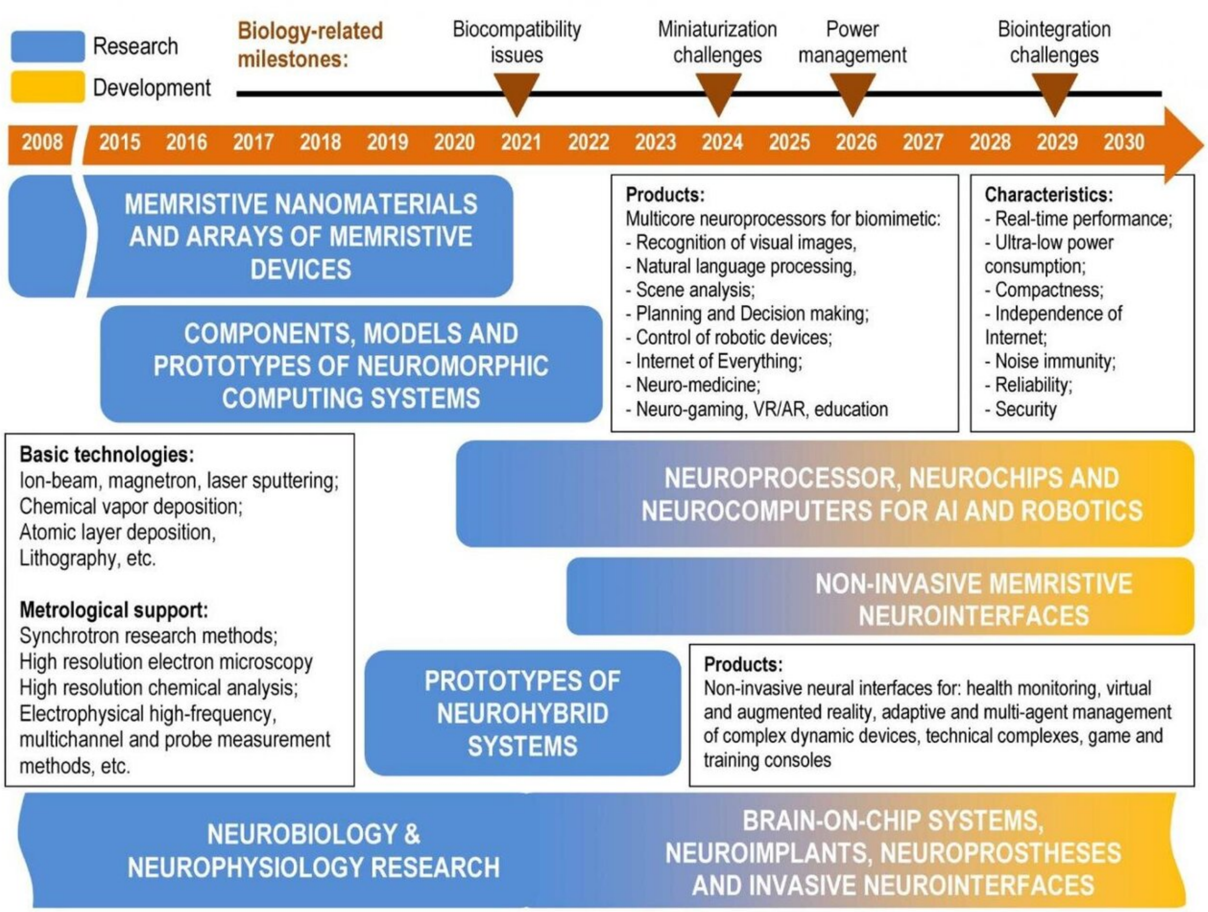


Roadmap for memristive neuromorphic and neurohybrid systems Credit: Lobachevsky University

Lobachevsky University scientists in collaboration with their colleagues from Russia, Italy, China and the United States have proposed the concept of a memristive neurohybrid chip to be used in compact biosensors and neuroprostheses. The concept is based on existing and forward-looking solutions at the junction of neural cellular and microfluidic technologies that make it possible to grow a spatially ordered living neural network. In combination with CMOS-compatible technologies for creating microelectrode matrices and arrays of memristive devices, this integrated approach will be used for registering, processing and stimulation of bioelectrical activity in real time.

According to Alexey Mikhaylov, head of the laboratory at the Lobachevsky University's Research Institute for Physics and Technology, the interaction of different subsystems is organized on a single crystal (chip) and is controlled by built-in analog-to-digital circuits. "The implementation of a biocompatible microelectronic system, along with the development of cellular technology, will provide a breakthrough in neuroprosthetics by offering an important competitive advantage: a miniature bioelectrical sensor based on micro- and nanostructures with an option to store and process signals in multiple manners, including feed-forward approach and feedback loops, may serve as an active neural interface for intelligent control and management of neuronal structures.

