MoS$_2$-based ferroelectric-like memristive devices

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Introduction & Methods

Non-Volatile Memory (NVM) devices are promising candidates for highly efficient Artificial Neural Networks (ANNs) [1]. However, the manufacture of NVMs is still to be developed. Several experimental examples have been successfully reported [2,3], but most of them rely on filamentary formation.

In this framework, ferroelectric-like mersistive devices appear as an adecuate alternative, specially when Transition Metal Dichalcogenides (TMDs) are employed in such devices [4]. In this work, we simulate and study the performance of MoS$_2$-based ferroelectric-like memristive devices.

Numerical simulation

Device simulations comprise the self-consistent solution in two dimensions of the Poisson equation along with the pseudo-Fermi energy level-based continuity equation for electrons and holes, and the ion drift-diffusion equation:

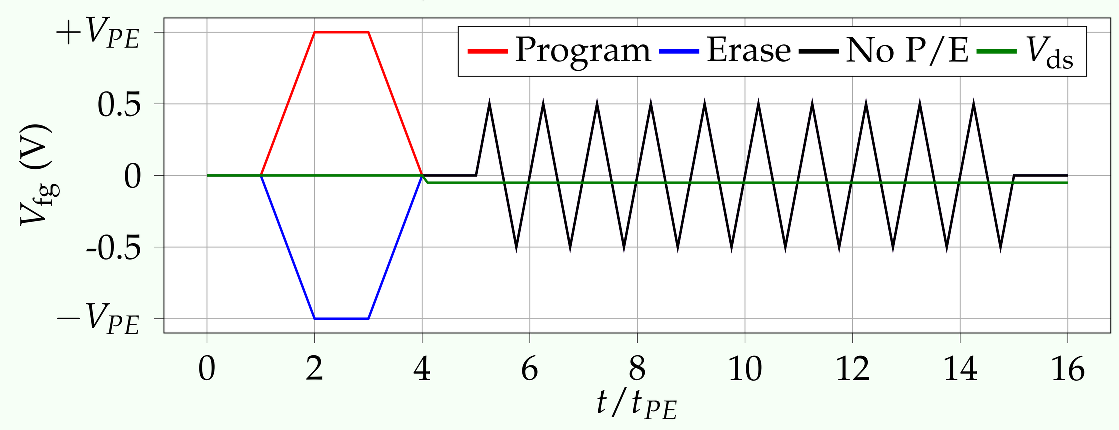
$$\nabla^2 V = -\frac{\rho}{\varepsilon}$$

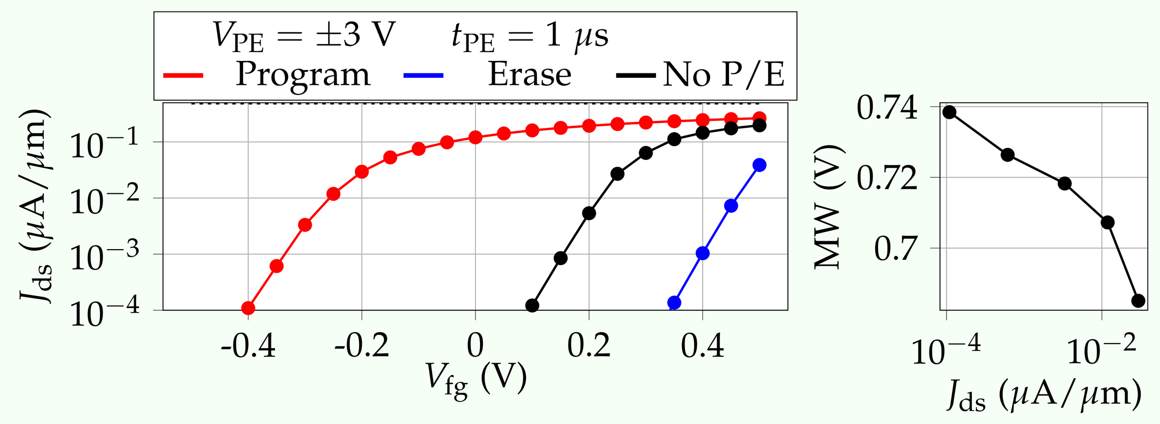
$$\begin{cases} \vec{\nabla}\cdot\vec{J}_n = \vec{\nabla}\cdot\left[q\mu_n n\vec{\nabla}E_{\mathrm{F,n}}\right] = +q\frac{\partial n}{\partial t} \\ \vec{\nabla}\cdot\vec{J}_p = \vec{\nabla}\cdot\left[q\mu_p p\vec{\nabla}E_{\mathrm{F,p}}\right] = -q\frac{\partial p}{\partial t} \end{cases}$$

$$\vec{\nabla}\cdot\vec{J}_i = \vec{\nabla}\cdot\left[-z_i q D_i\left(\vec{\nabla}c_i + s_i c_i\vec{\nabla}V\right)\right] = -z_i q\frac{\partial c_i}{\partial t}$$

