Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp19-20

Design and Simulation of Highly-Efficient Metal-Ferroelectric-Nanosheet Line-Tunnel FETs for Sub-5-nm Technology Nodes

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Abstract
This work for the first time investigates the promising structure of line-tunneling-field effect transistors by using advantages of ferroelectric polarization and nanosheet geometry to improve the tunneling probability. The results state that the I_{on} has been improved enormously (137.9 μA/μm) by utilizing the benefits of ferroelectric polarization ($Hf_{0.5}Zr_{0.5}O_2$). In addition, the off-current is achieved in the orders of aA/μm through the benefits of nanosheet geometry and hence excellent I_{on}/I_{off} ratios. In addition, the proposed structure able to improve the average subthreshold swing significantly.

1. Introduction
The current research is majorly focusing on the utilization of ferroelectric materials to solve the needs of thermionic emission issue in field effect transistors (FETs) with that of negative capacitance. In addition, the on-current limitation in tunneling FETs (TFETs) can be overcome through utilization of ferroelectric materials that has the capability to generate excess-field [1]. However, the major utilization of polarization induced by ferroelectric material gradually reduce through the gate-oxide thickness. Hence the metal-ferroelectric-semiconductor (MFS) combination is one of the effective option to utilize the benefits of ferroelectricity than metal-ferroelectric-insulator-semiconductor (MFIS). Furthermore, the MFS structure has been proven in 2D materials as suitable option [2]. Thus we model the MFS based nanosheet of ferroelectric scaled line-TFETs (FeSLTFETs) and investigated.

2. Model Calibration and Results Discussion
The device is modeled carefully by tuning the simulation parameters to meet the experimental data, as depicted in Fig. 1a [3], [4]. The proposed FeSLTFETs with $Si_{0.6}Ge_{0.4}$ (source) is depicted in Figs.1b and c, in the view of current technology node (sub-5-nm).

Foremost, the importance of MFS structure in comparison to MFIS in the proposed nanosheet structure of FeSLTFET is studied. The electric field distributions represented in Fig. 1d and Fig. 2a (along cult-line C_1) state that the influence of field is higher for MFS structure than MFIS structure. This is because, the absence of dielectric layer strongly influence the remnant polarization (P_r) and coercive field (E_c) on to the semiconductor region [2]. Therefore, the polarization strongly is influenced on the n-epitaxial layer and at the source-channel junction as shown in Fig. 2b. Since, the fields are higher therefore the MFS structure and thus produces high-electron BTBT generation rates, can be viewed from Fig. 1e and Fig. 2c. In addition, the generated field and the respective BTBT based on the applied tunneling model are evaluated for validation in results and depicted in Fig. 2d.

The performance of proposed structures (MFS and MFIS) at t_{FE} of 3 nm can be viewed in Fig. 2e. Based on the results, it is identified that the on-current boost is approximately 5 times higher than the MFIS structure (understood from Table I). Interestingly, good agreement with I_{off} even for reduced t_{FE} is achieved due to the concepts of wrapped around gate and optimum gate-on drain. To make our desingn as more robust, the design is further extended for comparative analysis with recently proposed geometry of ferroelectric vertical TFET (FeVTFET) (Fig. 2f) [5]. The observed field and BTBT can be viewed from the Figs. 2g and h. Fig. 3a, reveal that the on-current is closely equivalent to the proposed geometry, however the off-state current controllability is too difficult becuase of direct impact of ferroelectric layer on to the channel (p) region. Thus we state that the proposed structure is more convient to MFS geometry to utilize the benifits of ferroelectricity. The discussion is further extended to effect of I_D-V_G on scaled ferroelectric thickness (t_{FE}) (Fig. 3b). It has been stated that the polarization in HZO material is fluctuated and have a good aggreement at 3-5 nm [6]. Therefore, our reuslts are good agreement with t_{FE} of 3 nm in generating large I_{on} and fluctuations (inset of Fig. 3b) at very low t_{FE} due to uncontrollability of polarization.

