**INTRODUCTION**

Epidermal electronic systems for continuous physiological information monitoring are the next frontiers of personalized health care, smart diagnosis, and advanced therapy (1–3). In general, seamless integration of the system with the skin or tissues is essential to maximize the signal-to-noise ratio for weak biosignal acquisition and to promote long-term operational stability (1–4). Various epidermal electronic elements, including sensors (5, 6), transistors (7–9), memories (10–14), and simple circuits (15, 16), have emerged as promising alternatives to rigid conventional counterparts, affording intimate biotic/abiotic interfaces. However, integrated epidermal systems that use flexible devices rather than rigid chips to simultaneously provide physiological signal measurement, signal processing, and information storage functions are still scarce. Compared to wireless data transmission in real time, constructing a system with the strategy of storing information for later readout has advantages of being low cost, lightweight, and low power, which are preferred to applications in on-demand short-term monitoring, disposable monitoring patches for daily usage, easily deployed health care monitoring in remote geographical locations with constrained resources, under-water monitoring or other cases where wireless data transmission are not available, etc.

In building such an epidermal electronic system with information storage capability, a key bottleneck lies in the lack of flexible nonvolatile memory that has specifications comparable to those of commercial devices. Nonvolatile memories, especially the dominant type, flash memories, that can retain stored information for later retrieval and analysis, are expected to have low program and erase voltages of less than 10 V for low power consumption, a long retention time of over $10^8$ s for good information storage stability, and a good endurance for robust cyclic operation of over $10^6$ cycles in commercial use (17, 18). Because of the limited yield and insufficient uniformity of flexible memory devices, which are mainly constrained by the limited uniformity of active materials over a large area and/or incompatibility with conventional microfabrication process for batch device manufacturing (12, 19–22), integrated flexible memory arrays for system-level applications are still rarely reported. In addition, high-performance flexible sensor interface circuits that are responsible for weak physiological signal processing and act as an indispensable mating liaison between sensors and memories have long been valued in epidermal electronic systems (2, 7).

Carbon nanotubes (CNTs) have emerged as one of the most promising candidates for building next-generation electronics. Because of their excellent electrical properties, robust mechanical flexibility and large-scale processability, the superiority of CNTs in constructing both rigid and flexible systems has been demonstrated (23–27), providing opportunities to address the above critical issues if proper methodologies are adopted. At the same time, compatibility with conventional foundry manufacturing process enables uniform and high-yield fabrication of CNT devices for system integration (28).

Here, on the basis of CNT thin films, we established an epidermal system that incorporates flexible sensors [humidity, temperature, and electrocardiogram (ECG) sensors], sensor interface circuits (high-performance differential amplifiers), and an integrated flexible flash memory array (24 bit by 16 bit) for physiological information recording. Using hybrid stacked heterodielectrics, CNT-based flash memories simultaneously present a long retention time (projected to be approximately $10^8$ s), low program/erase voltages ($\pm 2$ V), and good endurance (projected to be over $10^6$ cycles), which are on par with industrial requirements. CNT-based differential amplifiers,
serving as the sensor interface, were constructed for processing weak physiological signals with great amplification capability (voltage gain of 27 dB), signal fidelity [common-mode rejection ratio (CMRR) of >43 dB], and a large gain bandwidth product (GBWP; >22 kHz). On the basis of these results, a system-level demonstration of physiological information recording was realized, and retrieval of the stored data was demonstrated, showing reliable retention properties that enable the data to serve as evidence/reference for later clinical analysis and diagnosis.

RESULTS
Design and architecture of the epidermal electronic system
Figure 1A shows a schematic illustration of the epidermal electronic system containing flexible sensors, sensor interface circuits, and a flash memory array for acquiring, processing, and storing physiological signals, respectively. As all the components are fabricated on an ultra-thin parylene film (~2 μm in thickness) attached to a 10-μm-thick elastic polydimethylsiloxane (PDMS) layer, the epidermal system can intimately adhere to the human skin (Fig. 1B and fig. S1A). Figure 1C and fig. S1B illustrate the spatial layout of the epidermal system, while the detailed architecture of each component is revealed in Fig. 1 (D to F). Ti/Au electrodes are patterned in serpentine geometry for ECG recording. Poly(3,4-ethylenedioxythiophene)–poly(styrenesulfonate) (PEDOT:PSS) and carboxymethylcellulose sodium (Na-CMC)/PSS sodium (Na-PSS) thin films are adopted as active materials in temperature and humidity sensors for body temperature and skin sweat condition measurements, respectively. The sensor interface circuits and memory arrays are both constructed with CNT thin-film transistors (TFTs) but with different device structures, which will be elaborated later (see Materials and Methods, note S1, and fig. S2 for the detailed fabrication process). Figure 1G shows the information flow in the epidermal electronic system. Physiological signals captured by different sensors are processed by differential amplifiers, which serve as sensor interface circuits for signal amplification and noise reduction, and, subsequently, physiological information extracted from these processed data is stored in the flash memory array. This stored information will be retrieved by peripheral equipment with powerful processing capability for postprocessing and analysis, which enables clinics to check and trace the wearer’s health status where timely access to medical resources is insufficient.