- **Program/Erase**: the P/E signal is a positive/negative square pulse applied at the gate contact at a constant $V_{ds} = 0$ mV. Mobile oxygen ions ($z = -2$) and vacancies ($z = +2$) drift across the top-gate oxide in opposite directions, inducing a change in the threshold voltage and the channel conductivity. After that, a $V_{fg} = 0.5$ V triangular Read signal is applied at a constant $V_{ds} = -50$ mV.

- **Memory Window**: the device memory window (MW) is defined as the difference between the V_{fg} values needed to obtain a current density $J_{\mathrm{ds}} = -0.01$ μA/μm after applying P/E pulses.

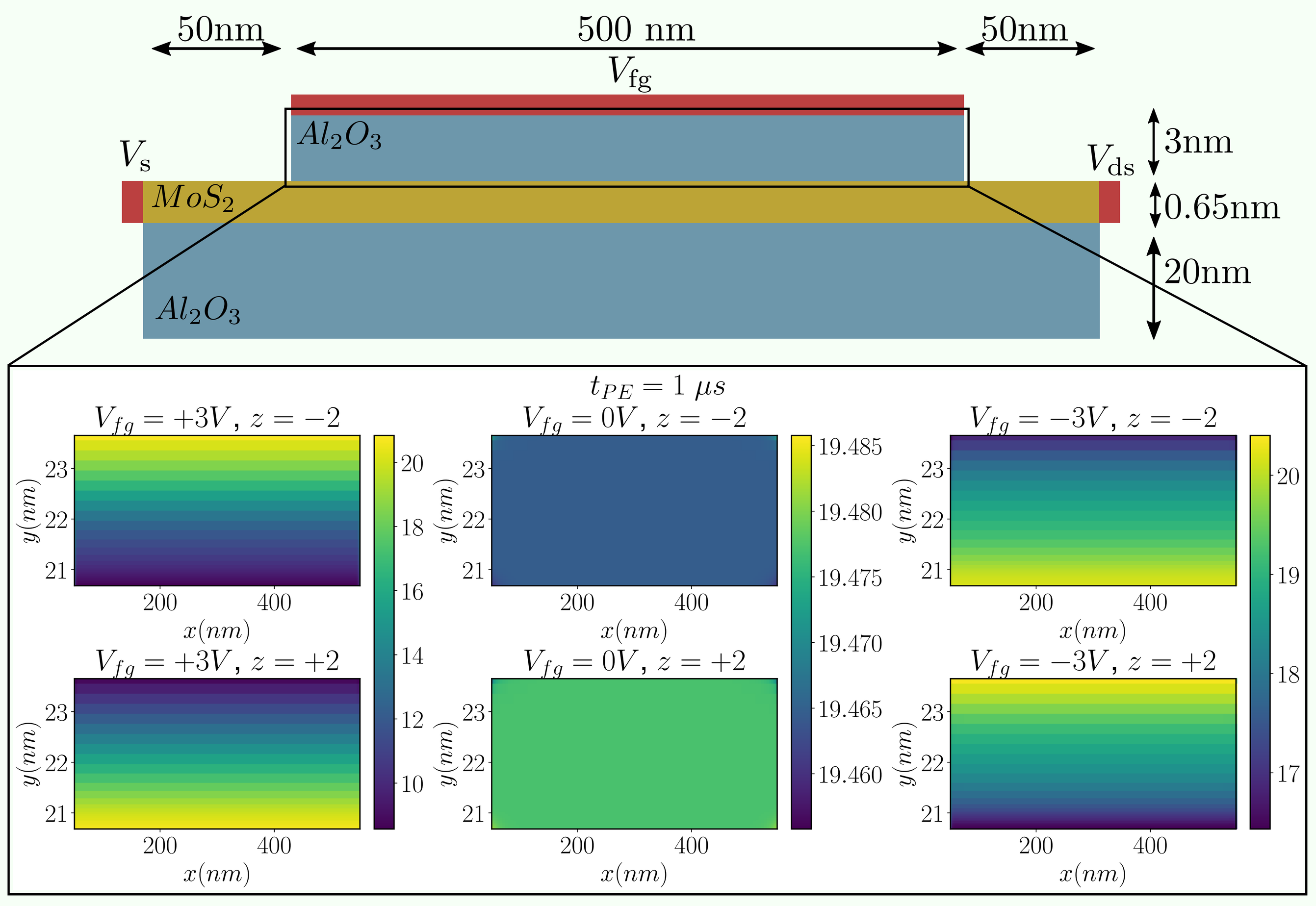




Results

