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Novel Steep-Slope Switch Device with Improved Figures of Merit (FOM) through Mechanism Engineering for Ultra-Low-Power Applications (invited)

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Abstract

This paper presents a kind of injection-tunneling hybrid-control operation mechanism for comprehensive property enhancement of traditional TFETs. Novel silicon based multi-finger Schottky barrier TFET (MFSB-TFET) with source pocket is presented and experimentally demonstrated, with SS_{min} of 29mV/dec, on current of ~20μA/μm, on-off ratio of 10^8 and other improved properties in terms of switching-on voltage, capacitance, delay and noise behavior. With improved FOM, as well as further possible combination with band engineering and structure engineering, the MFSB-TFET shows great potentials for future ultra-low-power applications.

1. Introduction

With CMOS technology continues scaling, the static power dissipation becomes one limiting factor, particularly for ultra-low power application, such as wearable products, IoT nodes and implantable medical components, etc.. Recently people intensively turns to steep-slope devices with new operation mechanisms as one possible solution, which can break the limit of subthreshold swing (SS) in MOSFETs (60mV/dec at room temperature), such as tunneling field-effect transistor (TFET) [1-2], negative capacitance FET(NCFET) [3-4], impact-ionization MOS (IMOS) [5], NEM-relay with movable suspended-beam [6-7], etc.. Among these new mechanism devices, the TFET attracts much attention, which featured as a gated reverse-biased p-i-n junction and switches on through quantum band-to-band tunneling (BTBT) mechanism with low off-current and reasonably low switching voltage. Since the high energy part of Fermi-Dirac carrier distribution can be effectively cut off, the SS of TFET can be theoretically lower than 60mV/dec at room temperature. However, for traditional TFETs, steep SS is difficult to be obtained in experiments due to the gradual source doping profile [8-9]. In addition, silicon based TFET suffers from low ON-current due to the poor tunneling efficiency, and thus relatively large intrinsic delay and lower gain. Lots of efforts have been made to alleviate the ON-current and SS issues, such as using III-V materials of smaller bandgap, multi-gate structure, heterojuntion design and advanced annealing process, etc.. On the other hand, besides the ON-current and SS issues, the TFETs need to face other challenges, such as super-linear onset of output characteristics, relatively large Miller capacitance and relatively large LF noise compared with MOSFETs. Therefore, comprehensive design of the steep-slope device for boosted figures of merit (FOM), rather than mere improvement of ON-current and SS, is in ample necessity in order to meet the practical requirements of ultra-low-power SoC applications. In this paper, mechanism engineering for comprehensive performance enhancement of TFETs is discussed as one possible solution of the above mentioned issues. Novel silicon-based steep-slope device based on injection-tunneling hybrid-control operation mechanism is designed and experimentally demonstrated for improved FOM, exhibiting great potentials for future ultra-low-power implementation.

2. Hybrid-Control Operation Mechanism

The injection-tunneling hybrid control operation mechanism is proposed, with different working mechanism dominating different operation region for optimized behavior [10]. High Schottky injection current of several orders higher than tunneling current is designed for on-state current boosting. To reduce the off-current, we propose a kind of self-depletion effect to increase the effective Schottky barrier height. As shown in Fig.1, the region between the two p+ parts will be self-depleted by the two adjacent p+-i junctions, which will cause increased effective barrier height and relatively high threshold voltage. This can remarkably reduce the off-current, as well as result in early turning-on of the tunneling current in the transition region. Thus the dominant quantum tunneling mechanism of the transition region inherently can ensure the steep sub-threshold slope. In such, this hybrid-control adaptive operation mechanism can intrinsically guarantee the high on current, low off current and steep transition of the switch device.

3. Multi-Finger Schottky Barrier TFET (MFSB-TFET) with Improved FOM

Based on the proposed hybrid control mechanism, a kind of multi-finger Schottky barrier TFET with source pocket (MFSB TFET) is presented, as shown in Fig.2. The device has a comb-shaped gate with one handle and multiple fingers connected to the dopant-segregated Schottky (DSS) source to form the Schottky junction [11]. DSS technology can further modulate the Schottky barrier height for higher ON current without affecting the low off current due to the above-mentioned separated on-off mechanism. The side tunnel junctions at the gate finger region can introduce the junction depleted-modulation effect [12] for equivalently more abrupt source junction, which is beneficial to steeper-slope. Source pocket can result in sharper band bending for higher tunnel electric field and further steeper slope. In addition, for the gate handle region tunneling, multi-finger configuration can increase the coupling action between the fingers and further enhance the tunneling field for improved average SS with larger current range. The MFSB-TFETs and TFETs were fabricated with compatible

CMOS technology. It can be seen from Fig.3(a) that the MFSB-TFET has about two orders higher on-current than traditional TFET with large on-off ratio, as well as smaller minimum SS (SS_{min}) and average SS (SS_{avg}). Fig.3(b) shows even better properties of MFSB-TFETs fabricated on SOI substrate, with the on-off ratio of 10^8, SS_{min} down to 29mV/dec with relative low turning-on voltage. The measured output behavior in Fig.4 indicates that MFSB-TFET is immune to the output super-linear onset. The measured C_{gd} of MFSB-TFET is much lower than traditional TFET, as shown in Fig.5, mainly resulting from the designed comb-gate-configuration for effective gate area reduction, which can alleviate the current overshoot and result in smaller delay. Regarding the noise behavior, MFSB-TFET show both 1/f noise and random telegraph noise behavior, but the normalized noise can be reduced compared with traditional TFET, although a little bit higher than MOSFET, as shown in Fig.6. Fig.7 illustrates that MFSB TFET has higher intrinsic gain than MOSFET but lower than traditional TFET due to the lower current and higher output resistance in traditional TFET. Fig.8 summarizes the comparison of the above mentioned properties among the fabricated MFSB-TFETs, traditional TFETs and MOSFETs. It is explicit that for low supply voltage the MFSB-TFET shows better performance tradeoff and better comprehensive advantages. With the defined FOM for the steep-slope devices shown in Fig. 8, it can be seen that the MFSB-TFET exhibits higher measured FOM than the TFET.

