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On the Dynamic characteristics of Ferroelectric and Paraelectric FETs

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Abstract

We derive the necessary conditions for a steep subthreshold switching of a Paraelectric FET with gate scan frequency. Despite an absence of a two-valley energy profile, paraelectric FETs can be represented by a series R-C circuit that exhibit sub-60 mV/dec switching under dynamic conditions during the reverse sweep of the gate bias.

(Keywords: Dynamic Behavior, Ferroelectric, Paraelectric, FET)

Introduction

Landau Switches, typically consisting of a gate dielectric with a ferroelectric material, have significant promise to meet scaling requirements of future technology nodes, due to their voltage amplification, that yields sub-60 mV/dec switching [1], [2]. The current work is motivated by observation of steep switching characteristics even in the absence of a ferroelectric, for example, by inserting a memristor switch in source or drain path of a transistor [3], or using electrolyte gating [4]. Here, we analyse the operation of ferroelectric (FE) and paraelectric (PE) FETs under the dynamic sweep of gate bias V_{GS} . We demonstrate that steep switching is possible despite the fact that the energy profile of a paraelectric material exhibits a single-valley landscape without a negative capacitance regime. This behaviour is explained in terms of an equivalent circuit model of a typical paraelectric, which can be interpreted as a series R-C circuit in its simplest form. A condition to achieve a body factor less than unity is derived in such FETs.

Dynamic Operation of Ferro & Para electric FETs

The free-energy profile of a typical ferroelectric (FE) or a paraelectric (PE) material is described as [5]

$$U = \alpha P^2 + \beta P^4 + \gamma P^6 - P\mathcal{E} \quad (1)$$

Here α , β and γ are material dependent constants, \mathcal{E} is the electric field, and P is the polarization. In a FE, $\alpha < 0$, whereas a PE material has $\alpha > 0$. As shown in Figs. 1 (a) and (b), the plots of U vs. P at electric field $\mathcal{E} = 0$, result in the widely reported single- and double- valley energy profiles for PE and FE materials respectively. However, in the presence of an electric field, the polarization of the material is shifted towards the minimum energy point, demonstrating distinctive characteristics in FE and PE materials respectively. Their dynamic behaviour under continuously varying \mathcal{E} is described by the LK equation as [6]

$$\rho \frac{dP}{dt} = -\frac{dU}{dP} = -2\alpha P - 4\beta P^3 - 6\gamma P^5 + \mathcal{E} \quad (2)$$

where ρ is a damping coefficient associated with the material, which controls the dynamic response. A plot of P vs. \mathcal{E} from Eq. (2) in the steady-state i.e. ($dP/dt = 0$) and under dynamic \mathcal{E} , is shown in Fig. 1 (c). Owing to the presence of a double-valley, FE

materials possess a negative-slope ($dP/d\mathcal{E} < 0$) around the origin, which causes instability, settling into one of two residual polarisation states, marked by $\pm P_R$ in Fig. 1 (c). In contrast, in a PE material, $P = 0$ at $\mathcal{E}=0$. This dissimilarity however, vanishes under a dynamic sweep, where both PE and FE show $P \neq 0$ at $\mathcal{E} = 0$, giving rise to an anti-clockwise hysteresis. This is explained by a finite rate of change in P as determined by ρ , highlighted in Fig. 1 (c). The U vs. P displayed in Fig. 1 (d) further confirms the similarity of the two materials under dynamic operation Fig. 2 highlights the commonly described non-linear RC equivalent circuit of the two materials according to Eq. (2) [5]. In this case, R and C are given by

$$R = \rho t_{ox} \quad (3)$$

$$C(Q) = [t_{ox}(2\alpha + 4\beta Q^2 + 6\gamma Q^4)]^{-1} \quad (4)$$

However, an important distinction is that while in a PE, the non-linear capacitor, always remains positive, it can become negative for a FE in a certain range of operation, owing to $\alpha < 0$ for this material. This implies that in a PE, negative capacitance originates from the delay of the response of the system to applied gate voltage at a specific scan rate, arising from the values of R and C. On the other hand, negative capacitance in a FE-FET is of physical origin and related to the ferroelectric domains.

To investigate the electrical properties of FE- and PE-FETs, their characteristic L-K equation is self-consistently coupled to the semiconductor channel simulated via the Poisson equation as illustrated in Fig. 3. The parameters of the L-K equation listed in Table 1 are similar to as reported in [7].

