Protonic ECRAM Dynamics: Insights from 2D Simulations

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Introduction: Electrochemical RAM (ECRAM) offers excellent deterministic and symmetric programming, as well as fast and low operating energy compared to other memory technologies [1-3]. Its three-terminal configuration allows for separate read/write paths, enhancing conductance modulation control. Combined with its ability to store a continuum of conductance states via reversible ion migration, ECRAM is a strong candidate for in-memory computing. In this work, we have built a 2D simulation environment to model the dynamics of protonic ECRAM based on a Pd proton reservoir/gate, WO_3 channel and a PSG electrolyte [1, 4-5]. We investigate potentiation and depression behavior and extract insights to improve device linearity and stability.

Methodology: We employed the TCAD Sentaurus to simulate 2D ECRAM devices, solving Poisson and continuity equations for electrons, holes, and protons. The proton diffusion coefficient in the PSG and WO_3 channel was modeled using the Field-Induced Activation Energy Lowering model [6]. In the WO_3, protons act as mobile dopants but do not react with electrons or holes. The geometry of the device is shown in Fig. 1a.

Results and Discussion: Fig. 1b shows simulations of the source current, I_S, in response to a gate voltage pulse, V_G (Fig. 1c), as reported by Onen [5]. Three regimes are identified: 1. FET operation without protons, 2–3. protonated ECRAM response under low gate voltage (2.) and high voltage (3.) Only case 3. results in a nonvolatile source current. During the top of the gate pulse, a field-effect I_S is observed, which is larger in regimes 2–3 due to a negative shift in threshold voltage caused by the presence of protons in the WO_3 and PSG layers. Regime 3 shows an increase in I_S during the pulse revealing proton intercalation in the channel and yielding a nonvolatile current afterward. Figs. 1d-e separate displacement and channel current contributions to the total current (Fig. 1f) for different V_G matching the experimental results of [5]. The electron channel current (Fig. 1e) clearly differentiates between regimes 2 and 3 with a threshold voltage of ~3.5 V for sufficient ion migration through the PSG and intercalation into WO_3 to take place.

We have also studied ECRAM response to trains of potentiation and depression pulses (Fig. 2). Under positive pulses, protons enter WO_3 via an electron accumulation layer in the channel (Fig. 2e), while under negative pulses, protons drift back toward the gate through a depletion region (Fig. 2g). The potentiation response is linear due to the accumulation layer's weak dependence on proton density and the resulting constant electric field across the PSG. In contrast, during depression, the depletion region widens as the proton concentration in the channel drops. This progressively reduces the electric field through the PSG and the efficiency of proton extraction declines. Our work suggests that to improve linearity and symmetry, a high initial proton concentration (Fig. 2b) and a depression voltage that is sufficiently lower than the potentiation voltage must be used (Fig. 2c).

References

[1] Onen, M. et al. Nano Letters, 2021. 21(14): p. 6111-6116. **[2]** J. Tang et al. 2018, IEDM, San Francisco, CA, USA, pp. 13.1.1-13.1.4. **[3]** S. Kim et al. 2019 IEDM, San Francisco, CA, USA, pp. 35.7.1-35.7.4. **[4]** Onen, M. et al. Science, 2022, 377, pp. 539-543. **[5]** M. Onen, et al. 2022 IEDM, San Francisco, CA, USA, pp. 2.6.1-2.6.4. **[6]** Dignam, M. J., & Gibbs, D. B. J. Phys. Chem. Solids, 1969, 30, 2, pp. 375-393.

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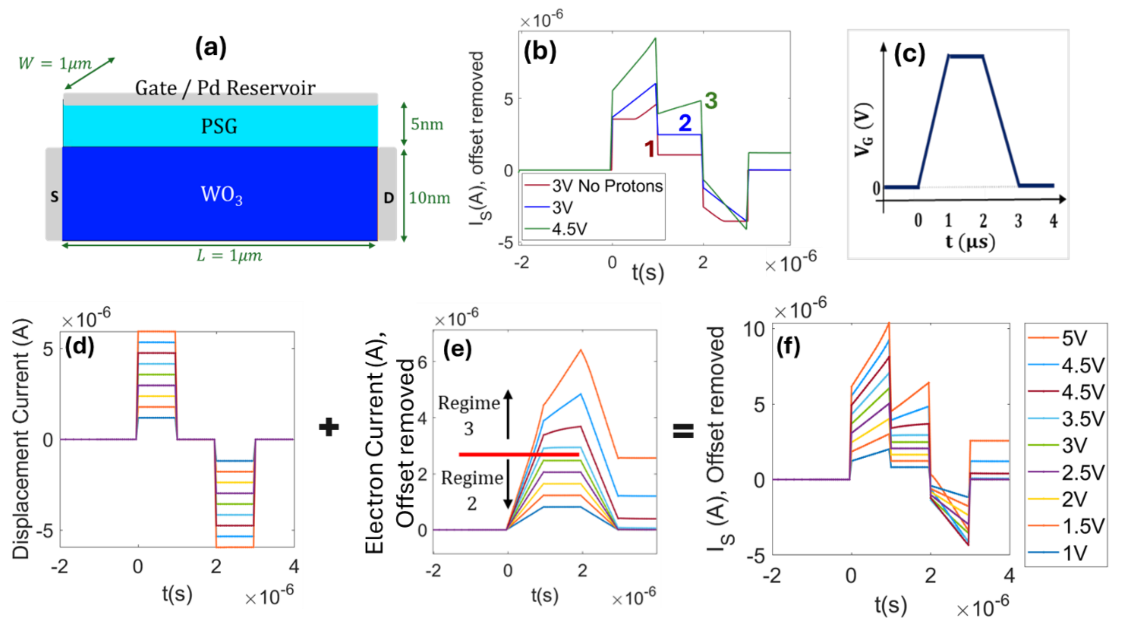

