# Read Current in Ferroelectric Tunnel Junctions: Transient versus DC Contributions and Trap Related Effects

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**Abstract:** Ferroelectric Tunnel Junctions (FTJs) performance as memristive devices is typically represented by the Tunneling Electro-Resistance Ratio (TER), defined as the ratio between the DC current measured in the low resistance state and the high-resistance state of the device. However, the transient contributions to the FTJ read current are often overlooked in the literature, possibly causing misleading interpretations of the experimental TER. Here we propose a new, comprehensive characterization of the read currents of different FTJ stacks, also investigating on their transient components. We report a solid interpretation of the experiments based on the response of traps in the ferroelectric, also supported by physics-based simulations.

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# Read Current in Ferroelectric Tunnel Junctions: Transient versus DC Contributions and Trap Related Effects

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**Introduction.** Ferroelectric Tunnel Junctions (FTJs) are memristors with high energy–efficiency targeting applications from memories to neuromorphic computing [1]. FTJ operation relies on the different tunneling currents observed in high-resistive (OFF) and low-resistive (ON) states induced by the ferroelectric (FE) polarization $P$ and FTJs are typically evaluated through the Tunnel Electro-resistance Ratio (TER), defined as the ON/OFF current ratio [2]. FTJ engineering aims to increase TER, enabling the multi-level operation [3]. For instance, Metal-Ferroelectric-Dielectric-Metal (MFDM, Fig.1) stacks exploit tunnel barrier engineering [4, 5], boosting tunneling w.r.t. Metal-Ferroelectric-Metal (MFM) [6, 7]. However, transients in FTJ currents and trap-related effects are often overlooked in the literature, even in the models proposed to interpret the TER results [8, 9]. We thoroughly characterized MFM and MFDM stacks based on $HfZrO_4$ (HZO) to evaluate the transient current contributions, demonstrating the impact of FE traps on the extracted TER.

**Fabricated devices.** MFM and MFDM stacks are fabricated on top of a W/TiAlN bottom electrode (BE, Fig.1) and both feature a 10.5 nm HZO. In MFDM, an $Al_2O_3$ dielectric (DE, 1 nm nominal thickness) is deposited before HZO. PVD is used for the 22 nm TiAlN top contacts that defines the device circular areas with diameter $\Phi$ varying between 110 and 450 $\mu$m [10, 11]. The whole characterization of the FE polarization switching dynamics is reported in [10, 11].

**Experimental procedure.** Fig.2 shows the absolute value of current $I$ of an MFM sample obtained by applying voltage double sweeps from negative to positive $V$ and backwards. Clockwise loops for $V>0$ are typical of MFM devices [12]. When approaching the coercive voltages, the FE polarization switches, thus inducing transient current peaks, modulated by the delay time (DT) inserted before each measurement point of the $V$ sweep. Note the current inversion during back-sweep before crossing $V=0$, already seen in literature [9, 12], indicating large and long transients. We investigated this behavior through the *Ginestra*$^{TM}$ simulator, after calibration against experimental $P$-$V$ loops (Fig.3a, Tab.1). Traps in the HZO layer are simulated to reproduce the FTJ read currents [13]. The simulated $I$ tracks well both the switching peak during forward sweep and the sign change of $I$ during backward sweep (Fig.3b). Upon increasing $V$, HZO traps are filled, while reducing $V$ electrons de-trap, thus inducing opposite transient currents (Fig.3b, inset). So we investigate how to eliminate or at least reduce these transients to correctly extract TER. Fig.4 reports $I$ recorded during double sweeps by using different voltage steps ($\Delta V$) between measurement points. A smaller $\Delta V$ reduces the negative $I$ during back sweeping (compare red and black). DT is instead much less effective, indicating very long transients that exclude significant contribution from displacement current and reinforce the interpretation related to traps. Then, we measured the samples by using a $\Delta V$ uniformly distributed over a logarithmic scale to leverage a small $\Delta V$ when $V$ is low, hence when DC current is very low and so transients are more impacting. Logarithmic $\Delta V$ steps largely reduce the negative $I$, but also reduce $I$ during the forward sweep at low $V$ (Fig.4). Hence logarithmic $\Delta V$ steps are used in the following to measure read currents so as to effectively reduce transients while maintaining the measurement time under control.

