Supplementary Information

Interpretable Kolmogorov-Arnold Network Using Vertical NAND Flash Memory

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Supplementary Note 1

V-NAND flash memory structure. The V-NAND flash memory investigated in this study was a commercial triple-level-cell (TLC) V-NAND device supplied by SK hynix[1,2]. The memory array consists of over 100 vertically stacked word-line (WL) layers. Each V-NAND string is selected by a particular combination of bit-line (BL) and drain-select-line (DSL)[1]. On the source side, the source-select-line (SSL) and source-line (SL) are positioned opposite to the DSL and BL. In contrast to the BL, however, the SL is formed as a common source line shared across a block in order to lower the source-line resistance[3,4]. As a result, string selection in the measured device is governed primarily by the BL and DSL, rather than by independently selecting the SL and SSL.

Each string in the V-NAND device consists of a polycrystalline silicon channel surrounded by a tunneling oxide, charge-trap nitride, and blocking oxide stack[2]. Data are stored through electron trapping in the charge-trap nitride layer. Within a string, the vertically stacked WLs share the same channel and charge-trap layer. When a specific WL layer is selected in combination with a given BL-DSL pair, the corresponding location forms an individual V-NAND flash memory cell, which acts as the fundamental storage unit of the array.

Supplementary Note 2

V-NAND flash memory operation. The operation of V-NAND flash memory is generally classified into three basic modes: program, erase, and read. Since program and read operations require the selection of individual cells within a V-NAND string, the applied bias scheme must be carefully optimized to avoid disturbance in half-selected and unselected cells.

During the program operation, a positive program voltage, V_{PGM}, is applied to the selected word-line (WL). This bias enhances the electric field between the channel and the selected WL, facilitating electron injection from the channel into the charge-storage layer[5]. As V_{PGM} increases, the electric field becomes stronger, leading to improved programming efficiency. For the unselected WLs, a pass voltage, V_{Pass_P}, is applied to transfer the channel potential along the string while reducing the potential difference between the WL and the channel, thereby suppressing unwanted programming. On the bit-line (BL) side, the selected BL is grounded to maximize the effective programming field, whereas the unselected BLs are biased with an inhibit voltage, V_{uBL_P}, so that program injection is prevented even under the selected-WL V_{PGM} condition. A conventional V-NAND flash memory precisely tunes V_{th} by using an incremental-step-pulse-programming (ISPP) scheme[6,7], in which program pulses are applied while progressively increasing V_{PGM}.

The erase operation is usually carried out on a block basis, in which the corresponding BLs, WLs, and drain-select-lines (DSLs) are activated together[8,9]. Erasing is driven by gate-induced drain leakage (GIDL), which is generated through suitable biasing of the BL and DSL. The potential difference between the BL erase voltage, V_{ERS}, and the DSL erase bias, V_{DSL_E}, determines V_{GIDL}. A larger V_{GIDL} promotes more efficient hole generation, thereby enhancing the erase operation. Comparable bias conditions may also be applied to the source-line (SL) and source-select-line (SSL) to assist additional GIDL generation. During erasing, the WLs are maintained at 0 V, producing an electric field that drives the generated holes from the channel toward the WL. Increasing V_{ERS} raises the channel potential, which further improves erase efficiency.

In the read operation, the selected BL and DSL are biased to establish a conduction path through the target V-NAND string. A read pass voltage, V_{Pass_R}, is applied to the unselected WLs, ensuring that the corresponding cells remain turned on and do not restrict the string current. The selected WL is then biased with the read voltage, V_{Read}, and the stored state of the selected cell is identified by sensing the resulting BL current.

Supplementary Note 3

Multimodal sensor integrating gas, pressure, and temperature sensing. A multimodal sensor platform was employed to detect gas species under varying environmental conditions[10]. The sensor system integrates gas, barometric pressure, and temperature sensing functions, allowing chemical information and ambient-condition information to be obtained simultaneously. This configuration is important because gas-sensor responses are often affected not only by the target gas concentration but also by external parameters such as pressure and temperature. Therefore, measuring these environmental variables together with the gas response provides a more reliable basis for gas analysis.

The gas-sensing part of the platform generates electrical responses depending on the concentration and type of exposed gas. In this work, three different sensing responses (*A*, *B*, and *C*) were obtained by varying the pre-bias conditions of identical gas sensors, thereby inducing different responsivities. Because different gases can produce overlapping or coupled responses, multiple gas-response channels are used to provide richer information than a single sensing signal.

In addition to the gas responses, the platform measures temperature (*T*) and barometric pressure (*P*). These two parameters describe the ambient condition during gas exposure. Temperature can influence gas adsorption, desorption, reaction kinetics, and carrier transport in the sensing material, while pressure can affect gas density and the interaction between gas molecules and the sensor surface. As a result, the same gas concentration may produce different sensing responses depending on the surrounding *T* and *P*. Including temperature and pressure information therefore helps distinguish true gas-induced changes from environmentally induced variations.

The sensing dataset consists of five input variables: *T*, *P*, and the three gas-response signals *A*, *B*, and *C*. The corresponding output variables are the concentrations of H_2S and NO_2, which represent the target gases in the mixed-gas environment. The dataset includes multiple combinations of temperature, pressure, and gas concentration, enabling evaluation of gas recognition under non-uniform environmental conditions. In particular, *T* was varied over 20, 40, 60, and 80 °C, and *P* was varied over 200, 350, 500, and 760 Torr. The H_2S concentration levels were 0, 10, 20, and 50 ppm, while the NO_2 concentration levels were 0, 100, 200, and 500 ppb.

This multimodal sensing configuration provides a practical test case for gas analysis because it includes both chemical selectivity and environmental dependency. By combining gas-response signals with temperature and pressure measurements, the sensor data contain sufficient information to estimate gas concentrations more reliably than gas-response signals alone. Thus, the multimodal sensor dataset reflects a realistic sensing scenario in which environmental compensation is essential for accurate mixed-gas detection.

Supplementary Note 4

Coefficients for KAN-based gas concentration fitting. The gas concentrations were fitted using the KAN model based on the multimodal sensor inputs. To simplify the fitted expressions, the pressure-normalized gas sensor responses were defined as

$$u = \frac{10^4 A}{P}, v = \frac{10^4 B}{P}, w = \frac{10^4 C}{P}$$

, where A, B, and *C* are the three gas-sensing responses obtained under different pre-bias conditions, and *P* is the barometric pressure.

Using these normalized variables, the fitted gas concentrations are expressed as

$NO_2 = (202.18-0.95941T)u + (-86.376+0.48784T)v + (25.790-0.15605T)w$

$H_2S = (23.089-0.21086T)u + (-42.056+0.38327)v + (6.3206-0.21331T)w$

These equations show that the contribution of each gas-sensing response is modulated by temperature. The use of pressure-normalized variables accounts for pressure-dependent changes in the sensing response, while the temperature-dependent coefficients compensate for thermal variations in gas sensitivity. Therefore, the fitted expressions provide compact analytical approximations for estimating NO_2 and H_2S concentrations from the multimodal sensor signals.

Supplementary References

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