Memristive radiofrequency switches show improved performance for mmWave applications

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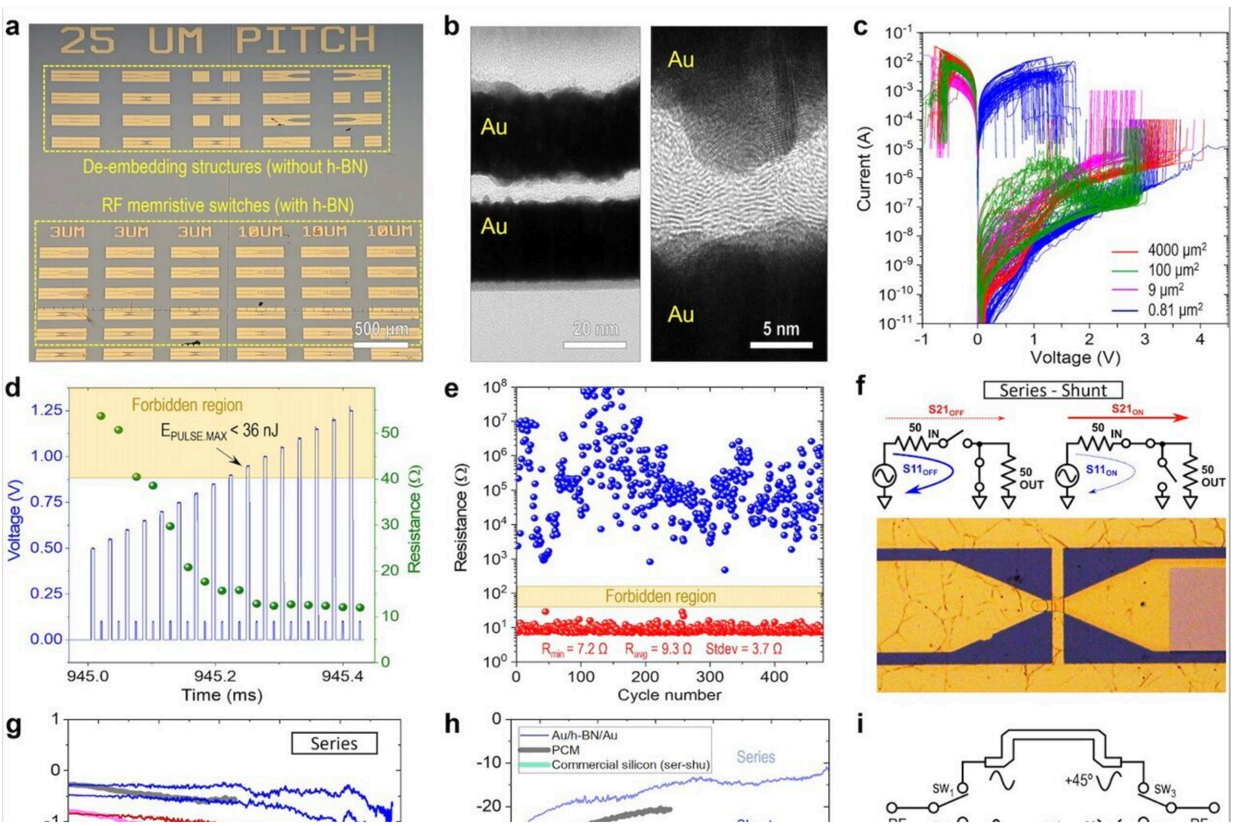

a, Optical microscope image of a meta/h-BN/metal array and RF de-embedding structures. b, Cross-sectional TEM images of a Au/CVD h-BN/Au device, showing layered structure. c, Characteristic I-V curves displaying at least 100 consecutive cycles for each device area. d, Conductance-enhancing protocol using 10 µs voltage pulses. e, Variability resistance through 475 cycles of a single device switched following the protocol from d. f, Circuit schematic and optical microscope image of a series-shunt Au/h-BN/Au device. g, Comparison of losses (S21ON) between conductance-optimized Au/h-BN/Au devices, non-optimized devices and other switching technologies. h, Isolation enhancement (better than 35 dB up to 120 GHz) with series-shunt Au/h-BN/Au. i, Schematic and layout of the evaluated phase-shifter as potential use-case. Credit: Pazos et al. (*Nature Electronics*, 2024).

Radiofrequency (RF) switches are electronic components that control the routing of RF signals between different segments of circuits, for instance turning the signals on and off or redirecting them. These switches are central to the functioning of numerous communication technologies, including smartphones, cell towers, and wireless networks.

Researchers at King Abdullah University of Science and Technology, Universitat Autonoma de Barcelona and other institutes recently developed memristive radiofrequency switches that can operate at remarkable frequencies beyond 100 GHz. These switches, presented in a paper published in *Nature Electronics*, could contribute to increasing the data transmission rates of existing communications devices.

The radiofrequency switches developed by the researchers are based on memristors, two-terminal electronic devices that can change their electrical resistance after being subjected to carefully tailored electrical stress. Memristors essentially act as switches, toggling on-demand between an OFF (i.e., with high resistance blocking the current flow) and ON (i.e., with low resistance allowing current to flow) state.

"RF data transmission switches for millimeter wave (mmWave) applications are a fundamental building block in modern wireless transceivers covering 5G and 6G communication bands," Mario Lanza, leading author of the paper, told Tech Xplore.

