DEVICE MODELING AND APPLICATION SIMULATION OF FERROELECTRIC-FETS WITH DYNAMIC MULTI-DOMAIN BEHAVIOR

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ABSTRACT

In this work, a ferroelectric-FET (FeFET) model based on multi-domain Preisach theory is developed. Instead of the single-domain Landau-Khalatnikvo (L-K) and tanh based model, the Preisach model with dynamic module is established to accurately model the dynamic behavior of multi-domain FeFET. Moreover, a FeFET-based neuron structure is presented and simulated based on the developed device model, showing the promising potential of FeFET for neuromorphic computing.

Keywords: FeFET model; Preisach theory; FeFET neuron

INTRODUCTION

In recent years, Ferroelectric-FET (FeFET) with non-volatile property has attracted great attention for many applications including memory and neuromorphic computing applications [1][2]. According to the multi-domain theory of ferroelectric material, polarization states of ferroelectric will not only depend on the applied voltage but also on its history [1]. In addition, the domain switching in ferroelectric material is not instantaneous, and shows the dynamic behavior. To evaluate the device and circuit performance based on FeFET, accurate current model of FeFET is perquisite. However, the current models of FeFET are mainly based on the single domain Landau-Khalatnikvo (L-K) model or the tanh function for ferroelectric materials [3][4], which cannot simulate the dynamic behavior and multi-domain effect in FeFET.

In this work, we develop a FeFET current model based on multi-domain Preisach theory with the dynamic module considered. Moreover, based on the established model, a FeFET neuron structure based on FeFET is presented and simulated to show the potential of FeFET in neuromorphic devices.

MODELING FRAMEWORK

The developed FeFET model in this work is composed of two components as shown in Fig. 1.

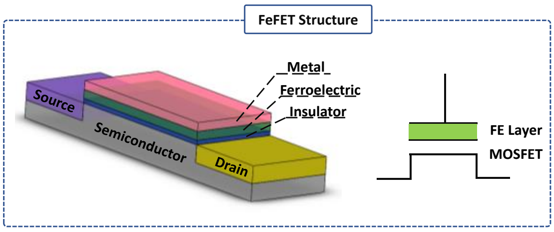

Fig. 1 Ferroelectric FET structure. FeFET model is composed of two parts, FE layer and conventional MOSFET.

The BSIM model is used for the MOSFET component of FeFET [5] in order to obtain the relationship between charge and internal gate voltage $Q_{\mathrm{MOS}}(V_{\mathrm{MOS}})$. The model of ferroelectric (FE) layer is described by the multi-domain Preisach theory with a RC-like dynamic module, through which the charge and the voltage relationship of FE layer $Q_{\mathrm{Fe}}(V_{\mathrm{Fe}}(t))$ in FeFET can be obtained. Based on the above relationships, the FeFET can be modeled as follows.

Since the FE layer is stacking on the internal gate of MOSFET in FeFET, the following two equations should be satisfied.

$$\begin{cases} Q_{\mathrm{Fe}} = Q_{\mathrm{MOS}} \\ V_{\mathrm{G}} = V_{\mathrm{Fe}} + V_{\mathrm{MOS}} \end{cases} \quad (1)$$

The equation above can be solved by iteration method as shown in Fig. 2. For each given gate voltage V_G, assuming the voltage drop on MOSFET component is V_{MOS}, then Q_{MOS} can be calculated based on BSIM model. By following the Eq.1, voltage drop on FE layer V_{Fe} can be calculated according to $V_{\mathrm{Fe}} = V_{\mathrm{G}} - V_{\mathrm{MOS}}$, and then Q_{Fe} can be obtained based on the developed multi-domain Preisach model of FE layer. Further by comparing Q_{Fe} and Q_{MOS}, if their difference is smaller than the error tolerance, denoting the assumed V_{MOS} and calculated $V_{\mathrm{Fe}}, Q_{\mathrm{Fe}}, Q_{\mathrm{MOS}}$ are correct; If not, assume another V_{MOS} until the results match. For each given V_{G} there is V_{MOS} that could satisfy the aforementioned modeling framework, and finally $V_{\mathrm{G}} - I_{\mathrm{D}}$ relationship of FeFET can be developed.