Device design and characteristics of CNT-based flash memories
The proposed flash memories are based on the CNT TFT structure (Fig. 2, A and B), wherein Al₂O₃ (5 nm), Al nanoparticles (2 nm), HfO₂ (10 nm), and randomly oriented CNT thin film (Fig. 2C and fig. S3) serve as the tunneling dielectric layer (TDL), charge trapping layer (CTL), blocking dielectric layer (BDL), and active layer, respectively. The stacked heterogeneous structure (Al₂O₃/Al/HfO₂)
can be easily distinguished in the cross-sectional transmission electron microscopy (TEM) image in Fig. 2D, while the spatial distribution of each composition is confirmed by the scanning TEM (STEM) image and energy-dispersive x-ray spectroscopy (EDS) result in Fig. 2E. Figure 2F illustrates the operation mechanism of the flash memory. During programming, when a sufficient negative bias is applied on the gate electrode, holes in the CNT layer tunnel through the ultrathin TDL and are trapped by Al nanoparticles in the CTL. During erasing, trapped carriers are discharged from the CTL to the CNT layer when a sufficiently large positive bias is applied on the gate electrode. Programming/erasing by charging and discharging the CTL leads to a threshold voltage ($V_{th}$) shift of the flash memory, which can be revealed by the hysteresis effect shown in fig. S4 and the shifted transfer characteristics of the CNT flash memory in Fig. 2G.

The program and erase voltages are key parameters for flash memories, which directly affect the power consumption of devices (12, 17). As shown in Fig. 2H, the drain current ($I_{ds}$) under the erased state ($I_{ers}$) and programmed state ($I_{prg}$) at a gate voltage of $V_{gs} = 0$ V are extracted from the transfer characteristics of the CNT flash memory for different program voltages ($V_{prg}$) and erase voltages ($V_{ers}$) (pulse width of 1 s) (fig. S5, A and B). This result indicates that our memory device can be programmed and erased at very small voltages of $V_{prg}/V_{ers} = 2/2$ V, with an $I_{ers}/I_{prg}$ of over $5 \times 10^4$ and a memory window of 0.83 V (fig. S5C). Here, the memory window is defined...
as the difference in \( V_{th} \) under the programmed state and erased state. Compared to other flexible flash memories (shown in Fig. S5D) (10–12, 14, 19, 20–29–36), this result demonstrates a much smaller program and erase voltage range while still maintaining ample difference between the programmed and erased states, with an \( I_{ces}/I_{prg} \) of over \( 10^4 \), offering great superiority in low-power data storage applications. The proposed memory device also exhibits good retention characteristics. As shown in Fig. 2I, under the programmed/erased voltage of \(-2/+2 \) V (pulse width of 1 s), the \( I_{ces}/I_{prg} \) could maintain from the initial time to over 200 s with a value of over \( 6 \times 10^4 \), and \( I_{ces}/I_{prg} \) started to decrease as the retention time further increased (shown in fig. S6). As the retention time increased up to \( 5 \times 10^4 \) s, \( I_{ces}/I_{prg} \) decreased to be about \( 1.2 \times 10^4 \). When the retention time further increases to \( 10^5 \) s, projected by the linear extrapolation, there is still at least a 10-fold gap between \( I_{ces} \) and \( I_{prg} \), which is sufficient to distinguish the programmed and erased states of the flash memory.