**TER in MFM stack.** Since the negative currents do not disappear completely during the backward sweep, to measure MFM ON/OFF currents, we used only forward sweeps. Fig.5 reports ON/OFF currents for both $V$ polarities correctly scaling with area and showing apparent TER, slightly larger ($\approx 10$) for $V>0$ than for $V<0$ ($\approx 3$), probably due to some stack asymmetry (e.g. HZO/TiN interfaces, trap profile). To verify if this TER is due to DC tunneling or instead largely influenced by transients, we applied a constant read voltage $V = \pm 0.4$ V to monitor $I$ and TER during time. Fig.6 shows that 400 s-long transients still not saturate to a DC level, so *the visible ON/OFF ratio is due to transient currents only and thus it cannot be considered a TER by definition.* Furthermore, while for $V>0$ (Fig.6a), ON current is always larger than OFF current (ON/OFF ratio comparable to that in Fig.5a), for $V<0$ (Fig.6b), there is no clear separation between ON/OFF transients, confirming the asymmetric behavior of the stack. Read disturb further reduce the ON/OFF ratio.

**TER in MFDM stack.** The boost of MFDM tunneling due to the DE presence is expected for $V>0$ (Fig.1c). Thus, ON/OFF currents are measured by $V>0$ double sweeps (Fig.7), observing a large $I$ increase w.r.t. MFM. No negative currents are visible sweeping back, possibly because *the DE layer prevents the release of trapped electrons* (Fig.8a,b), thus limiting the transients. So TER can be recorded directly by a single $V$ double sweep, that shows counterclockwise loops typical for MFDM [12] (Fig.7). To the sole purpose of confirming our interpretation of the DE layer blocking detrapping for $V>0$, we measured the current also for $V<0$ and Fig.9 shows again that $I$ changes sign during back sweep for both the FE polarization states. In this case, electron injection occurs from the top electrode and the electrons can detrap when back-sweeping, as in the case of MFM (Fig.8c,d), causing the current reversal. Note also the expected clockwise loops for this $V$ polarity [12] (Fig.9). Finally, to investigate the nature of the visible TER in Fig.7, current is measured over time (Fig.10). Despite the presence of some transients, now $I$ clearly saturate to a DC value, allowing the extraction of TER ($\approx$15). Read disturb only affects the transient component of $I$ (that fills traps) and not the DC tunneling.

**Discussion and conclusions.** We devised a characterization procedure to monitor TER in FTJs limiting transient currents and controlling the measurement time. For the first time to our knowledge, we demonstrated with experiments and simulations that ON/OFF current ratio in MFM stacks is dominated by transients and is not representative of DC characteristics. Of course, these transient characteristics hinder to reliably read MFM FTJs and make their readout strongly dependent on the reading voltage waveform. In MFDM stacks, instead, the DE layer not only boost $I$, but it is also beneficial effectively blocking the electron detrapping, thus reducing transient currents and easing the readout and the extraction of TER of the FTJ. Optimization of the DE layer may further reduce the transients in FTJ reading.

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| TE WF [eV] | BE WF [eV] | $\chi_{FE}$ [eV] | $\varepsilon_{FE}$ | $m_{FE}$ [$m_0$] | $P_r$ [$\mu$C/cm$^2$] |
|---|---|---|---|---|---|
| 4.77 | 4.57 | 2.6 | 25 | 0.37 | 21 |
| $N_T$ [cm$^{-3}$] | $\sigma_T$ [cm$^2$] | $\hbar\omega$ [meV] | Ionization energy [eV] | | |
| | | | donors | acceptors | |
| $4.5 \cdot 10^{19}$ | $10^{-14}$ | 60 | $3.5 \pm 0.05$ | $1.55 \pm 0.05$ | |

Table 1: Simulator parameters calibrated on the P-V experiment of Fig. 3(a) and then used to simulate the read current in Fig. 3(b). First row: material parameters, i.e. metal workfunction (WF), FE affinity $\chi_{FE}$, FE permettivity $\varepsilon_{FE}$, tunneling mass $m_{FE}$, remnant polarization $P_r$. Preisach model with 1.4 MV/cm coercive field is used for ferroelectricity. Second row: trap parameters including HZO trap density $N_T$, cross section $\sigma_T$, phonon energy $\hbar\omega$. Ionization energy is the trap energy depth w.r.t. HZO conduction band. Relaxation energy is 1.5±0.15 eV for both donors and acceptors.