The transfer characteristics of an FE-FET at different scan frequencies of gate bias are shown in Fig. 4 (a). Owing to the instability in the FE, steep switching is observed during both the forward and backward sweeps of gate bias. It has been explained in the literature by a sudden change in the polarization state of the FE that causes a change in the density of carriers in channel, are results in amplification [2]. In our simulated FE-FET, the capacitance introduced by the semiconductor channel is sufficient to stabilise the negative capacitance of the FE for the chosen parameters with negligible hysteresis [7], [8], at low scan frequency. In Fig. 4 (b), the variation of bias across the FE, V_{ox} vs. V_{GS} at low frequency shows that the slope dV_{ox}/dV_{GS} becomes less than zero during both directions of the sweep of V_{GS} , resulting in a body factor $m < 1$, as given by the equation in the inset of Fig. 4 (b). Fig. 4 (c) reveals a $SS < 60$ mV/dec at low frequency in both the forward and backward directions of V_{GS} . With an increase in frequency, the delay introduced by the equivalent R-C circuit (Fig. 2) becomes significant, the width of the hysteresis in the transfer characteristics becomes larger. As a result the SS during the forward sweep degrades, increasing above 60 mV/dec at a

frequency of ~ 3 MHz, while in the backward sweep, it remains as low as ~ 5 mV/dec. Employing a FE material to boost the SS does not always guarantee a sub-60 mV/dec operation. Since a ferroelectric affects the body factor the amplification depends upon the performance of the underlying MOSFET via the factor $n (= d \log I_{DS} / d \Psi_s)$. Moreover, the observed SS in FE-FETs can fluctuate owing to non-idealities such as multi-domain ferroelectricity, diverse polarization [9] or gate leakage [10].

Unlike a FE-FET, the transfer characteristics of a PE-FET, plotted in Fig. 5 (a), show no steep-switching at low scan frequency of V_{GS} , but the slope of the drain-current becomes steeper during the backward sweep as the frequency is increased. Further investigation of the V_{ox} vs. V_{GS} in Fig. 5 (b) reveals that at low frequency, the slope dV_{ox}/dV_{GS} remains positive, resulting in $m > 1$. At higher frequency, dV_{ox}/dV_{GS} turns negative only in the backward sweep, leading to $m < 1$. Fig. 5 (c) indicates that the SS remains greater than 60 mV/dec at low frequency in both forward and backward directions of V_{GS} sweep, but become less than 60 mV/dec in the backward sweep at a frequency greater than 12 MHz (for this value of ρ).

Conclusion

Sub-60 mV/dec switching in the dynamic characteristics of paraelectric FETs is possible via the equivalent R-C circuit based on the LK equation during the backward scan of the gate bias. FE and PE-FETs have different ranges of frequency of operation (for the same value of ρ) and this provides an additional handle for device optimisation beyond the dual energy landscape switches proposed to date.

Acknowledgments

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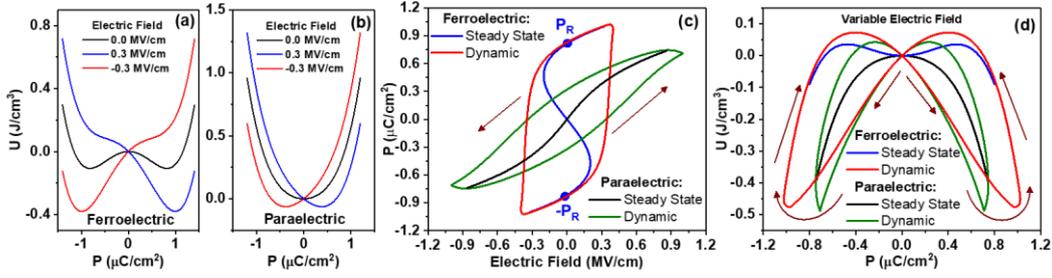


Fig. 1. Simulated energy profiles, U for (a) the ferroelectric (FE) and (b) paraelectric (PE) materials as a function of polarization, P at different electric fields. (c) Comparison of P vs. electric field for FE and PE in steady state and under the dynamic sweep of the electric field, and (d) corresponding U vs. P for FE and PE where the electric field changes as shown in (c). The parameters for simulations are summarized in Table 1.

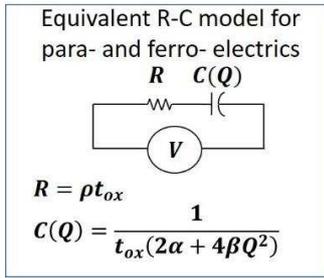


Fig. 2. R-C circuit equivalent for the L-K equation (Eq. (2)) for both the ferro- and para- electric materials [5], here LK equation with the t_{ox} represents the thickness of the semiconductor channel for ferroelectric ($\alpha < 0$) or paraelectric ($\alpha > 0$) material.

