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New acoustic resonators based on commercial field effect transistors

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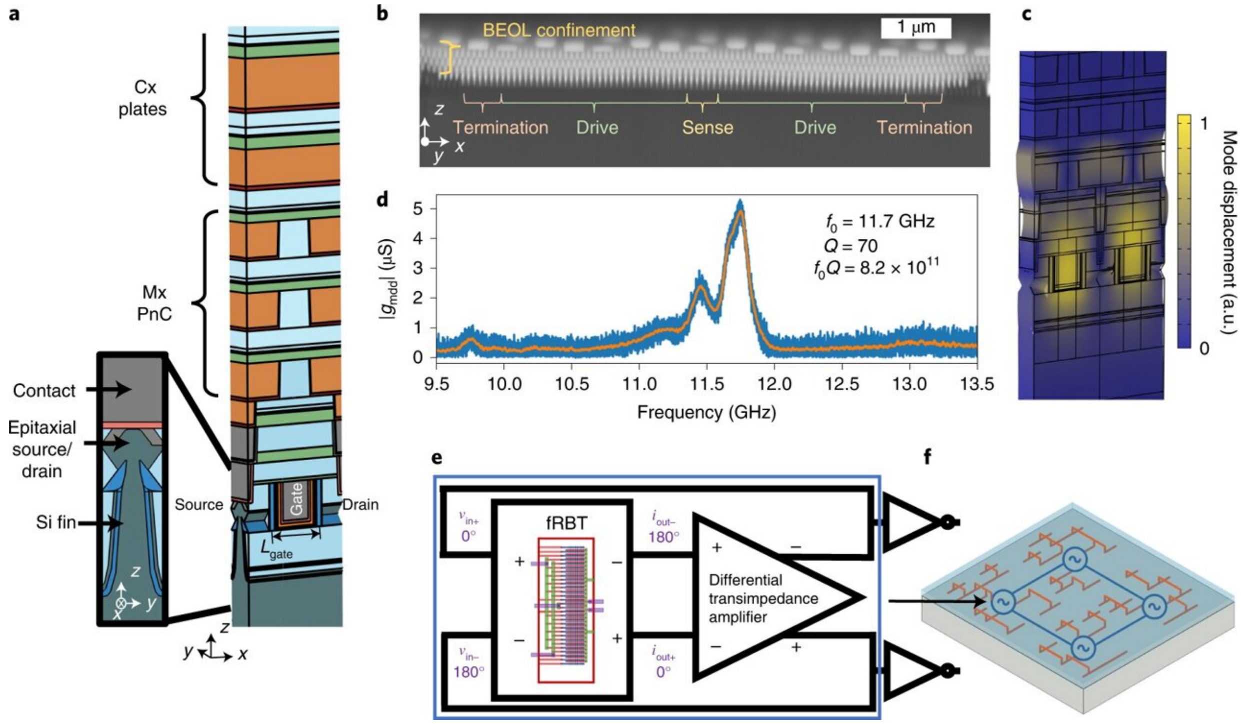

Overview of FinFET resonator. a, Cross-section of one period of the FinFET resonator, modeled in COMSOL, with the inset highlighting the Si fin (dark green) and epitaxial raised source and drain with silicide. The metal and contact layers are highlighted in orange and dark gray, respectively, and the dielectric layers are colored blue and green. The target mode is primarily defined along the x direction (L_{gate}) via the 180°-phase constraint due to the differential drive and sense. b, Representative acoustic cavity, consisting of a sense block sandwiched between two drive blocks, with terminations at either end to increase acoustic confinement. A differential input is applied in the two drive blocks, with the output current taken from the sense transistors at the center of the cavity. The grounded gates act as electrical isolation between the sense and drive blocks. c, Simulated target mode, with periodicity driven by L_{gate}, showing stress concentrated in the FinFET channel and confined by the BEOL metal layers. d, Experimentally measured mode, with f_0Q product of 8.2×10^{11}, placing it within an order of magnitude of the released MEMS resonators. e, Combined with a differential transconductance amplifier, the fRBT enables a high-frequency mechanically referenced two-phase oscillator in the standard CMOS process. Oscillator design considerations for active transduction resonators are presented elsewhere. f, Acoustically coupled (blue lines) network of oscillators in CMOS FEOL with local electrical clock routing (bronze lines), eliminating power-hungry phase-locked loops used for clock distribution. This could also enable scalable oscillatory computing for neuromorphic applications, directly interfacable with a classical CMOS circuit. Credit: *Nature Electronics* (2022). DOI: 10.1038/s41928-022-00827-6

A key objective of electronics engineering studies focusing on radio communication is the development of increasingly smaller, lighter, and low-power radio components. This could be achieved by integrating all radio components into a single chip, for instance by combining acoustic microelectromechanical systems (MEMS) with complementary metal oxide semiconductors (CMOS).

Researchers at Purdue University have recently used this approach to develop an acoustic resonator based on commercially available field effect transistors (FETs), which was presented in a paper published by *Nature Electronics*. FETs are a class of transistor that control the flow of electrical current in a semiconductor using an electrical field, which are commonly used to amplify signals and are the building blocks for all logic circuits.