In general, there is a conflict between low program/erase voltages and a long retention capability in flash memories. Here, by asymmetrically adopting Al\(_2\)O\(_3\) as the TDL and HfO\(_2\) as the BDL with different relative dielectric constants (\(-9 \) and \(-18 \), respectively) and different thicknesses (5 and 10 nm), a high electric field is introduced across the TDL to enhance the tunneling behavior for efficient program and erase operation, while the electric field across the BDL is always maintained at a low level to restrain charge flow through the BDL (detailed analysis and discussion are presented in note S2 and fig. S7) (31, 37). Thus, as the performance comparison shown in fig. S7D, low program/erase voltages and a long retention capability are simultaneously achieved in our flash memories on the basis of this asymmetric heterogeneous stacked dielectric design. Meanwhile, because of the asymmetric dielectric structure, compared with other CNT-based flash memory devices on both rigid and flexible substrates (table S1) (13, 30, 32, 38–41), our devices demonstrate smaller operational voltages, longer retention time, and better integration capability and conformability simultaneously.

The endurance of the flash memory is characterized by repetitive operation of the flash memory under the conditions of \( V_{prg}/V_{ers} = -2/+2 \) V and a pulse width of 0.1 s. Although slight degradation is observed (shown in fig. S8), reliable distinction of the programmed and erased states is realized, with an \( I_{ces}/I_{prg} \) of approximately 150 (Fig. 2J) after 10,000 cycles of program/erase operations. When the operation is projected to be \( 10^6 \) cycles, projected by the linear extrapolation, \( I_{ces}/I_{prg} \) is still over 100. Such a great endurance property of \( 10^6 \) cycles, together with very low operation voltages of \( \pm 2 \) V and a long retention time of \( 10^6 \) s, meets the industrial requirements for commercial applications. The operation speed characteristics of the flash memory are investigated by applying \( V_{prg}/V_{ers} = -5 \) V to \( 5 \) V with a pulse width ranging from 1 ms to 5 s (fig. S9). \( I_{ces} \) and \( I_{prg} \) split under a pulse width of 1 ms, and \( I_{ces}/I_{prg} \) becomes larger as the pulse width increases. When the pulse width increases to 20 ms, \( I_{ces}/I_{prg} \) reaches over \( 10^4 \) (Fig. 2K), which is decent for practical applications.

**Uniformity, mechanical robustness, and array integration of flexible flash memories**

Flash memory cells are supposed to have great uniformity to ensure the accuracy of data storage for further integration. As shown in Fig. 3A, the measured transfer characteristics of 100 flexible flash memories in programmed and erased states (\( V_{prg}/V_{ers} = -2/+2 \) V, pulse width of 1 s) present a very narrow distribution. The statistical distribution of \( V_{th} \) under the programmed and erased states is \(-0.84 \pm 0.03 \) and \(-0.05 \pm 0.03 \) V, respectively (Fig. 3B), and the SD of the memory window is only \( 37 \) mV, which is less than 5% of the average value of 0.79 V (Fig. 3C). The uniformly distributed Al nanoparticles in CTL contributed a lot to such a high uniformity. For flash memory devices, the threshold voltage shift between programmed and erased state could be expressed by the formula:

\[
\Delta V_{th} = \frac{\varepsilon \Delta n}{C_{BDL}}
\]

where \( \varepsilon \), \( \Delta n \), and \( C_{BDL} \) refer to the electron charge, charge density change in CTL, and area-normalized capacitance of BDL, respectively. Therefore, for a flash memory with a fixed structure, where \( C_{BDL} \) is fixed, the uniformity of charge trapping site distribution would have great effect on the uniformity of the flash memory devices. As shown in fig. S10, Al nanoparticles fabricated via the evaporation method can achieve a high-density (>\( 10^{15} /cm^2 \)) with small size variations (158.5 \( \pm 14.2 \) nm\(^2 \)), making that the charge-trapping capability varies negligibly from device to device. This negligible variation leads to nearly consistent readout characteristics of the fabricated memories, with statistical distributions of 3.98 \( \pm 1.37 \) pA in \( I_{ces} \) and 0.39 \( \pm 0.09 \) mA in \( I_{prg} \) (Fig. 3D), and \( I_{ces}/I_{prg} \) exhibits a narrow distribution of 5.02 \( \pm 0.2 \) decades (Fig. 3E), which provides a large difference in the programmed and erased states to enable accurate data storage, especially for further array integration.