"The concept of their functionality is rather straightforward: they switch between (i) blocking a high-frequency signal from different sections of a circuit (isolation), and (ii) transmitting it with the least power loss possible. As simple as this may sound, it is actually very challenging, particularly as wideband communication standards are being pushed to higher frequencies (beyond hundreds of GHz) to improve data rates for telecommunications."

At frequencies over 100 GHz, non-idealities, device parasistics and performance need to be carefully and collectively considered to attain acceptable performances. These needs are addressed by different components within integrated circuits (ICs), including micro-electro-mechanical systems (MEMSs), semiconductor devices like transistors, diodes or varactors, and, more recently, also memristors based on metal-insulator transition materials.

All these components have their unique advantages. However, utilizing them to develop wireless communication solutions that can operate at frequencies beyond 100Gz has so far proved highly challenging.

"Memristors are relatively simple structures, sandwiching an insulating or semiconducting layer between metal electrodes (namely, a capacitor), and capable of persistently switching their electrical resistance through electrical stimuli," said Dr. Sebastian Pasos, first author of the study.

"Memristors made of single-layer 2D materials—such as hexagonal boron nitride (h-BN) or molybdenum disulfide (MoS_2)—have been explored for use as RF switches."

The application of controlled stress to single-layer 2D material-based memristors prompts the formation and disruption of a conductive metallic filament. This filament results in a very low resistance when the devices are in the ON state, enabling operating frequencies of up to 480

GHz.

While they were found to attain promising operating frequencies, memristive radiofrequency switches based on single-layer 2D materials often come with significant limitations. Most notably, they often exhibit a limited endurance and an unclear yield, which can vary greatly across different devices and cycles.

"The simple series switch architecture typically studied also has limited applicability," Pazos said. "To sort out the endurance and variability issue, we thought of using multilayered h-BN (instead of monolayer) with which we have experienced a higher yield of memristors in the past. Therefore, we fabricated large arrays of metal/h-BN/metal memristors laid-out on a RF waveguide structure that allows characterizing the devices at high frequencies."

The multilayer h-BN RF switches developed by Lanza and his colleagues operate via the control of one or multiple conductive filaments across the h-BN. The formation, growth, and progressive disruption of these filaments can be prompted by carefully applying stressing electrical signals to the memristors, in the form of voltage/current pulses.

"Multilayered h-BN fabricated through chemical vapor deposition (CVD) is characterized by a good insulating performance, with relatively low dielectric constant (~4)," Lanza said.

"A unique characteristic of this insulator is the presence of clusters of defects that facilitate filamentary resistive switching through migration of metallic ions while constraining the growth of the filament within these defective regions surrounded by highly stable crystalline h-BN."

The metallic filaments formed in the team's device can be disrupted by the flow of current via a process known as Joule heating. This enables the switching of electromagnetic signals in the devices under any stress polarity.

In other words, the team's switches can be operated with positive or negative voltages, but also via a combination of both, as opposed to other memristors that only work if voltages of both polarities are applied to them. This could facilitate the integration of the new memristive RF switches inside circuits, as it simplifies their operation.

"The fact that the filaments are metallic, thanks to the unique properties that make h-BN a mostly inert insulator in the memristive structure (enables free migration of metallic ions without exchanging other ions, like oxygen, with the metal electrodes), allows for a very low ON resistance that results in very low power losses (

"Moreover, their simple structure of metal-insulator-metal sandwich makes them easy to integrate in a wide range of technology platforms and applications, ranging from monolithic integrated circuits, to microstrip and multilayered PCB technologies."

The recent study by Lanza and his colleagues demonstrates the potential of multilayer h-BN memristors for developing next generation communications technologies, showing that they can serve as high frequency switches. These memristive RF switches could potentially contribute to the introduction of future mobile network standards for faster communication, such as 5G and 6G.

Using pulsed control, Lanza and his colleagues were also able to attain a very low ON resistance in their devices, which is a key requirement for enabling high frequencies operation. This promising, low ON resistance was also accompanied by limited cycle-to-cycle variability, meaning that the team's device performed remarkably well between switching events and maintained its performance after hundreds and even thousands of switching cycles.

"Attaining these results is a fundamental challenge for memristors in general and particularly for 2D material-based memristors for RF mmWave applications," Lanza said.

"In fact, we reported an improvement of at least 10x compared to previous efforts. Moreover, building RF switching circuits through arrangements of memristors in series and shunt configurations gives a more practical scope to these memristive devices that has not been previously achieved.

"This is attained while showing potentially competitive performance with well-established technologies for RF switching (such as CMOS switches or phase change memristors) but into much higher frequencies exceeding 200 GHz."

The new memristive RF switches introduced by this team of researchers could soon be integrated into various ICs, to further assess their performance and real-world potential. A crucial advantage of these promising devices is that they should theoretically be easy to integrate with well-established electronics and fabrication processes.

"We have already shown in previous work that h-BN memristors can be integrated with CMOS circuits with promising performance results for memory and neuromorphic applications," Lanza added.

"Furthering this into the high frequency RF/mmWave realm will now help us build more elaborate applications that harvest the potential of our devices, further improve their reliability and get us even closer to real world applications. This can maximize the impact of this technology and provide a possible solution for next generation mmWave circuits, such as configurable high frequency communication circuits, components, and on-chip antenna arrays."

More information: Sebastian Pazos et al, Memristive circuits based on multilayer hexagonal boron nitride for millimetre-wave radiofrequency applications, *Nature Electronics* (2024). [DOI: 10.1038/s41928-024-01192-2](https://dx.doi.org/10.1038/s41928-024-01192-2)