SCIENCE CHINA
Information Sciences

• LETTER •

November 2025, Vol. 69, Iss. 11, 219405:1–219405:2
https://doi.org/10.1007/s11432-025-4937-x

High-isolation radio frequency switches enabled by Cu_2S/GeSe conductive bridge threshold switch

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Received 17 December 2025/Revised 4 March 2026/Accepted 20 April 2026/Published online 30 October 2026

Citation Sun X, Cai J W, Wu Y Q, et al. High-isolation radio frequency switches enabled by Cu_2S/GeSe conductive bridge threshold switch. Sci China Inf Sci, 2025, 69(11): 219405, https://doi.org/10.1007/s11432-025-4937-x

With the rapid evolution of wireless communication systems towards 5G-advanced and emerging 6G technologies, the demand for higher data rates and spectral efficiency is driving operating frequencies into the millimeter-wave regime. In such systems, radio frequency (RF) switches serve as key control components for signal routing and band selection, with their performance directly impacting the signal integrity of the entire system. Particularly when systems operate in complex electromagnetic environments, inter-channel signal crosstalk significantly intensifies. This makes off-state isolation a critical determinant of system performance, presenting unprecedented technical challenges [1].

Faced with increasingly stringent isolation requirements, the limitations of traditional RF switches are becoming ever more apparent. Mainstream technologies rely on semiconductor positive-intrinsic-negative (PIN) diodes or field-effect transistors (FETs) [2], whose isolation performance is severely constrained by parasitic capacitance, which leads to rapid degradation with increasing frequency. On the other hand, while microelectromechanical system (MEMS) switches demonstrate superior isolation and insertion loss performance, they face limitations in reliability, slower switching speeds, and difficulties in integration with standard complementary metal-oxide-semiconductor (CMOS) processes, making widespread deployment in practical systems challenging [3]. Therefore, exploring high-performance RF switches based on new materials and novel physical mechanisms has become a focal point for both academia and industry [4].

In recent years, conductive bridge threshold switches (CBTS) have garnered significant attention due to their unique physical properties. Initially, their potential application as a selector in large-scale crossbar arrays sparked extensive research interest. Their operation relies on the migration and reduction of active metal ions (Ag^+, Cu^+) under electric fields. This process forms or breaks nano-scale conductive filaments, enabling extremely high on-off ratios ($> 10^9$) and ultra-low off-state leakage currents (pA level) [5]. These properties enable off-state resistances reaching the GΩ range. By effectively suppressing resistive leakage paths during switching, this high turn-off resistance, combined with the minimal turn-off capacitance of solid-state electrolyte films, physically enables CBTS devices to achieve higher RF isolation than conventional switches. However, their relatively low on-state current limits their use in RF applications. Here, we report a CBTS based on a Cu_2S/GeSe heterostructure that addresses the intrinsic trade-off between off-state reliability and on-state drive capability. By leveraging the localized cation switching mechanism of the Cu_2S layer and the high-resistivity GeSe layer to block leakage paths, our device delivers an on-state current of 1 mA while maintaining ultra-low leakage currents below 300 pA. The RF switches based on this architecture achieve off-state isolation exceeding 28 dB across a broad 10 MHz to 40 GHz band. This work not only overcomes the low on-state current limitation of CBTS devices but also demonstrates the application potential of Cu_2S/GeSe-based CBTS in high-isolation RF switches.

Experimental. The RF switch employs a vertical via architecture fabricated on a high-resistivity silicon substrate to minimize dielectric losses. The functional core is a synergistically engineered heterostructure comprising a 22-nm Cu_2S cation source layer and an amorphous GeSe switching layer, as illustrated in Figure 1(a). Cu_2S was selected as a superionic conductor, serving as a dense reservoir of mobile Cu^+ cations, while the wide-bandgap GeSe functions as a high-resistance solid electrolyte for filament evolution. The thickness of the GeSe barrier was optimized to 20 nm based on a trade-off between leakage suppression and drive current capability. Detailed electrical and RF performance comparisons for various thicknesses (15, 20, and 27 nm), including the physical mechanisms of leakage and current throttling, are provided in Appendixes B and D, respectively. Focused-ion-beam (FIB) cross-sectional imaging (Figure A1) confirms precise dimensional control and structural integrity of the deposited films within the 1 μm diameter via. Detailed fabrication and characterization protocols are documented in Appendix A.

Results and discussion. A critical bottleneck in conventional CBTS technology is the trade-off between current drive and switching reliability. Operating at high on-state currents typically forms thick, over-stabilized filaments that are difficult to rupture, leading to permanent low-resistance failure. The Cu_2S/GeSe system circumvents this issue through a unique mechanism involving densely localized cation sources. As shown in Figures 1(b) and (c), the Cu_2S layer facilitates discrete, nanometer-scale superionic channels under bias. Since Cu^+ ions enter the GeSe layer only through these restricted windows, the lateral expansion of