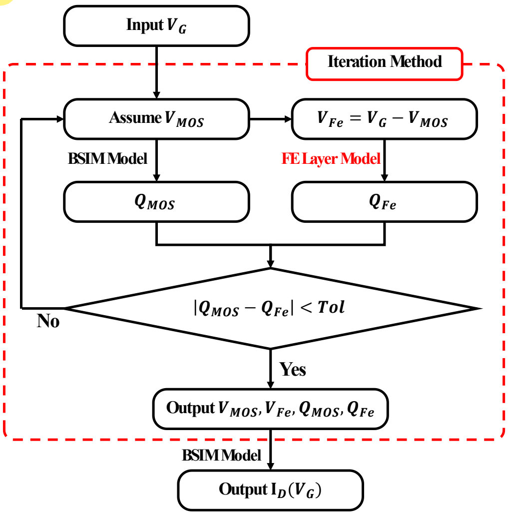

Fig. 2 Iteration method for solving relationship between gate voltage and drain current of FeFET.

MODELING of FERROELECTRIC FET

As mentioned above, key of FeFET modeling is the modeling of FE layer. Total charge of FE layer is the sum of spontaneous polarization and dielectric polarization. For spontaneous polarization, according to multi-domain Preisach theory, FE layer can be modeled as many domains with two different stable polarization states, normalized as +1 and -1, standing for the states of polarization up and down. Each domain has two coercive fields. Both the coercive fields of domains (-α_i and β_i) follow 2-D normal distribution (Fig. 3(b)). Spontaneous polarization of each domain can be influenced by the coercive fields, previous polarization state and external electric field. For each domain, when external electric field is smaller than coercive field α_i, the domain will switch to polarization down state instantly; when electric field is larger than coercive field β_i, domain will switch to polarization up state, and polarization state would maintain unchanged as previous state when electric field is between α_i and β_i as shown in Eq.2 and Fig. 3(a).

$$P_i(t) = \begin{cases} +1 & (E(t) \leq \alpha_i) \\ P_i(t-\Delta t) & (\alpha_i < E(t) < \beta_i) \\ -1 & (E(t) \geq \beta_i) \end{cases} \quad (2)$$

The spontaneous polarization of FE layer is calculated as the sum of polarization of domains.

As for dielectric polarization charge of FE layer, it can be calculated by external electric field E_{ext} and dielectric constant ε_{Fe} of the layer. The equation $P_{DE} = \varepsilon_{Fe} E_{ext}$ should be satisfied, where $\varepsilon_{Fe} = \varepsilon_0 \chi_e$ shown in Fig. 3(c).

For the dynamic switching behavior of ferroelectric material, a RC-like dynamic module is introduced into the above static Preisach model for FE layer in this work. The applied voltage $V_{Fe}(t)$ is converted into an introduced effective voltage $V_{eff}(t)$ for the non-instantaneous time response of the FE layer [4]. The $V_{eff}(t)$ is calculated by Eq. (3) .

$$\frac{dV_{eff}}{dt} = \tau(V_{Fe} - V_{eff}) \quad (3)$$

Where τ is the time constant of domain switching. The $V_{eff}(t)$ and $V_{Fe}(t)$ are illustrated in Fig. 3(d), and the simulation results are shown in Fig. 4(a). It can be seen that compared with V_{Fe}, the peak voltage of V_{eff} is decreased and a lagging effect is shown, reflecting the dynamic behavior in FE layer.

Based on aforementioned FE layer model, P-V response for given input voltage is simulated as shown in Fig. 4. When sweeping voltage is relatively high, P-V loop shows saturation characteristic; and when the sweeping voltage is relatively low (point "b" to "c"), an unsaturated minor loop will appear. At point "b" and "c", when the sweeping voltage change sweeping direction, P-V loops also demonstrate dynamic behavior of FE layer.

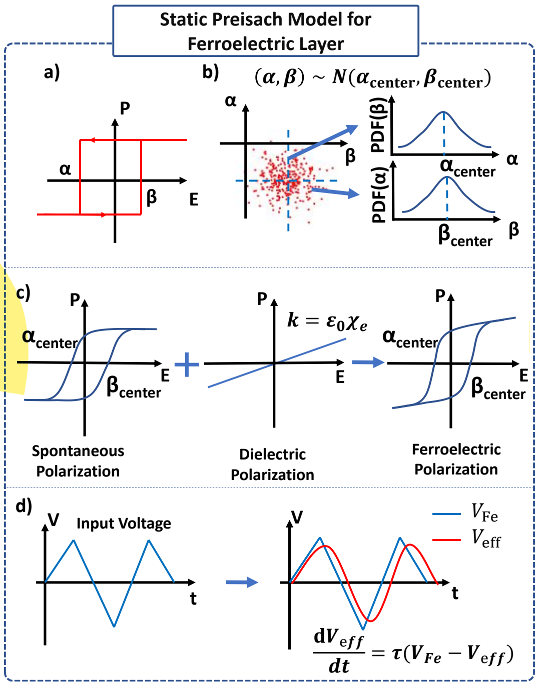

Fig. 3 (a) Single domain P-E loop, α and β indicate coercive field of one domain. (b) Multi-domain effect and classic P-E loop of FE layer with normal-distributed coercive field. (c) Total polarization is the sum of spontaneous polarization and dielectric polarization. (d) Dynamic module. FE layer will react to $V_{eff}(t)$ instead of $V_{Fe}(t)$ to simulate dynamic polarization switching behavior.