"This paper is a culmination of years of work involving multiple graduate students and collaborations with semiconductor companies, including IBM, Global Foundries, and Intel," Dana Weinstein, one of the researchers who carried out the study, told TechXplore.

"It began with the recognition of a need for high-Q frequency sources embedded in microchips (CMOS) despite the huge barrier to entry for any new materials or processes into CMOS manufacturing. We decided to see how the existing technology could be leveraged to make these vibrating cavities."

Acoustic resonators are electromechanical components that can amplify or absorb sound in specific frequency ranges and can be coupled to electronic circuits. Successfully developing these components using conventional CMOS-based technologies entails tackling and overcoming numerous engineering challenges. To develop their devices, Weinstein and her colleagues first had to devise an effective strategy to efficiently drive and sense vibration within a microchip.

"We developed electromechanical transducers using the front-end-of-line MOS capacitors and transistors that make up the basic building blocks for logic circuits," Weinstein said. "We then had to figure out what vibrations could be launched and what structures would best confine them in a small region including the transducers. This is atypical for microelectromechanical (MEMS) devices, which are normally freely suspended."

To demonstrate compatibility with a commercial process, Weinstein and her team had to ensure that no post-processing was performed on their chip. To do this, they decided to use the many layers combined in a CMOS stack to engineer slow-wave acoustic modes.

These unique acoustic modes would be unable to propagate down into the substrate, where they would be lost, or up into the metal layers (i.e., away from then transducers that drive and sense them). This was realized through the careful and creative design of phononic metamaterials that were based on existing CMOS structures.

"Acoustic vibrations can be much less lossy than electrical signals typically used to make clocks and frequency sources on chip," Weinstein explained. "The resonators we demonstrate in this paper can serve as low-loss building blocks for clocks and analog signal processing, and their high frequency provides additional benefits for low noise and faster computation."

The acoustic resonators developed by Weinstein and her colleagues are driven by capacitors that are inherently part of the CMOS stack. These capacitors are essentially transistors with source and drain contacts shortened together.

When a voltage is applied to a capacitor, the equal but opposite charges generated on the capacitor's two opposing sides are electrically attracted to each other. This results in the squeezing of the film sandwiched between the capacitor's two sides.

"If we wiggle that voltage, then the force on the plates also wiggles, and we can launch acoustic waves through that time-varying stress, kind of like a speaker," Weinstein said. "But we don't want these vibrations to just leak away, so we trap them. This is done by manipulating the properties of the surrounding material so that it simply won't let the wave propagate."

To guide acoustic waves in a specific desired region, Weinstein and her colleagues used a series of periodic structures patterned in the CMOS layers. Due to their periodic nature, these structures only let certain frequencies of vibrations through, while reflecting others (i.e., including the target frequency).

"We are basically guiding the wave only in the region where we want it using these periodic structures," Weinstein explained. "The vibrations build up in this trap (or resonance cavity) as more and more vibrational energy is pumped in using the capacitors. Finally, we sense these built-up vibrations using standard transistors, which are sensitive to stress. These transistors convert the mechanical vibrations into an electrical signal, which can then be routed for use in nearby circuits."

The acoustic resonators created by this team of researchers are the first vibrational structures developed to date that are embedded in CMOS technology and require no modifications to the chip. While other approaches to integrating resonators with CMOS involve depositing films on the chip or etching away parts of the chip post-fabrication, theirs is the only mechanical resonator that utilizes an unmodified standard CMOS process.

"Taking advantage of high-performance transistors and nm-scale feature sizes in standard ICs gives us better performance at higher frequencies than possible with conventional MEMS processes," Weinstein said. "In addition, the direct integration with circuits in close proximity means simpler electrical routing, translating to better performance at GHz frequencies."

The acoustic resonator design introduced by Weinstein and her colleagues could be implemented using any copper-based CMOS platform and can be optimized for even better performance. In the future, it could thus open valuable opportunities for the creation of smaller, highly performing acoustic resonators that are easier to implement on a large-scale.

"The possible implications of our work include the development of on-chip clocks for low power, small footprint, low cost, robust, and secure microelectronic chips," Weinstein said. "The idea is to replace off-chip frequency sources like the quartz crystals used today."

The devices created by this team of researchers could also enable the creation of physical, chemical, and biological sensors with an integrated radio communication component. Finally, they could also help to enhance the security of hardware components, for instance by creating unique acoustic "fingerprints" for each chip and allowing devices to assess the integrity of packaged chips using embedded ultrasonic transistors.

"We are most interested in working with CMOS foundries to take advantage of emerging materials in their technologies to improve resonator performance," Weinstein added. "Upcoming opportunities for use of ferroelectric materials for enhanced electromechanical transduction are particularly exciting and promising. Once we have those in place, we can close the loop on the resonators and demonstrate high frequency, low noise clocks in CMOS."

In their next studies, Weinstein and her colleagues would also like to explore the possibility of broadening acoustic manipulation capabilities using the metamaterials used in their recent work. For instance, they would like to explore their value for enhancing waveguiding, lensing, convolution, and filtering tools.

More information: Jackson Anderson et al, Integrated acoustic resonators in commercial fin field-effect transistor technology, *Nature Electronics* (2022). DOI: 10.1038/s41928-022-00827-6

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