

Disentangling Hysteresis in Emerging Transistors: Beyond Threshold Shifts to Area-Based Decomposition

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Abstract—Emerging transistors often exhibit pronounced hysteresis in the transfer characteristics, compromising reliable circuit operation. Conventionally, the hysteresis is evaluated at the threshold voltage, which is not only an arbitrarily defined criterion, but can also become ambiguous when multiple mechanisms coexist. Here, we propose a systematic hysteresis-analysis framework based on signed area contributions, enabling decomposition of competing mechanisms and improved hysteresis optimization. Calibrated simulations of a 2D MoS₂/SrTiO₃ transistor show that individual contributions with distinct microscopic origins can be recovered from the observed mixed hysteresis response.

Index Terms—hysteresis, transfer characteristics, reliability, 2D materials

I. INTRODUCTION

The scaling limitations of silicon technology motivate the search for alternative materials and device concepts [1], such as 2D materials which offer promising electrostatic and scaling properties [2,3]. However, such emerging transistors often exhibit pronounced threshold voltage (V_{th}) shifts and hysteresis in transfer characteristics ($I_D V_G$) [4]. Consequently, hysteresis has become an important benchmark for assessing new technologies [5]. The common approaches evaluate hysteresis either at a current criterion (I_{cr}) or around the threshold voltage, extracted by various procedures such as the g_m/I_D method [6]. However, the extracted hysteresis can strongly depend on the extraction criterion [7].

This issue becomes particularly critical when multiple physical mechanisms contribute simultaneously. In devices consisting of novel 2D materials, both negative hysteresis and positive hysteresis may occur [5,8]. Positive hysteresis, can arise from charge trapping from the channel, while negative hysteresis may originate from charge trapping at the gate [5,9], migration of mobile ions [10], and ferroelectricity [11]. The importance of this ambiguity is illustrated in Fig. 1, which shows an experimental hysteresis measurement ($I_D V_G$ during a gate bias ramp-up followed by the reverse ramp-down) of a 2D transistor consisting of a MoS₂ channel and a SrTiO₃ gate insulator. As can be seen, a crossing between the up-sweep and down-sweep divides the transfer curve into regions of positive hysteresis above the crossing

point and negative hysteresis below it. Consequently, the extracted hysteresis depends on the chosen readout criterion, and the extraction method can affect not only the apparent magnitude but also the sign of the hysteresis. This ambiguity may lead to different interpretations of the same measurement. Here, we first present a method to extract the maximum hysteresis and then introduce a more comprehensive metric based on the area enclosed by the hysteretic $I_D V_G$ curves.

II. METHODOLOGY

The investigated MoS₂/SrTiO₃ device was modeled using our 1D TCAD tool Comphy [12] and calibrated against the measured $I_D V_G$ characteristics. Based on this calibrated setup, three cases were simulated to isolate and combine the relevant hysteretic mechanisms. The first case represents a pure positive hysteresis contribution caused by charge trapping in the SrTiO₃ oxide, modeled within the non-radiative multi-phonon (NMP) framework [13]. The second case represents a pure negative hysteresis contribution caused by the migration of mobile ions in the gate dielectric, described by an ion drift-diffusion model [10]. Finally, the realistic mixed case including both mechanisms was considered. Hysteresis was simulated over a wide switching frequency range from 10 nHz to 0.1 GHz, and the resulting transfer characteristics were analyzed.

III. EVALUATING MAXIMUM SHIFTS

As can be seen in Fig. 1, one can identify an I_{cr} at which the maximum positive (ΔV_{max}^+) or negative (ΔV_{max}^-) hysteresis occurs. Searching for these current criteria and evaluating the corresponding hysteresis over the considered frequency range yields the results shown in Fig. 2, together with hysteresis extracted using conventional procedures. While both approaches produce similar results when only a single mechanism is active, the response differs markedly in the real mixed case. While evaluating hysteresis at a fixed I_{cr} reveals a complicated trend in the mixed case, extracting ΔV_{max}^+ and ΔV_{max}^- yields curves that preserve the trends of the individual mechanisms, suggesting that the maximum-shift approach is more robust for identifying the

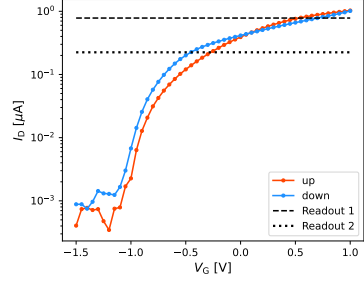


Figure 1: Exemplary hysteresis measurement on a MoS₂/SrTiO₃ FET illustrating the impact of competing mechanisms and read-out selection. Measured $I_D V_G$ during up- and down-sweeps (from $V_G^{\min}$ to $V_G^{\max}$ and from $V_G^{\max}$ to $V_G^{\min}$ with $V_G^{\min} = -1.5\text{V}$ and $V_G^{\max} = 1\text{V}$), with two read-out current levels yielding hysteresis values of opposite sign.