4. Conclusions

The injection-tunneling hybrid control operation mechanism is proposed for steep-slope devices to solve some critical issues of traditional TFET, with the on state dominated by Schottky injection current, transition region dominated by band-to-band tunneling and the off current greatly suppressed with increased effective barrier height. Silicon based MFSB-TFET is presented and experimentally demonstrated to verify this new mechanism, exhibiting improved FOM with higher on current, steeper transition and other improved properties in terms of turning-on voltage, SS_{avg}, capacitance, delay and noise behavior, and thus remarkably promising for future ultra-low-power applications.

Acknowledgements

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References

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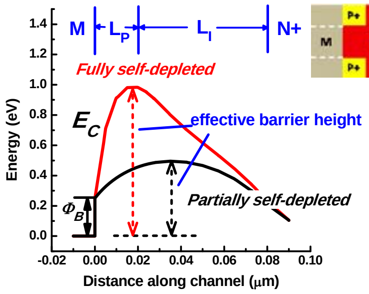


Fig.1

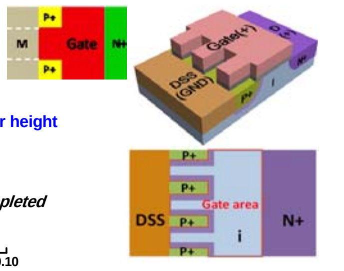
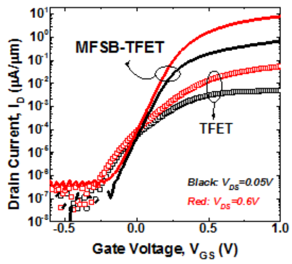


Fig.2

Fig.1 Simulated effective barrier height of self-depletion effect between two adjacent junctions Fig.2 Schematic view of the proposed multi-finger Schottky Barrier TFET (MFSB-TFET)



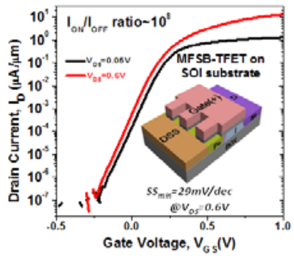
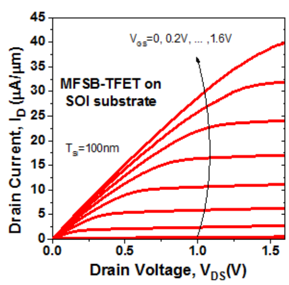


Fig.3(a) Fig.3(b)

Fig.3 Measured transfer characteristics of the MFSB-TFET on bulk substrate (a) and SOI substrate (b)



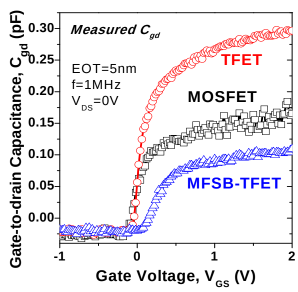


Fig.4 Fig.5

Fig.4 Measured output characteristics of the MFSB-TFET

Fig.5 Measured C_{gd} of MFSB-TFET, TFET and MOSFET

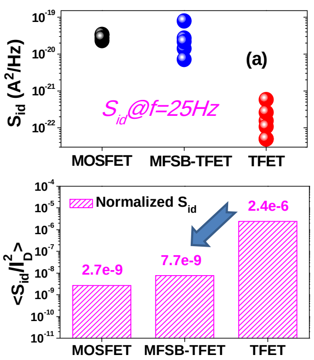


Fig.6

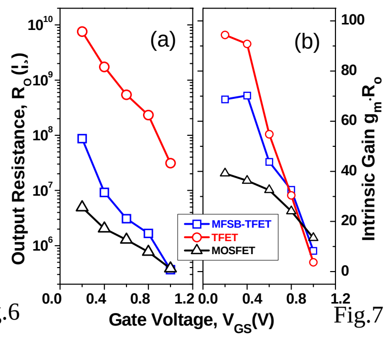
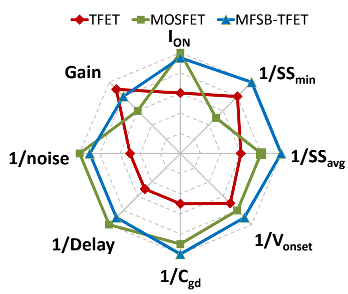


Fig.7



$$FOM = \frac{\sqrt{EOT}}{\sqrt{SS_{avg}}}\cdot\frac{1}{\sqrt{|V_{DD}|}}\cdot\log\left(\frac{I_{on}\sqrt{EOT}}{I_{off}}\right)\cdot\frac{1}{\sqrt{|V_{onset}|}}\cdot\log\left(\frac{1}{<S_{id}/I_d^2>}\right)\cdot\frac{1}{\sqrt{t_{delay}}}\cdot\log(g_m\cdot R_o)$$

device	MFSB-TFET	TFET
FOM	**6.48**	**0.99**

Fig.8

Fig.6 Measured S_{id} and normalized S_{id}/I_d^2 Fig.7 Extracted R_o and intrinsic gain Fig.8 Comparison of comprehensive properties and FOM