On the basis of these highly uniform flash memory devices, a 24 bit by 16 bit memory array is constructed by integrating 384 flash memory cells through 24 serpentine-shaped word lines (WLs) and 16 serpentine-shaped bit lines (BLs) (Fig. 3F). In an integrated memory array, the disturbance between memory cells should be carefully considered to ensure accurate data storage, and a NOR flash architecture is therefore adopted with small cross-talk among memory cells (17). In such an architecture, the gate, source, and drain electrodes of each memory cell are directly connected to the WLs, ground lines (GLs), and BLs, respectively, by which parallelly connected memory cells are individually addressable. As shown in Fig. 3G, when a certain memory cell is selected to be programmed or erased, there are four kinds of memory cells associated in this array: the selected cell (C\(_S\)), neighboring cell connected to C\(_S\) by a WL (C\(_{NW}\)), neighboring cell connected to C\(_S\) by a BL (C\(_{NB}\)), and nonselected memory cell (C\(_{NS}\)). Negligible disturbance is observed among these cells, which is proven by the example of selective programming of C\(_S\), as shown in Fig. 3H. Compared to their initial states (dashed lines in Fig. 3H), the transfer characteristics of C\(_{NW}\), C\(_{NB}\), and C\(_{NS}\) show negligible changes after C\(_S\) programming (solid lines in Fig. 3H).

Considering the epidermal application in which many deformations occur, mechanical robustness is verified by bending tests of the flash memories laminated on a polyethylene terephthalate film (Fig. 3I and fig. S11). The transfer characteristics of the flash memory change very slightly with the bending radius of curvature (fig. S12A), where the shift of \( V_{th} \) is less than 50 and 150 mV under programmed and erased states (\( V_{prg}/V_{ers} = -2/+2 \) V, pulse width of 1 s), respectively; the memory window is maintained over 0.62 V (fig. S12B); and the measured \( I_{ces} \) and \( I_{prg} \) remain at the levels of \( 10^{-7} \) and \( 10^{-12} \) A (Fig. 3J), respectively. The cyclic bending test of the flash memory under a radius of curvature of 1.33 cm 1000 times (fig. S13A) shows that the \( V_{th} \) shifts for both the programmed and erased states are less than 25 mV (fig. S13b), which is negligible with regard to the memory window of approximately 0.8 V. Meanwhile, \( I_{ces} \) and \( I_{prg} \) are almost fixed at values of approximately 0.4 \( \mu \)A and 4 nA (Fig. 3K), respectively. These results indicate that the flash memories
have great mechanical robustness for reliable memory readout under deformations, which is critical for wearable or biological applications (10, 30).

**High-performance CNT-based differential amplifiers as sensor interfaces**

In an epidermal system for weak physiological information acquisition, sensor interface circuits close to the sensors are of undoubted significance to the sensing signals in terms of improving their quality for the back ends (2, 7, 43). Here, we use differential amplifiers as the sensor interface to amplify the weak signals captured from the human body and simultaneously decrease the unwanted noise from the surroundings. The basic building blocks to construct the flexible amplifiers are CNT TFTs (Fig. 4, A and B), which differ from the flash memory devices in the construction of the gate dielectrics, which is only formed by HfO$_2$ (15 nm) here. The transfer characteristics of 50 CNT TFTs in Fig. 4C exhibit average values of a very small hysteresis voltage of 0.16 ± 0.05 V (Fig. 4D), a large current on/off ratio ($I_{on}/I_{off}$) of 6.47 ± 0.09 decades (Fig. 4E), and a field-effect mobility of 10.43 ± 1.73 cm$^2$/V per second (fig. S14), which would greatly contribute to constructing integrated circuits (ICs) with superiorities in stability, switching properties, and driving ability, respectively. Compared with other CNT-based flexible transistors (table S2) (44–52), our devices demonstrate a moderate mobility for good driving capability, a large current on/off ratio for great switching characteristics, and a small standard variation in threshold voltage for further integration. On the basis of these TFTs, a single-ended inverter is constructed (Fig. 4F), which can operate at a voltage as low as 3 V with a voltage gain up to 85, exhibiting great amplification capability. By symmetrically interconnecting two inverters, a differential amplifier is constructed (Fig. 4, G and H) with a connected bias transistor, which is used to adjust the static operating point of the
According to these two tests, the CMRR, which is a key parameter of differential amplifiers, is 43 dB. The differential amplifier also demonstrates a 3-dB bandwidth \( f_{\text{3db}} \) of 1 kHz (Fig. 4K) and a GBWP (GBWP = \( f_{\text{3db}} \times \text{open-loop gain} \)) of over 22 kHz, indicating its suitability for working with physiological signals captured from the human body surface considering their amplitude and frequency ranges (2, 53). Meanwhile, during low-frequency operation (below \( f_{\text{3db}} \)), the phase shift is only approximately 45° (Fig. 4L), providing good stability in practical applications. Compared with other CNT-based flexible amplifiers (table S3) (44, 45, 54, 55), because of the adoption of the differential amplifier circuit architectures, our devices demonstrate a large open-loop gain, a good gain bandwidth, and a great signal-to-noise ratio simultaneously, indicating its superiority for small physiological signal amplifying.