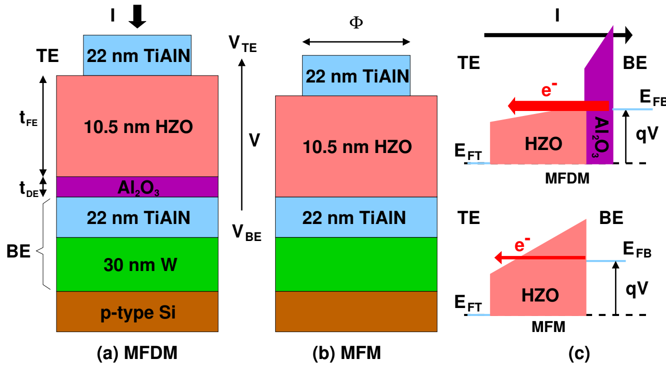


Figure 1: MFDM (a) and MFM (b) stacks are fabricated with the same FE thickness. In MFDM, the $Al_2O_3$ thickness is 1 nm. Bottom electrode (BE) is a sandwich of TiAlN and W to lower resistance. Top electrode (TE) defines the device diameter Φ. $V = V_{TE} - V_{BE}$ is applied to write, erase and read the FTJ. (c) Energy bands in read mode show that band bending increases tunneling in MFDM. $E_{FT}$ and $E_{FB}$ are the Fermi levels in TE and BE, respectively.

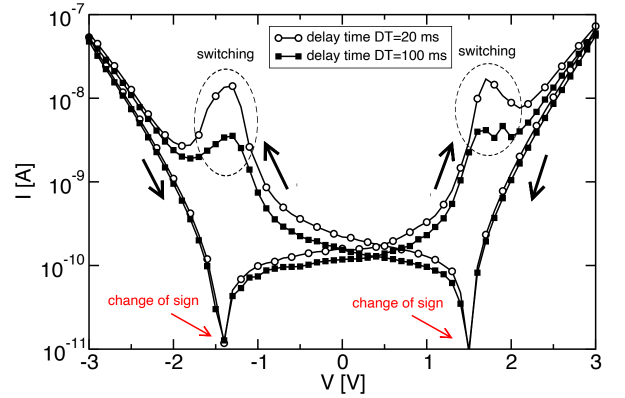


Figure 2: Absolute value of current measured during voltage double sweeps on an MFM sample (Φ=450 $\mu$m) for two delay times used before each measurement point. Increasing the voltage magnitude, the ferroelectric switches, inducing current peaks at the coercive voltages. A sign change of $I$ is highlighted by the red arrows.

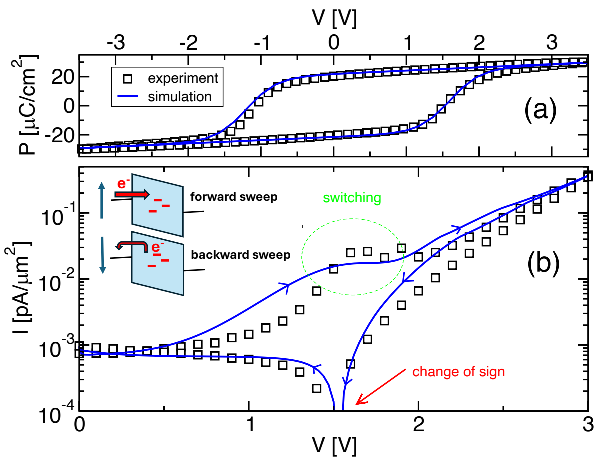


Figure 3: (a) Measured $P$-$V$ loop of an MFM device (squares) is well reproduced by the simulator (line) validating its calibration (see Tab. 1). (b) Experimental and simulated $I$ during $V$ double sweep. During backward sweep, $I$ becomes negative because of the release of electrons trapped in FE traps during the forward sweep (inset).

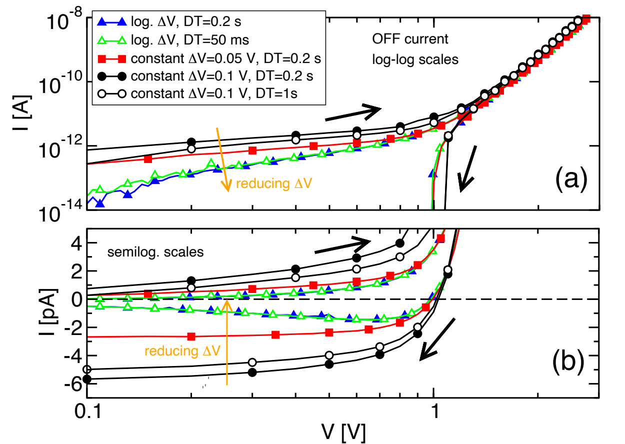


Figure 4: MFM currents for $V$ double sweeps in logarithmic (a) and linear (b) scales (Φ=450 $\mu$m). $V$ in logarithmic scale is reported. Sweeps with constant voltage steps ($\Delta V$) show that a smaller $\Delta V$ reduces the negative current during back-sweeping. So $\Delta V$ distributed as logarithmic steps is then used to measure with small $\Delta V$ at low applied $V$, obtaining a further reduction of negative current (b). DT is not effective in reducing transients. Integration time is long.