Fig. 1. (a) Simulated Pd/PSG/WO_3 ECRAM structure. (b) Source current response under $V_{DS} = 0.1\ V$ to a (c) trapezoidal gate voltage pulse, illustrating three regimes: a device without protons (simple FET behavior) (1), ECRAM without nonvolatile behavior (2), and ECRAM with nonvolatile current (3). (d) Displacement current and (e) electron channel current components are separated from (f) the total source terminal current in regimes 2 and 3 for different gate voltages.

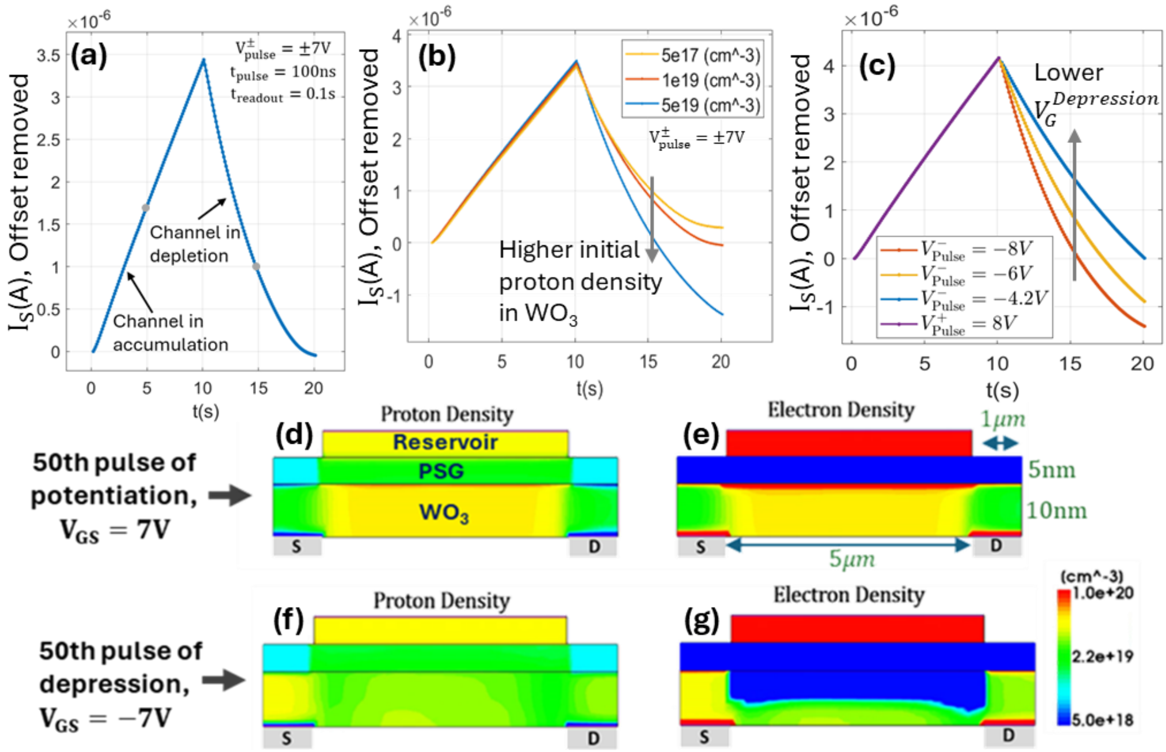

Fig. 2. Conductance modulation in response to 100 potentiation and 100 depression pulses for: (a) an initial proton density of 10^{19} cm^{-3} in WO_3, showing very linear potentiation but nonlinear depression behavior; (b) various initial proton densities in WO_3, highlighting its strong impact on the depression response; and (c) an initial proton density of 5×10^{19} cm^{-3}, with a high $V_G^{Potentiation}$ and three different $V_G^{Depression}$ introduced to improve linearity. (d) Proton and (e) electron density distributions during the 50th positive (potentiation) gate pulse showing an accumulation layer in the WO_3 channel. (f) Proton and (g) electron density distributions during the 50th negative (depression) gate pulse showing a depletion layer in the WO_3 channel.