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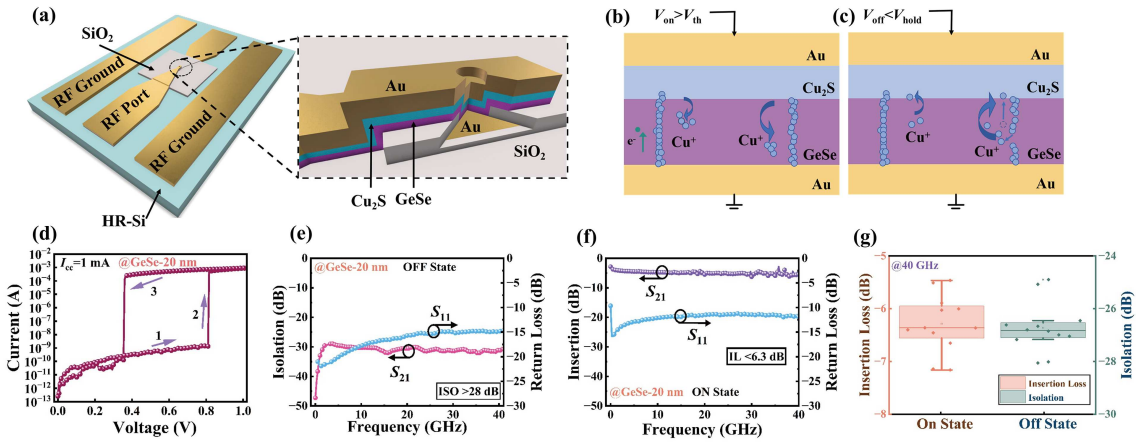

Figure 1 (a) 3D schematic illustration of the Cu_2S/GeSe-based RF switch fabricated on a high-resistivity silicon substrate. (b) Schematic of the turn-on process: under applied bias, Cu^+ ions migrate to form multiple nanofilaments bridging the electrodes. (c) Schematic of the turn-off process: upon bias removal, the filaments spontaneously dissolve. (d) Representative I-V characteristics showing 1 mA on-state current. (e) The off-state performance of the optimized device demonstrates a high isolation of 28 dB and a return loss better than 15 dB. (f) The ON-state RF performance of the optimized device, demonstrating an insertion loss (S_{21}) of less than 6.3 dB. (g) Statistical box plots of the insertion loss and isolation extracted at 40 GHz for the 12 devices, highlighting excellent reproducibility.

filaments is intrinsically confined. Upon bias removal, these filaments rapidly rupture, driven by defect-assisted diffusion within the GeSe layer and the spontaneous retraction of Cu^+ ions into the Cu_2S layer. This retraction is thermodynamically favored because S possesses a higher electronegativity than Se, which endows the Cu-S bond with a stronger ionic character and greater thermodynamic stability relative to the transient Cu-Se interactions within the switching layer. This dual mechanism ensures rapid filament dissolution to prevent low-resistance failure, enabling the device to reconcile a high on-state current of 1 mA with ultra-low off-state leakage, as experimentally verified in Figure 1(d). The figure also reveals a low threshold voltage (< 0.8 V). This logic-compatible operating voltage ensures that the switch can be directly integrated with advanced CMOS control circuits. Furthermore, the optimized device demonstrates stable direct current (DC) switching behavior over 100 consecutive cycles (see Figure B1).

To validate the device's efficacy for high-frequency signal transmission, broadband S-parameter characterization was performed from 10 MHz to 40 GHz. Prior to measurement, the system was calibrated to the probe tips using the short-open-load-through (SOLT) method. The optimized 20-nm device achieves a remarkable off-state isolation (S_{21}) of > 28 dB across the entire 40 GHz bandwidth (Figure 1(e)). This exceptional performance is prominently highlighted in the comparative benchmarking analysis (see Table D1). It is noteworthy that these S-parameters represent raw measurement data without on-chip de-embedding. The parasitic capacitance of the ground-signal-ground (GSG) pads introduces an additional high-frequency coupling path, implying that the intrinsic off-state isolation of the active switching region is practically better than the measured raw data. Complementary on-state measurements reveal an insertion loss (S_{21}) remains below 6.3 dB up to 40 GHz (Figure 1(f)). We attribute this moderate attenuation primarily to the finite intrinsic resistance of the nanoscale conductive filaments. Future optimization, architecturally through parallel multi-via layouts and materially by tuning the Cu_xS stoichiometry, is expected to mitigate this ohmic loss. To validate the scalability and reproducibility of this technology, we systematically evaluated the device-to-device (D2D) uniformity across 12 distinct devices. The statistical box plots (Figure 1(g)) confirm a tightly grouped distribution for both insertion loss and isolation, underscoring that the localized cation source engineering effectively regulates the filamentary processes. Device-to-device uniformity and power handling evaluations (see Figure D1) further underscore the reliability of this technology for practical implementations. Furthermore, the device exhibits sub-microsecond switching kinetics, with a turn-on time of 260 ns and a turn-off time of 100 ns. Robust operational stability was sustained over 1.2×10^4 pulse switching cycles (detailed measurement setups and transient response data are provided in Appendix C).

Conclusion. In summary, we have demonstrated that a Cu_2S/GeSe bilayer heterostructure provides a powerful platform for next-generation RF switches. By synergizing the densely localized cation sources of the Cu_2S layer with the geometric confinement of the GeSe barrier, we have reconciled the fundamental trade-off between on-state conductivity and switching reversibility. This architectural optimization enables a robust on-state current of 1 mA while strictly suppressing off-state leakage, resulting in exceptional broadband isolation (> 28 dB from 10 MHz to 40 GHz) alongside logic-compatible operation (< 0.8 V). This work establishes the Cu_2S/GeSe system as a promising material platform for future RF front-ends where exceptional isolation and ultra-low static power consumption are paramount.

Acknowledgements This work was supported by National Key R&D Program of China (Grant No. 2021YFA1202804) and National Natural Science Foundation of China (Grant No. 62174065).

Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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