4. Conclusions
Thus, we have designed and studied the effect of MFS and MFIS nanosheet FeSLTFETs with $Si_{0.6}Ge_{0.4}$ as source for the first time. The relevant discussions on device performance has been addressed. Among all, the MFS based FeSLTFETs are delivering superior performance, provided that the reasonable t_{FE} has been maintained. The proposed structure has been made for the needs of high-drive current and low I_{off} with very good average and minimum subthreshold swings.

Acknowledgements
This work was supported in part by the Ministry of Science and Technology, Taiwan, under Grant MOST 108-221-E-009-008 and Grant MOST 108-3017-F-009-001, and in part by the "Center for mmWave Smart Radar Systems and Technologies" under the Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education in Taiwan**"**.

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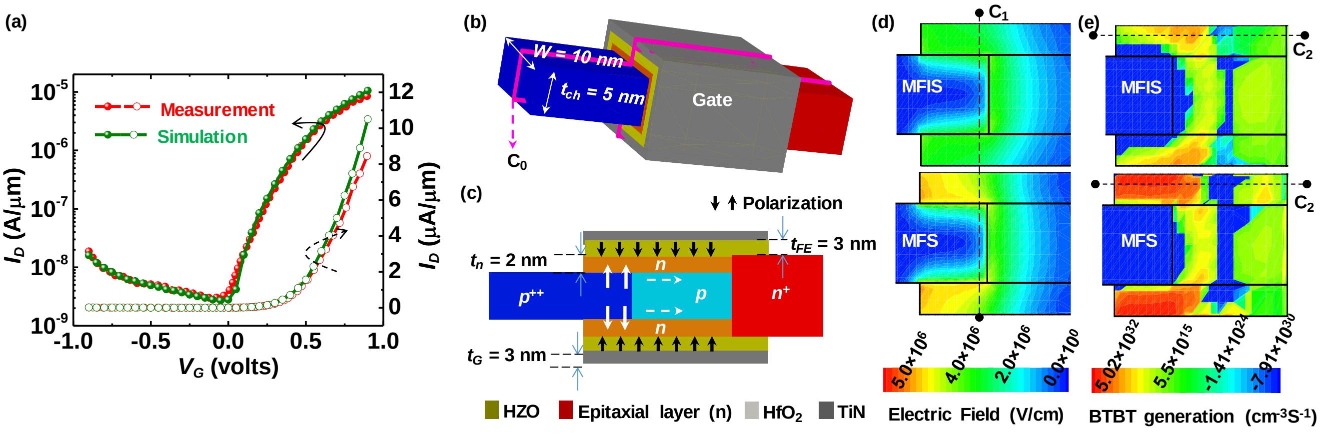

Fig. 1: (a) Experimental validations to simulation results [3]. (b) Proposed FeSLTFET (MFS based) with specifications as mentioned in (c) along with the doping specifications as 5×10^{20}, 1×10^{16}, 1×10^{19}, and 5×10^{18} for source (p^{++}), channel (p), drain (n^{+}) and epitaxial layer (n), respectively. The work function is considered as 4.4 eV with the material of TiN. (d) Electric field and (e) as electron BTBT distributions of proposed MFIS and MFS structures.

