SCIENCE CHINA
Information Sciences

• PERSPECTIVE •

October 2021, Vol. 64 206401:1–206401:3
https://doi.org/10.1007/s11432-020-3241-9

Nanomechanics: emerging opportunities for future computing

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Received 29 December 2020/Revised 22 March 2021/Accepted 2 April 2021/Published online 3 June 2021

Citation Wang Z H, Fang J W, Zhang P C, et al. Nanomechanics: emerging opportunities for future computing. Sci China Inf Sci, 2021, 64(10): 206401, https://doi.org/10.1007/s11432-020-3241-9

The exploration for greater computing power has existed for a long time. Since the 1960s, transistors in modern electronic computers have kept advancing following Moore's law. However, as silicon transistors continue to scale down, they face challenges such as increases in OFF-state leakage power due to the limited subthreshold swing, incompatibility with high-temperature operation, and lack of reconfigurability. Therefore, new types of computing devices are being explored to address these problems.

With advances in micro/nanofabrication technology, mechanical computation has emerged as a promising alternative to transistors, offering advantages such as ultralow power consumption, high-temperature compatibility, and reconfigurability, by leveraging the mechanical degree of freedom. In particular, micro/nanoelectromechanical systems (MEMS/NEMS) technology is now being actively explored to realize future computation devices. They can be categorized based on their mode of operation (Figure 1): contact (mostly switches/relays) and noncontact modes (typically resonators), which we discuss in more detail below.

Mechanical computing based on MEMS/NEMS switches/relays. MEMS switches have been studied for decades. Over the years, different designs of MEMS/NEMS switches with different driving mechanisms have been investigated [1], with electrostatic MEMS/NEMS switches being most widely explored.

Electrostatic MEMS and NEMS switches usually contain a movable electrode (beam or membrane) and a static counter electrode, separated by a small air or vacuum gap. In the OFF state, such physical separation ensures zero leakage current. Besides near-zero leak current and abrupt switching, NEMS switches are more resistant to harsh environments than metal-oxide-semiconductor field-effect transistors (MOSFETs). SiC nanowire NEMS switches and logic inverters based on these SiC NEMS switches can function reliably up to 500°C [2], whereas MOSFETs would fail due to the generation of intrinsic carriers. The SiC NEMS switches can achieve $> 10^7$ cycles of "hot switching" in ambient air, with a motional volume of only 1 μm^3 [1]. Such high-temperature capability of these NEMS switches benefits from the switching mechanism: as the switching between ON/OFF states relies on mechanical motion rather than changes in electrical potential, the presence of the air/vacuum gap can ensure nearly zero OFF-state leakage, maintaining abrupt switching behavior.

While NEMS switches show such advantages over MOSFETs, they face several significant challenges, including operation voltage, which should be overcome before they can be more broadly used. Some of the early MEMS switches required > 10 V to operate, making them unsuitable for use in most circuit designs. With advancements in lithography techniques, device feature sizes continue to decrease, and the switching voltage can be lowered with a reduction in actuation gap size. Recent progress includes a low-voltage operation of three-terminal NEMS switches with 55-nm width and 30-nm air gap, demonstrating switching voltage down to 100 mV [1]. Furthermore, NEMS switches have been implemented in standard complementary metal-oxide-semiconductor (CMOS) fabrication processes using back-end-of-line metal layers [3]. With such compatibility with CMOS processes, it is expected that NEMS switches can continue to scale down and achieve even better device performance metrics.

Another significant challenge is related to the contact surface. When two surfaces get into contact, quantum mechanical fluctuations of vacuum will generate an electrodynamic force (EDF) between them at atomic scale [4]. Such force is called the van der Waals force at a shorter distance or Casimir force at a longer distance, and it can generate strong attraction at interatomic distances. In a NEMS structure, stiction failure happens when the adhesion force exceeds the elastic restoring force, affecting the operation and life-

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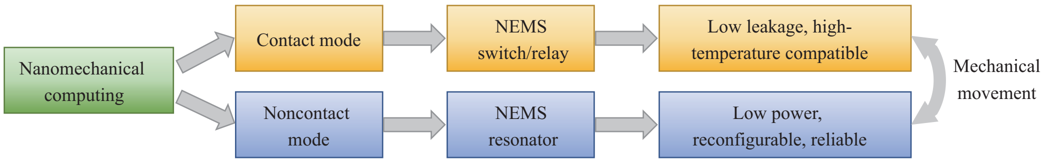

Figure 1 (Color online) Two categories of nanomechanical computing devices and their respective advantages.

time of NEMS switches. In addition, oxidation of contact surface, material transfer, and welding-induced failure pose challenges for the contact property. Recent studies show that proper engineering of the contact surface material and surface geometry, such as using a grooved surface, can alleviate the stiction problem [4].