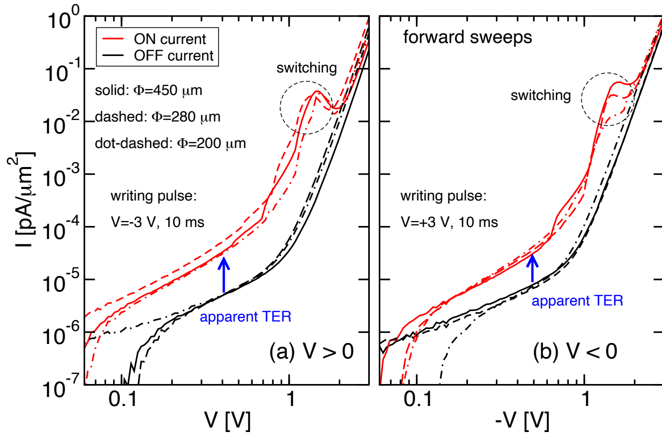


Figure 5: ON/OFF currents measured during forward sweeps for (a) $V$>0 and (b) $V$<0. After the writing pulse, the ON current is measured during a first $V$ sweep, that also causes FE switching. Then, OFF current is recorded during a subsequent forward sweep. Current scales with area. At reading voltages lower than coercive voltages, an apparent TER is visible for both polarities.

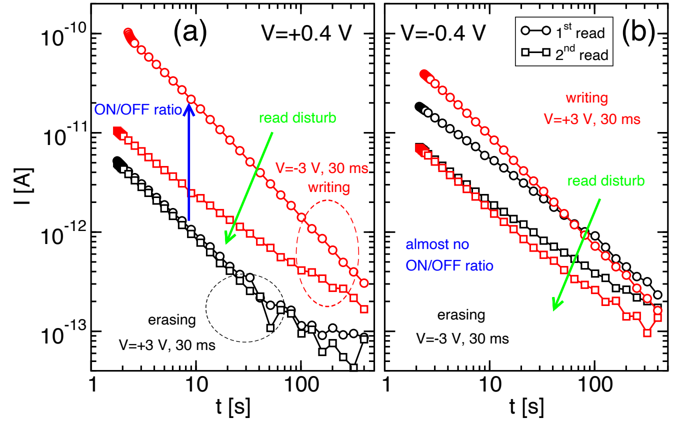


Figure 6: MFM currents vs. time in the two $P$ states, showing very long transients. (a) For $V$>0, ON/OFF ratio is similar to that in Fig.5(a). (b) For $V$<0, a small ON/OFF ratio is barely visible during the first seconds of the experiments. Read disturb reduces currents and ON/OFF ratio for both polarities. $\Phi = 450~\mu$m.

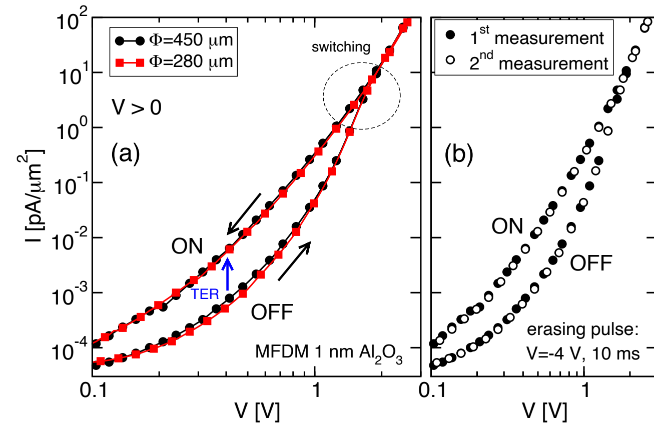


Figure 7: MFDM FTJs: after the erasing pulse, ON/OFF currents are measured during a $V$ double sweep. $V$>0 is used to exploit the DC tunneling boost guaranteed by the band bending in Fig.1c. $I$ correctly scales with area (a) and shows good repeatability (b). During forward sweep, FE switches, so the ON current is recorded directly during backward sweep. At $V$ lower than coercive voltages, TER is visible.

