

# Next-generation nanoelectronics: A decade of progress, coming advances

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Traditional silicon-based integrated circuits are found in many applications, from large data servers to cars to cell phones. Their widespread integration is due in part to the semiconductor industry's ability to continue to deliver reliable and scalable performance for decades.

However, while silicon-based circuits continue to shrink in size in the relentless pursuit of Moore's Law — the prediction that the number of transistors that can fit on an integrated circuit doubles every two years — [power consumption](#) is rising rapidly. In addition, conventional silicon electronics do not function well in extreme environments such as high temperatures or radiation.

In an effort to sustain the advance of these devices while curbing power consumption, diverse research communities are looking for hybrid or alternative technologies. Nanoelectromechanical (NEM) switch technology is one option that shows great promise.

"NEM switches consist of a nanostructure (such as a carbon nanotube or nanowire) that deflects mechanically under electrostatic forces to make or break contact with an electrode," said Horacio Espinosa, James N. and Nancy J. Farley Professor in Manufacturing and Entrepreneurship at the McCormick School of Engineering at Northwestern University.

NEM switches, which can be designed to function like a silicon transistor, could be used either in standalone or hybrid NEM-silicon

devices. They offer both ultra-low power consumption and a strong tolerance of high temperatures and radiation exposure.

Given their potential, the past decade has seen significant attention to the development of both hybrid and standalone NEM devices. This decade of progress is reviewed by Espinosa's group in the current issue of journal *Nature Nanotechnology*. Their review provides a comprehensive discussion of the potential of these technologies, as well as the primary challenges associated with adopting them.

For example, one longstanding challenge has been to create arrays of millions of the nanostructures, such as carbon nanotubes, that are used to make these NEM devices. (For perspective, modern [silicon](#) electronics can have billions of transistors on a single chip.) The researchers' review describes the methods demonstrated to date to create these arrays, and how they may provide a path to realizing hybrid NEM-CMOS devices on a mass scale.

Similarly, while individual NEM devices show extremely high performance, it has proven difficult so far to make them operate reliably for millions of cycles, which is necessary if they are to be used in consumer electronics. The review details the various modes of failure and describes promising methods for overcoming them.

An example of the advances that facilitate improved robustness of NEM switch technologies is reported in the current issue of *Advanced Materials*. Here Espinosa and his group show how novel material selection can greatly improve the robustness of both hybrid NEM-CMOS and standalone NEM devices.

"NEM devices with commonly-used metal electrodes often fail by one of a variety of failure modes after only a few actuation cycles," said Owen Loh, a PhD student at Northwestern University and co-author of

the paper, currently at Intel.

Simply by replacing the metal electrodes with electrodes made from conductive diamond-like carbon films, the group was able to dramatically improve the number of cycles these devices endure. Switches that originally failed after fewer than 10 cycles now operated for 1 million cycles without failure. This facile yet effective advance may provide a key step toward realizing the NEM devices whose potential is outlined in the recent review.

The work reported in *Advanced Materials* was a joint collaboration between Northwestern University, the Center for Integrated Nanotechnologies at Sandia National Laboratories, and the Center for Nanoscale Materials at Argonne National Laboratories. Funding was provided by the National Science Foundation, the Army Research Office, The U.S. Department of Energy, and the Office of Naval Research.

"Ultimately, realizing next-generation hybrid NEM-CMOS devices will enable continued scaling of the electronics that power numerous systems we encounter on a daily basis," Espinosa said. "At the same time, it will require continued push from the engineering, basic sciences, and materials science communities."

Provided by Northwestern University

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