The simulated device consists of a monolayer MoS$_2$-based MOSFET with a 500nm-long channel. The gate insulator is a 3nm-thick Al$_2$O$_3$ layer. The electron and hole mobility is set to $\mu_{\mathrm{n,p}} = 50\mathrm{cm}^2/(\mathrm{Vs})$.

- Mobile oxygen ions and vacancies are set in the gate-oxide with a mobility of $\mu_i = 2\cdot10^{-8}$ cm^2/(Vs) and a uniform initial concentration of $c_0 = 3\cdot10^{19}$ cm^{-3}.
- The amplitude, V_{PE}, and duration, t_{PE}, of the P/E signal determines the polarization of ions.



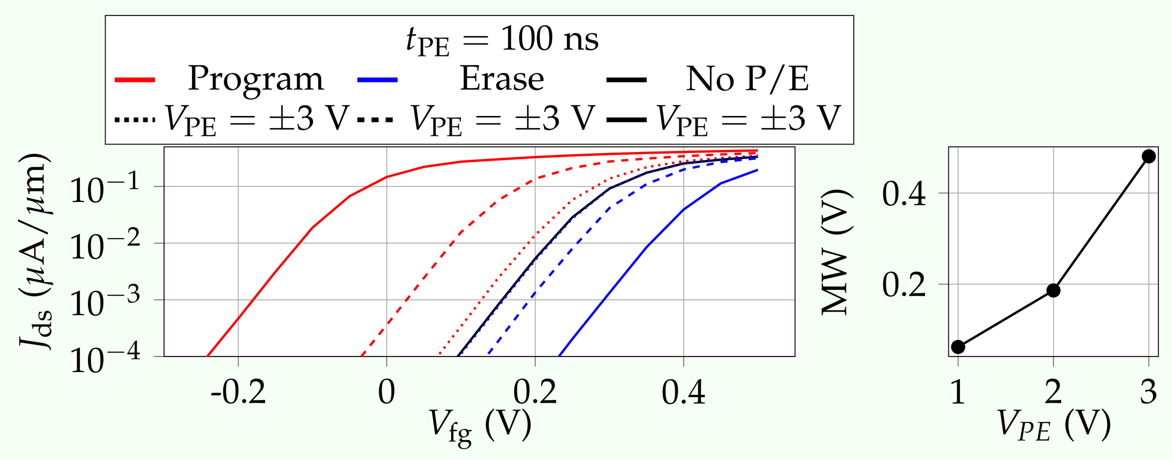
The device MW is analysed for P/E signals with different amplitude, $V_{\mathrm{P/E}} = \pm1\mathrm{V}, \pm2\mathrm{V}, \pm3\mathrm{V}$, and duration, $t_{\mathrm{PE}} = 100\mathrm{ns}, 1\mu s, 10\mu s$.