Mechanical computing based on MEMS/NEMS resonators. Resonant MEMS/NEMS devices are also explored for logical computations. One such example is a MEMS resonator with a four-input configuration using four AC input signals at the same frequency [5]. This resonator-based device can be reconfigured to achieve important logic operations, such as OR and XOR gates. Another design of a single MEMS structure containing several suspended beams can achieve frequency tuning using Joule heating from input voltages [6]. Similarly, by varying the output electrodes used and the frequency of operation, reconfigurable logic functions of OR, NOR, XOR, and AND logic gates are experimentally demonstrated. These results show that resonant MEMS/NEMS designs hold promise for realizing reconfigurable logic devices. Not only can MEMS/NEMS resonators be used to realize conventional logic gates, but also build nonconventional devices for new computing paradigms, such as reversible computing. For example, reversible Fredkin gate that can achieve reversible Boolean logic has been experimentally demonstrated by connecting four mechanical resonators and forming a three-input, three-output structure [7]. Such reversible logic devices have the potential to overcome the von Neumann-Landauer limit of energy dissipation in nonreversible computing, leading to more energy-efficient computing schemes.

Nonlinearities in MEMS/NEMS resonators can also be explored to realize logic and memory functions. In the nonlinear regime, two stable and distinct states are allowed at a certain frequency range, which can be used to express different logic states. Such property can be used for logic calculation and memory operation. A nonlinear comb-drive MEMS resonator with external control circuit has been used to demonstrate a highly reliable and multifunctional logic and memory device [8]. As a logic gate, the Duffing resonator can perform OR and AND logic functions simultaneously by leveraging the mechanical hysteresis; additionally, it can perform the memory function where the current state depends on the previous state. This type of device combines the functionality of memory and logic, and offers new opportunities for realizing computing-in-memory (CIM) architecture.

Promise of nanomechanical computing. Nanomechanical computing can play an important role in a few future research areas, including low-power computing and reconfigurable computing. As previously stated, NEMS switches benefit from the steep subthreshold slope and low OFF-state current, and can be advantageous in reducing both static and operational power consumption. Meanwhile, the power consumption of resonant NEMS devices can also be minimal: to maintain the mechanical vibration, one just needs to supply the power dissipated in each cycle, which can be minimized by improving the quality factor Q. Recently, NEMS resonators with Q exceeding 10^6 have been demonstrated, implying that they only consume one-millionth of the mechanical energy stored in the device within each cycle, which can be translated to low-power logic operations. For example, using a silicon nanocantilever resonator with two drive electrodes and three inputs, XOR, AND, NOR, OR, and NOT logic gates have been achieved [9] with an ultralow power consumption of only 0.4×10^{-9} and 15×10^{-9} W at “0” and “1” states, respectively.

NEMS resonators based on two-dimensional (2D) materials are particularly promising in this sense. This is because the power consumption of NEMS resonators is directly related to the size/mass of the resonator; thus, energy consumption can be further decreased by several orders of magnitude by using low-dimensional materials to build the motional part of the resonant logic devices. Recently, 2D NEMS resonators have shown orders of magnitude lower power consumption than MOSFETs, down to the range of 10^{-12} W, promising for computing devices with ultralow sustaining power [10]. Besides the sustaining power, another important factor to consider is the ability to switch between different states. 2D NEMS resonators are highly sensitive and tunable by strain, which can be induced by various means, including voltage; therefore, they are promising for building computing devices with low switching power.

Another important advantage of NEMS-based computing is its high reconfigurability, a feature that is less readily available in MOSFETs. NEMS resonators can achieve multiple logic gates using the same device. The logic gate functionality can be reconfigured by changing the combination of inputs or outputs, and memory function can be achieved by leveraging the Duffing nonlinearity of these resonators. Such reconfigurability can reduce the device footprint and enhance the functionality in complex circuit designs, resulting in more efficient use of the wafer area.

Conclusion. In summary, there are enormous opportunities for future computing using nanomechanical devices. Contact-mode NEMS switches are promising for ultralow-leakage computing devices and can function at high temperatures, making them suitable for harsh-environment applications. Noncontact NEMS resonators are ultralowpower, highly reconfigurable, and could perform reversible computing and CIM functions. Furthermore, the introduction of low-dimensional materials offers new opportunities in building novel devices. We envision that, with continued research and development, these nanomechanical computing devices can lead to new technology enabling new computing paradigms, such as ultralow power, reversible, reconfigurable, analog and neuromorphic computing.

Acknowledgements This work was supported by Ministry of Science and Technology of the People's Republic of China (Grant No. 2018YFE0115500), National Natural Science Foundation of China (Grant Nos. 61774029, 62004032), Science and Technology Department of Sichuan Province (Grant Nos. 21CXTD0088, 2019JDTD0006, 2019YFSY0007), Shanghai Sailing Program (Grant No. 19YF1424900), and Shanghai Jiao Tong University Major Frontier Program (Grant No.

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