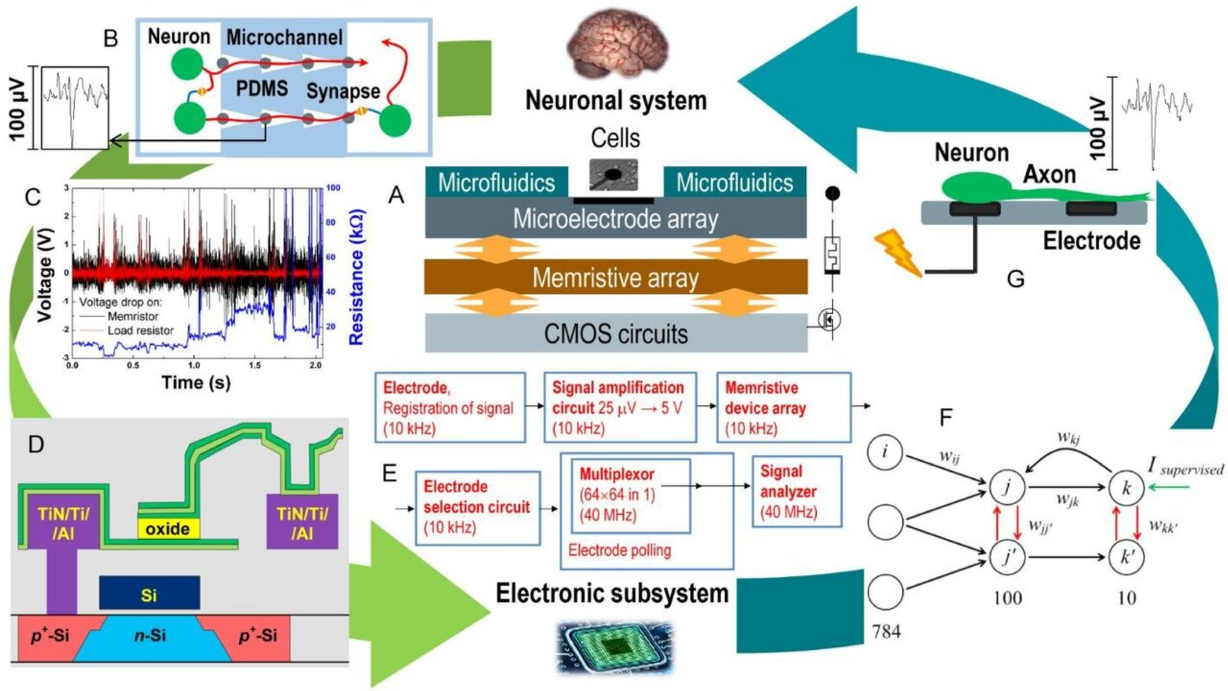
This potential (unattainable with the use of traditional neural interface architectures) can be extended to other types of bioelectric signals for registering signals of brain, heart and musular activity, as well as the state of the skin using portable signal processing and diagnostics systems," says Mikhaylov.

To develop and fabricate bidirectional neurointerfaces, scientists currently apply complex electronic circuits realizing special mathematical models and neuromorphic principles of information processing. Such electronic systems use traditional components and cannot meet the requirements of energy efficiency and compactness for safe interaction with living cultures or tissues on the same chip.

"Memristors created by scientists from Russia and Italy have the unique property of nonlinear resistive memory and are promising elements for analog information processing systems, including those with a neuron-like structure. They can also serve as electrophysiological activity sensors performing at the same time the function of accumulation and non-volatile storage of information," Mikhaylov notes.

A schematic representation of the proposed neurohybrid system demonstrates several functional layers combined in one CMOS-integrated chip. The top layer is a part of the neuronal system represented here by a culture of dissociated hippocampal cells grown on a multielectrode array and functionally ordered by a special layout of microfluidic channels.

The microelectrode layer serves for extracellular registration and stimulation of neurons in vitro. It is implemented on the top metallization layers of the CMOS layer together with an array of memristive devices.



Memristive neurohybrid chip. Credit: Lobachevsky University

"The simplest task performed by memristive devices is the direct processing of spiking activity of the biological network; however, self-learning neural network architectures based on fully connected cross-bar memristive arrays can be designed for adaptive decoding of spatiotemporal characteristics of bioelectric activity. The output of this artificial network can be used to control the cellular network via gradual modulation of extracellular stimulation according to the given protocol. Analog and digital circuits for accessing and controlling the multielectrode array and memristive devices, amplifying, generating, and transmitting signals between layers should be implemented in the main CMOS layer," Alexey Mikhaylov explains.

To create a neurohybrid chip, collaborative design and optimization of all these elements at the levels of materials, devices, architectures, and systems will be required. Of course, this work must be in pace with the development of bio- and neurotechnologies to address a number of problems related primarily to biocompatibility, mechanical effects, geometry, location and miniaturization of microelectrodes and probes, and also to deal with the reaction of living culture/tissue on the interface with an artificial electronic subsystem.

In the words of Alexey Mikhaylov, the concept reveals the idea of creating a brain-on-chip system belonging to a more general class of memristive neurohybrid systems for next-generation robotics, artificial intelligence and personalized medicine.

To illustrate the proposed approaches and related products on a foreseeable time scale, a roadmap of memristive neuromorphic and neurohybrid systems has been proposed . The key focus in the roadmap will be on the development and commecialization of specialized hardware using the architecture and principles of biological neural networks to support the development and mass introduction of artificial intelligence, machine learning, neuroprosthetics and neural interface technologies.

"We assume the roadmap had its starting point in 2008, just as the current wave of interest in memristors was getting underway, and this roadmap includes ongoing research and development in broad areas of neurobiology and neurophysiology," comments Alexey Mikhaylov.

The following product niches are envisaged by researchers in the roadmap at different stages of the work in this direction: neuromorphic computing devices; non-invasive neural interfaces; neuroimplants, neuroprostheses and invasive neural interfaces, etc.

"The unique properties of memristive devices determine their critical importance in the development of applied neuromorphic and neurohybrid systems for neurocomputing devices, brain-computer interfaces and neuroprosthetics. These areas will take a significant share of the world high technologies market worth trillions of dollars by 2030, given the speed of development and implementation of artificial intelligence technologies, the Internet of Things, "big data" and "smart city" technologies, robotics, and—in the near future—neuroprosthetics and instrumental correction/support/enhancement of human cognitive abilities," says Mikhaylov in conclusion.

More information: Alexey Mikhaylov et al, Neurohybrid Memristive CMOS-Integrated Systems for Biosensors and Neuroprosthetics, *Frontiers in Neuroscience* (2020). DOI: 10.3389/fnins.2020.00358

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