**System-level demonstration of physiological information recording**

An epidermal electronic system is constructed to record human physiological information, including ECG, body temperature, and...
perspiration, as shown in Fig. 5A. The biosignals are first captured from the epidermis by various flexible sensors. Figure 5B demonstrates the ECG sensors with a serpentine geometrical design, which aims to improve the flexibility of the sensors and achieve conformal contact with the human body. To obtain ECG signals with high quality, which are generally in the range of millivolts and easily disturbed by environmental noise (53), a CNT differential amplifier is connected to the flexible ECG sensor (see the detailed setup in fig. S15) to amplify the weak signals and attenuate the noise. Because of the large CMRR of the differential amplifier, the processed
ECG signals measured from a participant (a 27-year-old male) have defined P wave, QRS complex, and T wave, as shown in Fig. 5C. Such a setup can also support monitoring for a long time, with the results shown in Fig. 5D, in which the participants’ ECG signals are measured every 20 s before and after exercise, providing plenty of real-time information about cardiac functionality. Temperature and humidity sensors are also integrated into the system using PEDOT:PSS and Na-CMC/Na-PSS thin films as sensitive materials for body temperature and perspiration recording. As demonstrated in figs. S16 and S17, the fabricated temperature and humidity sensors exhibit good repeatability and long-term stability. A linear response is achieved for both sensors (Fig. 5, E and F), with a sensitivity of 1.27%/°C for temperature and 1.18%/% for relative humidity (RH). Similarly, amplifiers are connected to the temperature and humidity sensor to amplify the amplitudes of the biosignals. Continuous physiological information monitoring on the chest surface is carried out, with the results presented in Fig. 5G, indicating dynamic changes in heart rate (data extracted from ECG signals in Fig. 5D), body temperature, and perspiration (reflected by humidity) of the participant before and after exercise.

As presented in Fig. 5A, this physiological information is row-by-row written into an integrated flash memory array (24 by 16). The eight neighboring cells interconnected by the same WL are grouped as a byte to store the data string (fig. S18, A and B). The write-in data of this NOR flash memory array are encoded in two ways (fig. S18C): alphabetic letters using the American Standard Code for Information Interchange (ASCII) code and a numeric string using binary code. For example, the letter “T” is programmed as a corresponding ASCII code of “01010100,” while the numeric data “65” is converted to a binary code of “01000001.” The row-by-row stored physiological information in the integrated flash memory array is shown as the encoding map in Fig. 5H. The stored information is retrieved from the flash memory immediately after writing (Fig. 5i) and 1 day after writing (Fig. 5j), which complies well with the encoding map and demonstrates good retention properties. These stored data that contain continuous health monitoring information can be read out later as medical evidence or records for clinical analysis, showing great promise for advanced remote health care applications in areas lacking timely medical resources.

**DISCUSSION**

Epidermal electronic systems that can simultaneously provide biosignal acquisition, processing, and storage are highly desired for future health care, diagnosis, and clinical applications. Here, on the basis of CNT thin films, we demonstrate such a system that incorporates an integrated flexible flash memory array (with a long retention time, low program/erase voltages, and good endurance), high-performance differential amplifiers (with a voltage gain of approximately 27 dB, a CMRR of over 43 dB, and a GBWP of over 22 kHz), and flexible sensors recording various physiological information from the skin. The integration density and scale of the memory array could be further increased to realize a larger data capacity in future multimodal abundant biosignal recording. Moreover, developing other key components, such as high-performance analog-to-digital converters, central control units, and wireless modules, is still highly needed to expand the functionality of the obtained system, which could drive us toward the ultimate goal: advanced epidermal electronics providing monitoring, analysis, and feedback functions for future predictive, preventive, and personalized health care and clinical applications.

