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Physics based circuit compatible model for hybrid antiferroelectric random access memory

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Appendix A Definitions

When AFRAM operates in volatile mode, the $\mathrm{MW_{neg}}$ and $\mathrm{MW_{pos}}$ are defined as $\mathrm{MW_{neg}} = V_{\mathrm{BLneg`01'}} - V_{\mathrm{BLneg`00'}}$ and $\mathrm{MW_{pos}} = V_{\mathrm{BLpos`11'}} - V_{\mathrm{BLpos`10'}}$, respectively. When AFRAM operates in non-volatile mode, the MW is defined as MW= $V_{\mathrm{BL`1'}} - V_{\mathrm{BL`0'}}$.

Appendix B Detailed description about AFRAM EDA model

According to Ref [1], the relationship between the energy of the AFE U and polarization charge Q can be described as:

$$U = [(\alpha_p + \alpha_n/2)Q^2 - P_\mathrm{a}\alpha_\mathrm{n}Q + \beta\left(2P_\mathrm{a} - Q\right)^4/4 + 2\alpha_\mathrm{n}P_\mathrm{a}^2 + 7\beta Q^4/4 - 6\beta P_\mathrm{a}Q^3 + 6\beta P_\mathrm{a}^2Q^2 - EQ]\mathrm{AT} \tag{B1}$$

where $\alpha_{\mathrm{p(n)}} = \alpha \pm \gamma/2$. To simplify, the equation (B1) is translated into a relationship between the voltage across the each sublattice and the polarization (in equilibrium conditions: $dU/dQ = 0$),

$$\begin{aligned} V_{\mathrm{sublattice1,2}} &= \mathrm{T}[8\beta Q^3 - 24\beta P_\mathrm{a}Q^2 + (3\alpha + \gamma/2 + 24\beta P_\mathrm{a}^2)Q - (2\alpha - \gamma)P_\mathrm{a} - 8P_\mathrm{a}^3\beta] \\ &= b_{0(1,2)} + b_{1(1,2)}Q + b_{2(1,2)}Q^2 + b_{3(1,2)}Q^3 \end{aligned} \tag{B2}$$

where α, β, and γ are the Landau coefficients. Then the V_{kv1} and V_{kv2} are defined as:

$$V_{\mathrm{kv1,2}} = b_{3(1,2)}Q^3 + b_{2(1,2)}Q^2 + b_{1(1,2)}Q + b_{0(1,2)} \tag{B3}$$

The nonliner relationship between the voltage across sublattice and polarization charge of was achieved by a nonlinear voltage-controlled voltage source (VCVS) within the AFRAM model. Further, in order to obtain the change of charge Q intuitively in the circuit, the voltage-controlled current sources (gv1 and gv2) with transconductances equal to 1 are in parallel with R_3, C_3, and R_4, C_4 in the output part of the nonlinear voltage-controlled current sources. While $R_{\mathrm{j\ (j=3,4)}} = 1G\Omega$ and $C_{\mathrm{j\ (j=3,4)}} = 1F$, thus the relationship between polarization charge of sublattice $Q_{\mathrm{sublattice1,2}}$ and the output voltage of the nonlinear voltage-controlled current sources(V) is written as: $dQ_{\mathrm{sublattice1,2}}{=}C_{\mathrm{j(j=3,4)}}dV = 1 \cdot dV$. To simulate the linear features, each sublattice EC model consists of $R_1(R_2)$ and $C_1(C_2)$ in series at the input of a nonlinear voltage-controlled voltage source (kv1 and kv2).

$$R_{j(j=1,2)} = \rho\mathrm{T}/\mathrm{A} \quad C_{j(j=1,2)} = \epsilon_0\mathrm{A}/\mathrm{T}$$

where ρ, ϵ_0, T, and A are resistivity, vacuum permittivity, thickness and area of AFE capacitor, respectively. P_c is the switching polarization of the AFE S-shape P-V curve entering forward into the negative slope region. P_a represents the sublattice polarization. $P_\mathrm{a} = \mathrm{P_s}/2$ is extracted. $\mathrm{P_s}$ is the saturated polarization of AFE.

Appendix C Logic in memory within AFRAM

The AFE featuring the typical double hysteresis loops and multiple non-overlapping polarization current peaks is capable of storing two states (e.g. 1bit) per hysteresis loop. By encoding the four states as '00', '01', '10', and '11', the initial state of AFE capacitor can be denoted as $\mathrm{Z_1Z_2}$, and the final state as $\mathrm{F_1F_2}$. In other words, each bit within the AFRAM can process an operation. Thus, two logic functions $\mathrm{F_1}$ and $\mathrm{F_2}$ can be output in parallel in LIM cell with one AFRAM. The specific BD0 - BD3 and TD0 - TD3 waveforms applied to MUX in the LIM applications are shown in **Figure C1**.The input voltage pulse sequence of 3/1 V, 3/2 V, 0/0 V, and 3/0 V to the BD are denoted as $\mathrm{B_{s0}B_{s1}}$ = '00', '01', '10', and '11', respectively, and the input voltage pulse sequence of 0/0 V, 0/3 V, 3/1 V, and 3/0 V to the TD are denoted as $\mathrm{T_{s0}T_{s1}}$ = '00', '01', '10', and '11' respectively. Pulse width of BD0-BD3 and TD0-TD3 is 4 μ s, which is to ensure that the AFE can achieve full polarization and stability [2].

References

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2 Tian G, Chen J, Yan G, et al. Highly Reliable Logic-in-Memory by Bidirectional Built-in Electric-Field-Modulated Multistate IGZO/AFE Nonvolatile Memory. ACS Appl Electron Mater, 2023, 5: 1041-1049

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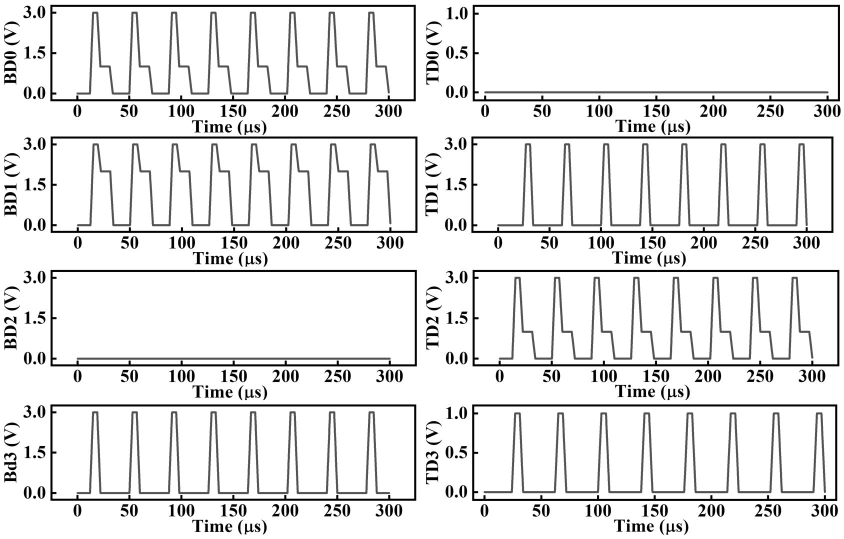

Figure C1 Waveforms of BD0-BD3 and TD0-TD3 applied to MUX in the LIM applications.