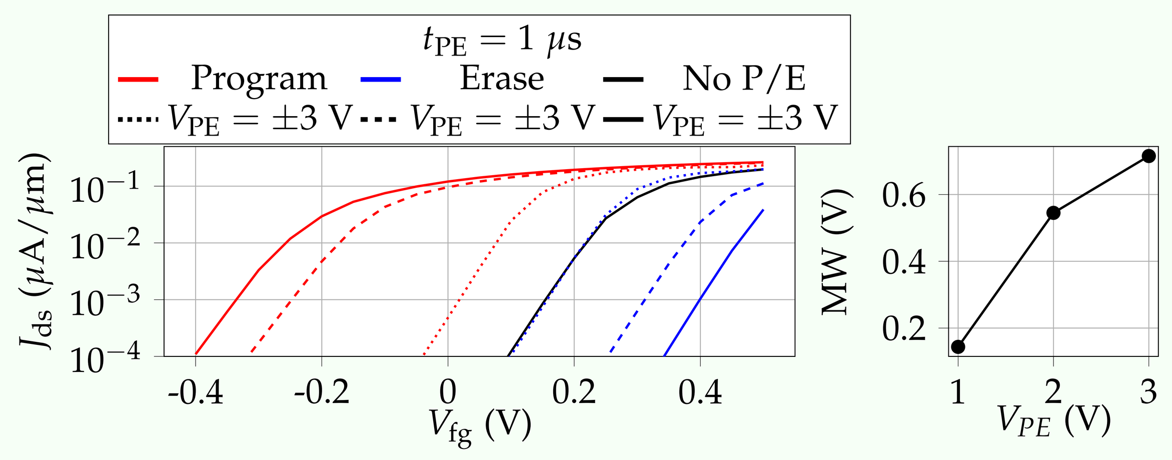
A higher V_{PE} produces a larger modulation of the channel conductivity.

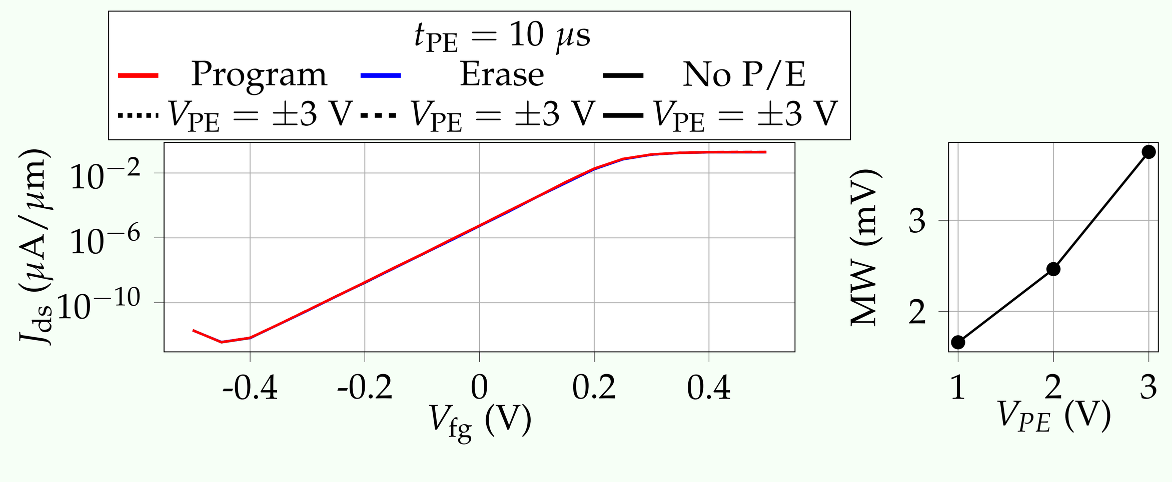
- For a given t_{PE}, the higher the V_{PE}, the greater the shift of the threshold voltage.
- In some cases, $V_{\mathrm{PE}} = -1$ V seems to barely affect the output current.

The P/E duration, t_{PE}, is tightly related to the width of the MW.

- For a short P/E pulse, $t_{\mathrm{PE}} = 100$ ns, ions have not enough time to drift. Thus, the resulting MWs are narrow.
- For a long P/E pulse, $t_{\mathrm{PE}} = 1$ μs, ions distribute across the gate-oxide layer, producing wide MWs.
- For a large enough frequency, $t_{\mathrm{PE}} = 10$ μs, ions polarize the gate-oxide, but they also follow the Read signal without delay, reversing the P/E situation and yielding negligeable MWs.







Conclusions

- We introduced a self-consitent numerical tool for the simulation of 2DM-based ferroelectric-like meristive devices.
- The application of gate voltage pulses polarize the mobile ions inside the gate-oxide layer, thus shifting the transfer characteristic.
- A large V_{PE} is required to obtain high MW values up to 0.715 V.
- Both a short and a long t_{PE} can reduce the width of the MW, whether if ions do not polarize completely, or if the Read signal changes their distribution.

References

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