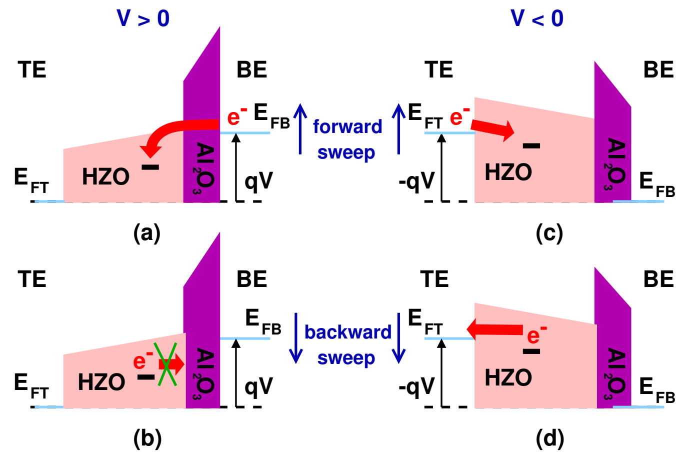


Figure 8: MFDM band bending during the application of positive (a, b) and negative (c, d) voltage $V$. During forward sweep (a, c), electrons are trapped inside the HZO. Sweeping back, for $V$>0, electrons are blocked by the $Al_2O_3$ layer (b), while for $V$<0, electrons can be emitted causing current reversal (d). $E_{FT}$ and $E_{FB}$ are the Fermi levels in the top electrode (TE) and bottom electrode (BE), respectively.

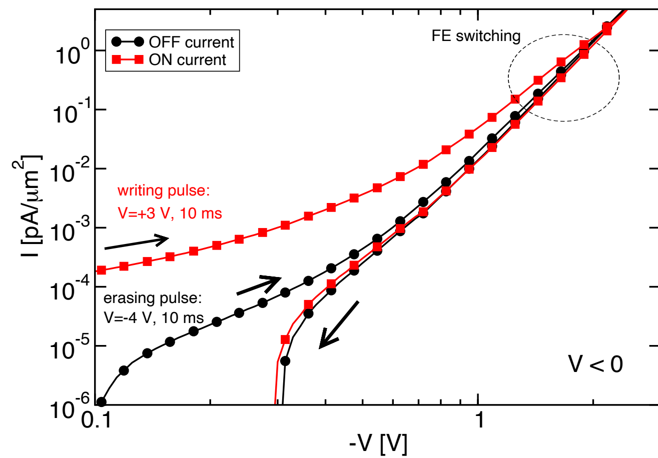


Figure 9: MFDM FTJs: ON/OFF currents recorded for $V < 0$. After the writing/erasing pulse, $I$ is measured during a $V$ double sweep. Starting from opposite $P$ states, an apparent TER is visible during forward sweeping. During back sweeping, current reversal is evident, as observed in the case of MFM samples in Fig.2.

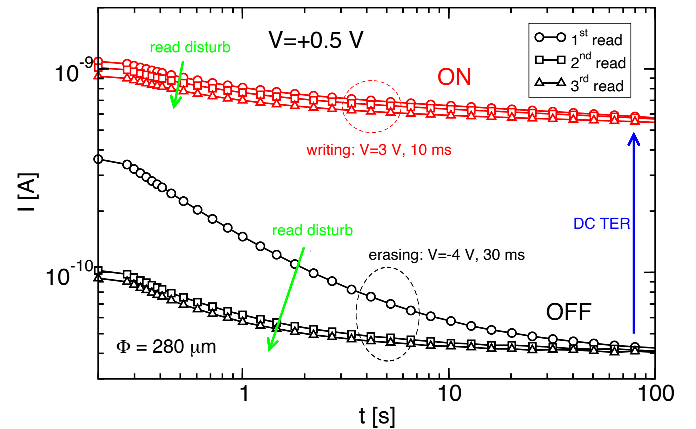


Figure 10: MFDM currents vs. time in the two $P$ states. After the initial transients, saturation of $I$ to the DC tunneling component is evident, defining the TER of the device. Read disturb clearly impacts only the transient components (mainly on the OFF state), not affecting TER of the DC currents.