**MATERIALS AND METHODS**

**Preparation of CNT thin films**

The CNT thin film preparation began with obtaining a high-purity semiconducting CNT solution, which is achieved mainly on the basis of a density-gradient centrifugation method (56). Raw arc-discharged single-walled CNTs (100 mg) purchased from Carbon Solution Inc. were mixed with 9-(1-octylonyl)-9H-carbazole-2,7-diyl (200 mg) into 100 ml of chloroform. The obtained solution was then ultrasonicated by a top-tip disperger (VC500, Sonics) for 30 min at an amplitude level of 50%. Afterward, centrifugation was performed at 20,000g for 1 hour (Allegra X-22R centrifuge) to remove most of the bundles and insoluble materials. Next, the solution was centrifuged at 50,000g for 2 hours to remove the residual metallic nanotubes, and the semiconducting nanotube was reserved. CNT thin films were then fabricated by the dip-coating method (57) after the preparation of the CNT solution using a dipping machine. After repeated 15 dip-coating cycles, a CNT thin film was deposited on the substrate with high semiconducting purity, a density of ~20 CNTs/nm, a thickness of ~4 nm, and great uniformity.

**Fabrication of CNT flash memories and TFTs**

After the deposition of the CNT thin films, inductively coupled plasma was introduced to pattern the CNT thin films to remove unwanted CNTs for electrical insulation between different devices. Source and drain electrodes (0.5-nm Ti/30-nm Pd) were then fabricated through photolithography, electron beam evaporation (EBE), and a liftoff process. Next, to construct the dielectric layer of flash memories, a 5-nm Al2O3 film was grown by atomic layer deposition (ALD) at 90°C (Savannah, Cambridge NanoTech), followed by deposition of 2-nm Al to form Al nanoparticles as the CTL at a vacuum level of 10−7 torr via EBE (DE 400BH, DE Technology Inc.) and a 10-nm HfO2 film via ALD at 90°C. For the dielectrics of CNT TFTs, only 15-nm HfO2 was deposited by ALD at 90°C as the high-k gate dielectric. The gate electrodes (3-nm Ti/40-nm Au) for flash memories and TFTs were defined by photolithography, EBE, and a standard liftoff process, similar to the source/drain electrode fabrication.

**Fabrication of flexible temperature sensors**

PEDOT:PSS dry pellets (Sigma-Aldrich) were added to deionized (DI) water to form a uniform dispersion (1.5% by weight) under vigorous stirring. Tetraoctylammonium bromide (J&K Scientific) was dissolved in ethylene glycol at a concentration of 0.05 M, followed by ultrasonication for 30 min. The above two solutions were then mixed (volume ratio of 10:1), stirred, and ultrasonicated to obtain a PEDOT:PSS solution. Then, two interdigital electrodes (3-nm Ti/40-nm Au) were evaporated by EBE on a flexible substrate. Last, the obtained PEDOT:PSS solution was drop-cast on the electrodes, baked, and concentrated at 120°C for 3 min.

**Fabrication and calibration of flexible humidity sensors**

Na-PSS and Na-CMC were first dissolved in DI water at 0.06 and 0.08% by weight, respectively. Then, the obtained solution was drop-cast on the fabricated interdigital electrodes (3-nm Ti/40-nm Au) and baked at 80°C for 30 min. For humidity sensor calibration, different
RH environments were realized by different saturated aqueous salt solutions of LiCl, MgCl₂, NaBr, NaCl, KBr, and K₂SO₄, providing RHs of 11, 33, 57, 75, 85, and 97%, respectively.

Preparation of ultrathin parylene-C substrates
First, a layer of parylene-C with a thickness of 2 μm was deposited on a heavily doped silicon wafer (with a resistivity of less than 0.009 Ω·cm) by chemical vapor deposition (SCS Labcoter 2, Specialty Coating Systems Inc.) at room temperature. Then, to reduce the surface roughness of the substrate, poly(4-vinylphenol) (PVP) in propylene glycol monomethyl ether acetate mixed with a cross-linking agent of poly-(melamine-co-formaldehyde) was spin-coated on the parylene-C film and annealed in vacuum for 2 hours. Last, 5-nm HfO₂ was deposited on the PVP by ALD as the buffering layer between the polymer substrates and the devices.

Characterization of the CNT flash memories, TFTs, and circuits
The electrical performances of CNT flash memories, TFTs, and ICs were measured using a Keithley 4200 semiconductor parameter analyzer and a probe station (Summit 11000, Cascade Microtech). The input signal was generated by a signal generator (MXG N5181A, Agilent). The outputs were measured by an oscilloscope (DSO7054A, Agilent) and the Keithley 4200 system, while the inputs were measured using an oscilloscope (DSO7054A, Agilent).

SUPPLEMENTARY MATERIALS
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