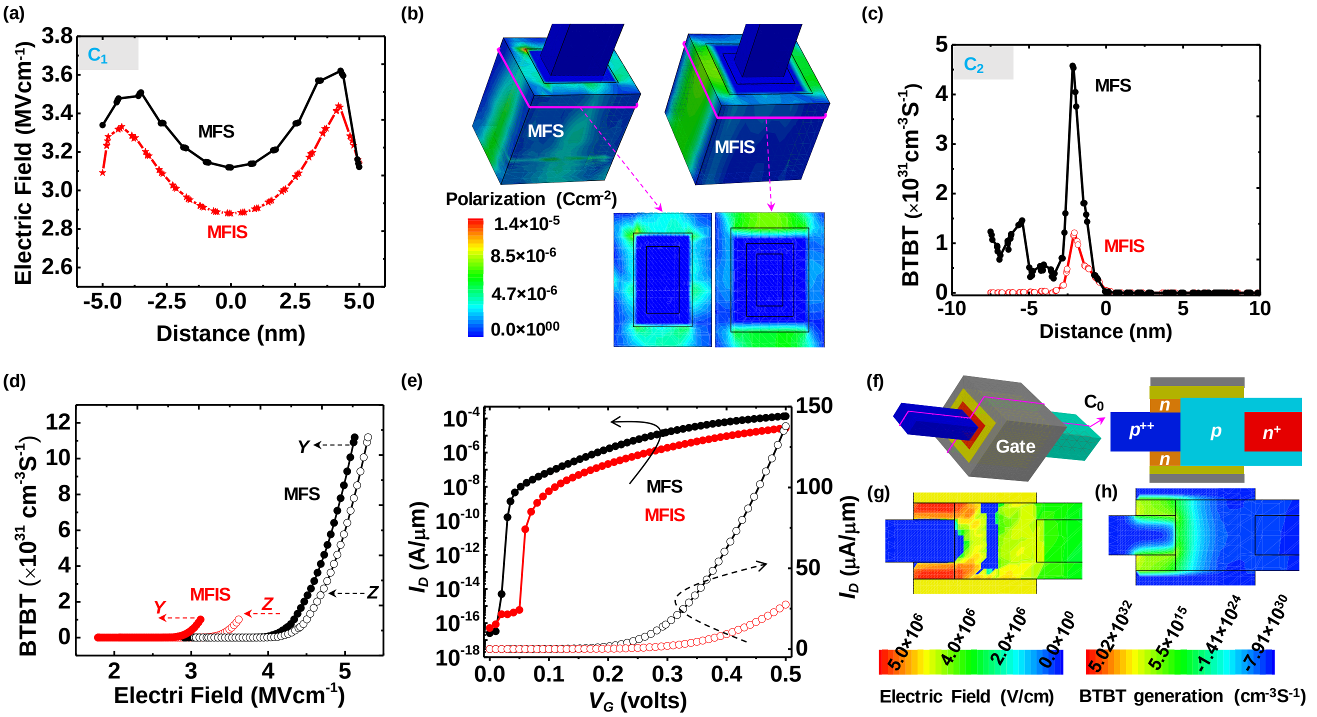

Fig. 2: (a) The electric field distributions along cut-line C_1 for the depicted structure of Fig. 1(d). (b) Distribution of polarization on MFS and MFIS. (c) Electron BTBT along C_2 for the depicted structures shown in Fig. 1(e). (d) The observed electron BTBT generation in MFIS and MFS structures, with respect to electric field generated in the semiconductor region. (e) I_D-V_G characteristics of the proposed MFS and MFIS structures. (f)-(h) The designed nanosheet structure based on the concept of [5], shown with field and BTBT distributions.

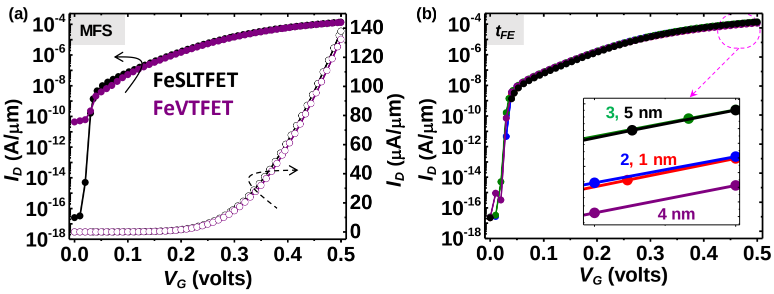

TABLE I

EXTRACTED DC RESULTS OF MFS AND MFIS STRUCTURES

Structure	I_{on} (μA)	I_{off} (aA)	V_t (V)	SS (mV/dec) SS_{min}	SS_{avg}
MFS FeSLTFET	137.9	25.29	0.119	2.99	29.8
MFS FeVTFET	132.3	43.24 $\times10^6$	0.118	12.9	76.1
MFIS FeSLTFET	27.52	51.12	0.180	3.47	41.6
MFIS FeVTFET	18.30	11.01	0.190	3.43	51.6

Fig. 3: (a) The I_D-V_G comparison on MFS structure of proposed and referred structure as stated in Fig. 2(f). (b) Effect of t_{FE} on I_D-V_G characteristics of MFS FeSLTFET structure.