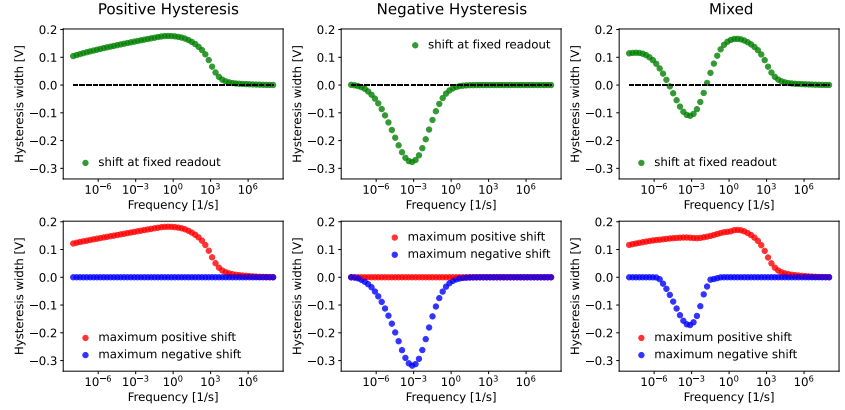


Figure 2: Comparison of hysteresis extraction methods over the considered frequency range. Columns 1-3 correspond to a purely positive, a purely negative, and the mixed hysteresis case with both positive and negative contributions. The first row shows hysteresis extracted at a fixed read-out current, the second row shows the maximum positive and negative shifts, $\Delta V_{\max}^+$ and $\Delta V_{\max}^-$, in red and blue.

dominant mechanism at a given frequency. This analysis correctly captures the locations of both peaks, although the extracted magnitudes still vary. Moreover, the maximum shifts generally occur at different I_{cr} values and therefore cannot be subtracted directly, which motivates a different approach based on a quantity that can be combined linearly, thereby enabling separation of competing mechanisms.

At the same time, this analysis reveals an important limitation. Although the extracted $\Delta V_{\max}^+$ and $\Delta V_{\max}^-$ correctly capture the peak locations associated with the two competing mechanisms, their magnitudes do not directly reflect the underlying individual contributions. This is because the maximum positive and negative shifts necessarily occur at different I_{cr} values and therefore probe different regions of the transfer curve. Consequently, they do not define a common quantity that can be directly added, subtracted, or otherwise combined in a physically meaningful way. This limitation motivates the introduction of a better hysteresis metric. Instead of relying on selected read-out points, we seek a quantity that characterizes the hysteretic response of the entire loop and can be combined linearly. Such a metric would not only provide a more systematic description of hysteresis, but also enable separation of competing mechanisms in the mixed case.

IV. AREA-BASED HYSTERESIS DECOMPOSITION

As shown in Fig. 3, the enclosed area of a positive or negative hysteresis loop, given by $A^+ = \int \max(0, \Delta I_D) dV_G$ and $A^- = \int \min(0, \Delta I_D) dV_G$, defines a quantity with the unit of power, here referred to as hysteresis area. In contrast to $\Delta V_{\max}^+$ and $\Delta V_{\max}^-$, A^+ and A^- can be combined linearly. This is illustrated in Fig. 4, where the individual A^+ and A^- , corresponding to isolated positive and negative mechanisms, are compared with the mixed-case A^+ and

A^- , corresponding to the simultaneous presence of both mechanisms. Subtracting the mixed responses from the corresponding individual responses yields nearly symmetric results, suggesting an effective cancellation caused by partial compensation between the two mechanisms. To further validate this interpretation, and motivated by the fact that the hysteresis area has the unit of power, we plot the absolute values of these hysteresis areas in Fig. 5. As can be seen, the differences between the mixed and individual $|A^+|$ and $|A^-|$ are nearly identical. Minor deviations arise because the underlying physical effects do not act as a rigid voltage shift over the full transfer curve. Otherwise, one mechanism must dominate in each hysteresis measurement (each frequency), and no crossing point in $I_D V_G$ would occur. In such case, the cancellation would reduce to the linear term defined by:

$$C_{\text{lin}} = \min(|A_{\text{individual}}^+|, |A_{\text{individual}}^-|).$$

In the mixed case, the simultaneous nonzero $|A^+|$ and $|A^-|$ contributions introduce a residual term:

$$R = \min(|A_{\text{mixed}}^+|, |A_{\text{mixed}}^-|).$$

The actual cancellation is then obtained as $C = C_{\text{lin}} - R$. Adding C to the mixed-case $|A^+|$ and $|A^-|$ recovers the individual $|A^+|$ and $|A^-|$ in the absence of the competing mechanisms. The close agreement between the reconstructed and reference positive and negative hysteresis areas in Fig. 5 demonstrates that the underlying mechanisms can be reliably reconstructed. The remaining minor deviations arise from self-consistent changes in the potential and numerical errors.