Therefore, with the MOSFET BSIM model and the aforementioned dynamic Preisach model of FE layer, the FeFET model can be finally developed. The simulation results based on the FeFET model are shown in Fig. 5, showing that the FeFET have two different V_T with different gate voltage sweeping direction.

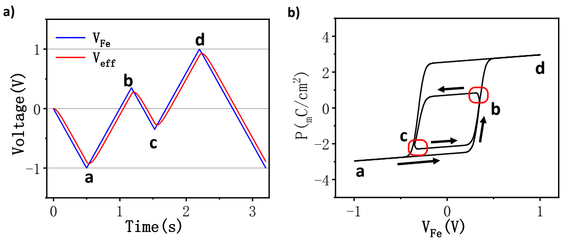

Fig. 4 (a) Simulation result of dynamic module, the peak voltage of V_{eff} is smaller than V_{Fe}, and time lagging effect. (b) P-V loop of ferroelectric capacitor simulated with the voltage input of (a), the saturation loop and unsaturation loop are shown. Point b and c reflect the dynamic behavior of ferroelectric.

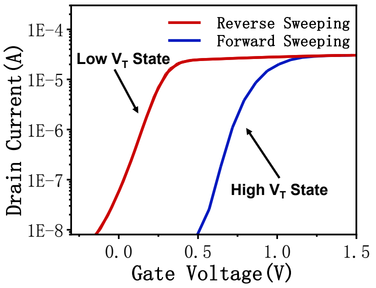

Fig. 5 FeFET simulation result with V_{DD}=1V. Different sweeping direction shows different V_T state.

FEFET-BASED NEURON AND SIMULATION RESULTS

CMOS based implementation for neuron structures usually requires high hardware cost [6]. In this work, we present a FeFET-based neuron structure with low hardware cost, showing the potential of FeFET to build neuron devices. Simulation results of FeFET neuron is based on the aforementioned FeFET model.

'Leaky Integrate and Fire (LIF)' function is the most basic neuron behavior. Neuron can integrate input pulses from dendrites, which give rise to the potential of neuron. When potential reaches threshold, the neuron will 'fire' with output spike delivered to axon, and 'leaky' stands for spontaneous protentional drop between input pulses.

The proposed FeFET-based neuron structure is shown in Fig.6. Gate of n-type FeFET can integrate input pulses and source is designed to give output pulse. Polarization of FE layer in the FeFET will accumulate gradually with the input pulses, and change the device threshold voltage.

The simulation result of FeFET neuron is shown in Fig. 7, the FE model is calibrated with experimental results in [7]. It is shown that after 9 input pluses of 2V, the neuron will fire when V_{DD} is 1.5V. However, since the FE layer of FeFET usually has relatively long retention time, there is no obvious potential drop after the fire. To realize the leaky effect, accelerated polarization degradation is required for the FE layer design of FeFET [8][9].

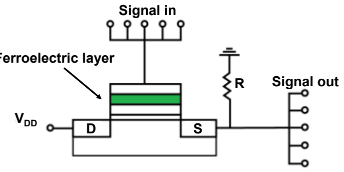

Fig. 6 FeFET-based neuron structure. The gate will integrate input pulses acting as dendrites, and source will give output pulse as axons.

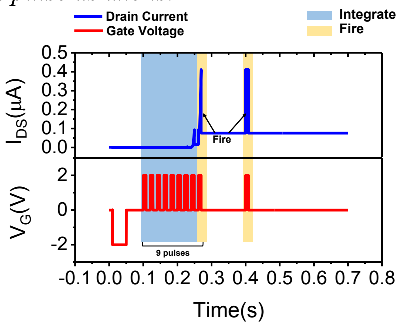

Fig. 7 Simulation results of FeFET-based neuron structure. V_{DD} is 1.5V and V_G is 2V for the input pulses, with initialize pulse -2V/50ms. The neuron will fire after 9 pulses.

CONCLUSION

In this work, we develop a FeFET model based on dynamic multi-domain Preisach theory. In contrast to single-domain L-K model and tanh approaches, non-instantaneous behavior is realized in this model. Moreover, we present and simulate a FeFET neuron structure based on developed model, showing the potential of FeFET for neuromorphic computing, especially for neuron devices.

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