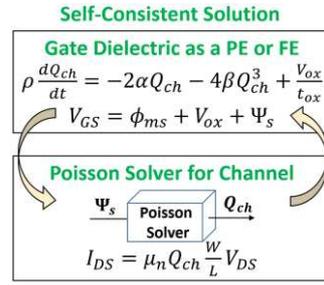


Fig. 3. The flow diagram showing the self-consistent coupling of the LK equation with the Poisson solver for channel computing the drain current in FE- or PE- FETs.

Table 1. The L-K equation parameters, used in the simulations FE- and PE-FETs, similar to typical values in the literature [7].

$$\rho \frac{dP}{dt} = -2\alpha P - 4\beta P^3 - 6\gamma P^5 + \frac{V_{ox}}{t_{ox}}$$

Parameters	Values	Comment
α (cm/F)	-3.2×10^{11}	For ferroelectric
α (cm/F)	3.2×10^{11}	For paraelectric
β (cm ⁵ /FC ²)	6.8×10^{23}	For FE and PE
γ (cm ⁹ /FC ⁴)	0	For FE and PE
ρ ($\Omega \cdot \text{cm}$)	3000	For FE and PE
t_{ox} (nm)	10	Dielectric thickness

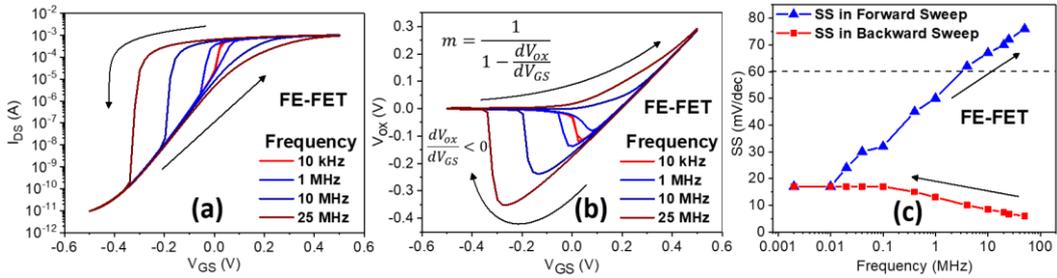


Fig. 4. (a) Transfer characteristics, (b) Voltage across the ferroelectric dielectric V_{ox} vs. the applied gate bias V_{GS} at different frequency of gate bias sweep. (c) SS vs. scan frequency in both directions of gate bias sweep for a ferroelectric FET (FE-FET). A sub-60 mV/dec switching is present at low frequency (where hysteresis virtually disappears). At higher frequency the width of the hysteresis increases and the switching becomes more gradual because of the delay introduced by the equivalent R-C circuit in Fig. 2 compared to the change in V_{GS} .

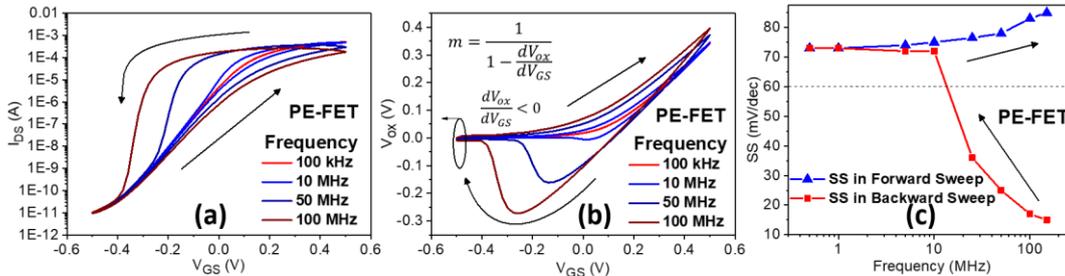


Fig. 5. (a) Transfer characteristics of a PE-FET with gate scan frequency (b) Voltage across the paraelectric dielectric V_{ox} vs. the applied gate bias V_{GS} , and (c) SS vs. frequency of gate bias sweep in forward and reverse directions for a PE-FET. No steep-switching at low frequency is present in either forward or backward direction of sweep. At a scan frequency > 15 MHz, the device shows a $SS < 60$ mV/dec in the backward sweep for chosen parameters.