As mentioned earlier, area-based hysteresis metrics encode information over the full electrostatic range of the transfer characteristic rather than at a single arbitrarily selected read-out point. As a result, when a TCAD model is

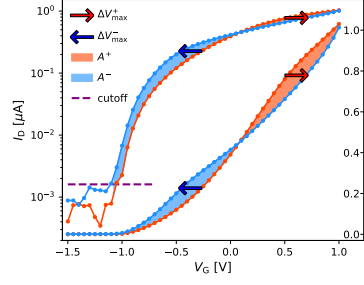


Figure 3: Illustration of the hysteresis metrics, based on the same measurement data on MoS₂/SrTiO₃ FETs as in Fig. 1. The maximum horizontal distance between the up- and down-sweeps, defines the maximum signed widths (arrows) while the enclosed loops areas (shaded regions) define the signed hysteresis area (left: logarithmic scale, right: linear scale).

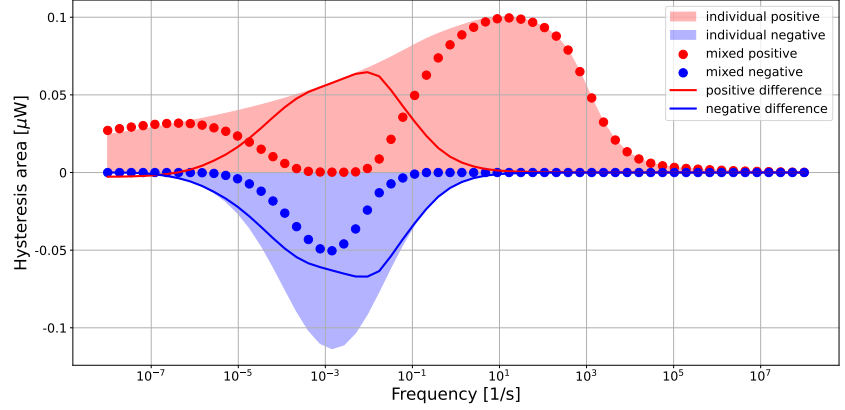


Figure 4: Calculated hysteresis area. The edges of shaded red and blue regions denote the individual A^+ and A^- if only one mechanism causing positive/negative hysteresis is active. Red and blue circles show the corresponding overall device response if both mechanisms are active simultaneously. Solid red (blue) lines indicate the difference when subtracting the mixed from the individual positive (negative) areas.

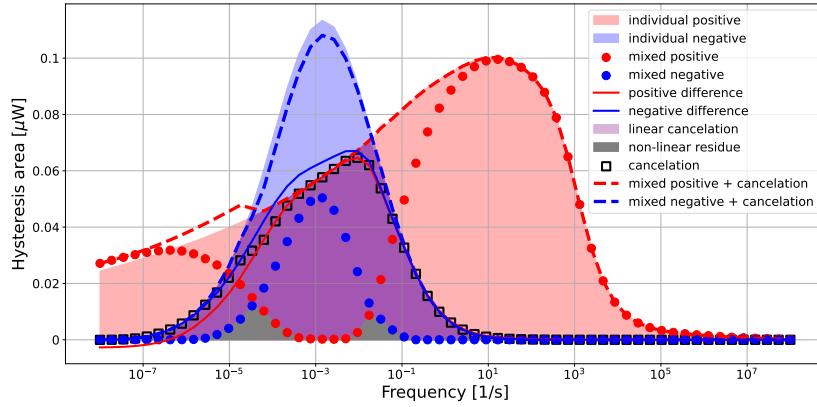


Figure 5: Decomposition of (absolute valued) hysteresis area. The edges of shaded red and blue regions denote the individual $|A^+|$ and $|A^-|$ while red and blue circles show only the corresponding mixed $|A^+|$ and $|A^-|$. Solid lines indicate the difference between the mixed and individual hysteresis areas. The edges of the purple and gray shaded regions represent the linear cancellation term C_{lin} and residual term R , respectively, yielding the actual cancellation $C = C_{lin} - R$ shown by the black squares. Adding C to data in the mixed-case $|A^+|$ and $|A^-|$ recovers the individual contributions of the mechanisms responsible for positive/negative hysteresis, indicated by the red and blue dashed lines.

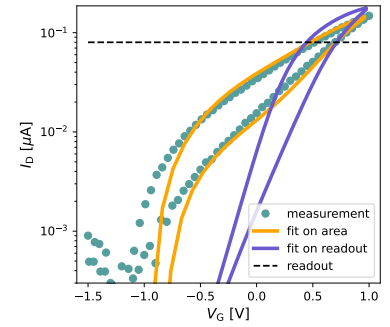


Figure 6: Comparison of $I_D V_G$ reconstruction after fitting hysteresis using TCAD simulations. While a fit using the fixed read-out approach (purple line) reproduces the similar shift only at one current level (dashed line), the area-based approach optimization result (orange line) matches the experimental data (green circles) more closely by incorporating information across all drain-current decades.

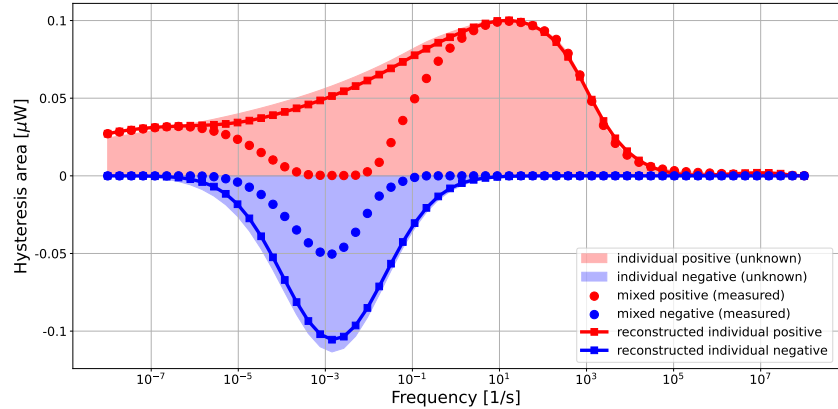
calibrated to experimental hysteresis data using such metrics, the extracted model parameters are constrained by the global shape of the hysteretic response and therefore provide a more physically representative description of the device. This, in turn, improves the reproduction of the individual $I_D V_G$ curves. This effect is illustrated in Fig. 6, which shows a representative $I_D V_G$ of the investigated MoS₂/SrTiO₃ device after fitting hysteresis across a large set of measurements using TCAD to extract defect and mobile-ion parameters. Compared with a calibration based on a fixed I_{cr} , the calibration based on the measured hysteresis area yields a substantially closer match to the measured $I_D V_G$. The reason is that the fixed- I_{cr} metric constrains the model

only at one arbitrary read-out point and therefore leaves significant freedom in the remaining parts of the curve. In contrast, the area-based metric constrains the overall loop shape and the distribution of the hysteretic response over the full gate-voltage range. Consequently, it leads not only to a more robust hysteresis metric, but also to a more realistic and predictive calibration of the underlying physical mechanisms.

V. RECONSTRUCTION OF INDIVIDUAL CONTRIBUTIONS

In experiments only the mixed response is directly accessible, which makes extraction of the cancellation term C a nontrivial inverse problem. In practice, this means that addi-

Figure 7: Reconstruction of individual hysteresis areas from the overall response. The edges of the shaded red and blue regions denote the individual contributions used for validation, but are inaccessible with measurements. Red and blue circles show the measured hysteresis areas if both positive and negative hysteresis mechanisms are present and overlap to a mixed response. The reconstructed individual hysteresis areas calculated from the mixed hysteresis areas are given by lines with square markers.



tional mathematical assumptions or dedicated experimental strategies are required to reliably separate the underlying contributions. The result of such a procedure is illustrated in Fig. 7, where only the mixed hysteresis areas are used as input. The individual positive and negative contributions are represented by flexible parametric trial functions and reconstructed through a stochastic search. For each trial pair, a common cancellation term is derived from the overlap between the reconstructed individual contributions and the observed mixed response, and the corresponding mixed curves are reproduced. The optimal reconstruction is then identified by minimizing the deviation between the reproduced and measured mixed hysteresis areas, while additionally enforcing smoothness and other physically motivated constraints to regularize the inverse problem and suppress non-unique solutions. In principle, this allows the individual contributions to be inferred solely from the mixed response. In practice, however, the procedure is sensitive to experimental noise, since fluctuations can destroy the smoothness of the score function and thereby hinder robust identification of the optimum. For this reason, reliable decomposition generally requires either strong mathematical regularization or dedicated experiments that provide additional constraints. The pure positive and negative cases are therefore used here only for validation.

VI. CONCLUSIONS

The proposed area-based approach provides a systematic framework for hysteresis analysis and separation of competing hysteretic contributions. By moving beyond read-out-current-based metrics, it captures the hysteretic response over the full electrostatic range and therefore offers a more robust and physically meaningful basis for evaluation. Within the calibrated model, this framework enables approximate reconstruction of the individual positive and negative components from the observable mixed response, thereby providing insight into the interplay of competing mechanisms. In addition, the area-based metric improves the consistency of TCAD calibration, since it constrains the

overall loop shape rather than a single arbitrary operating point. As a result, the proposed method is better suited for understanding, modeling, and optimizing hysteresis in emerging transistors.

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