Negative Capacitance Tunnel FETs: Experimental Demonstration of Outstanding Simultaneous Boosting of On-current, Transconductance, Overdrive, and Swing

A. Saeidi[1], F. Jazaeri[2], I. Stolichnov[1], G. V. Luong[3], Q. T. Zhao[3], S. Mantl[3], and Adrian M. Ionescu[1]
[1]Nanoelectronic Devices Laboratory, EPFL, Lausanne, Switzerland, email: ali.saeidi @epfl.ch
[2]Integrated Circuits Laboratory, EPFL, Lausanne, Switzerland
[3]Peter Grünberg Institut 9 (PGI-9), Forschungszentrum Jülich, 52425 Jülich, Germany

Abstract

This paper demonstrates and experimentally reports the highest ever performance boosting in strained silicon-nanowire homojunction TFETs with negative capacitance, provided by matched PZT capacitors. Outstanding enhancements of I_{on}, g_m, and overdrive are analyzed and explained by *most effective reduction of body factor,* $m < 1$, especially for $V_G > V_T$, which greatly amplify the control on the surface potential TFET, which dictates a highly non-linear BTBT regime. We achieve a full non-hysteretic negative-capacitance switch configuration, suitable for logic applications, and report *on*-current increase by a factor of 500x, *voltage overdrive* of 1V, *transconductance* increase of up to 5×10^3x, and *subthreshold swing* improvement.

Introduction

The challenges of using both band-to-band tunneling [1] and Negative Capacitance (NC) effect [2, 3] in a single device are related to achieving *simultaneously* matched design of the ferroelectric and in-series stabilizing MOS capacitance, in a regime of operation where a significant boosting of TFET performance can occur [4]. This paper experimentally investigates the impact of ferroelectric's NC on DC electrical behavior of TFETs, fabricated in strained-silicon nanowire CMOS-compatible process [5]. We report multiple improvements in *on*-current, trans-conductance, gate overdrive, and subthreshold swing, by mean of NC, after validating these trends with numerical simulations.

Predictive Simulations: NC as Performance Booster

We focused our analysis on an *n*-type low-doped ultra-thin body (UTB) fully depleted silicon-on-insulator (FD-SOI) Fe-TFET, as shown in Fig. 1. The device behavior of the metal-ferroelectric-MOS structure is numerically calculated by combining Silvaco Atlas TCAD simulations with Landau-Khalatnikov theory of ferroelectrics [4]. The experimentally extracted Landau parameters are used for PZT as the gate ferroelectric. The transfer characteristic of an NC-TFET is qualitatively compared with the conventional TFET and plotted in Fig. 2. The following phenomena are expected via the NC effect: (i) subthreshold swing (SS) improvement, and (ii) overdrive current enhancement due to the reduction of the device body factor (m) for the gate voltage larger than the threshold voltage. As simulation results in Fig. 3 clarify, by changing the thickness of the PZT in the range of 20-60nm, a strong effect of performance boosting can be induced on an NC-TFET. The simulated device corresponds to a 14nm CMOS technology node *p-i-n* gated structure with L_{ch}=20nm, $N_{ch}=10^{15}$cm^{-3}, EOT=0.9nm, t_{BOX}=25nm, and V_{dd}=1V. Results are presented for different values of PZT thickness, which plays the major role for matching conditions of NC in-series with the gate of a transistor ($C_t=(C_{Fe}^{-1}+C_{MOS}^{-1})^{-1}>0$ and $\beta=C_{Fe}/(C_{Fe}+C_{MOS})>>1$) [4, 6]. As simulation results predict, by increasing the PZT thickness, after a critical thickness, the NC condition for a non-hysteretic switch is not anymore fulfilled [2, 4]. Moreover, significant *on*-current, transconductance, and overdrive boosting and a relatively limited improvement in SS is predicted. The amplification factors, due to the body factor lowering and the matching conditions are reported in Fig. 3. We greatly demonstrate that the saturation of the TFET current with respect to V_G is removed due to the differential internal amplification effect of $\beta=dV_{int}/dV_G >> 1$. Physically, this corresponds to the body factor of the NC-TFET which is smaller than 1 (the body factor is predicted around 0.6).

Experiments: NC-TFET Performance Boosting

As shown in Fig. 4, the PZT capacitor (see electrical characteristics of PZT in Fig. 5) is externally connected to the gate of a Si-NW array TFET [7]. Such external electrical connections offer the flexibility of testing tens to hundreds of PZT capacitor values until the best matching is obtained. To have a non-hysteretic NC booster, the slope of the device charge line must be smaller than the negative slope of the polarization in the whole range of the operation (Fig.6) [8]. Fig. 7 depicts the experimental performance boosting that has been achieved on a relatively fair homojunction TFET characteristic (corresponding to well-behaved Si-NW TFETs with subthreshold swing in the order of 100-150mV/dec and I_{ON}~0.1 to 1µA/µm at 300K, with ambipolar characteristics), when the ferroelectric and transistor gate capacitances are matched, so that a non-hysteretic NC-TFET, as predicted by Sallahuddin [2], can be achieved. First, a significant improvement in overdrive and a limited enhancement in the SS (Fig. 8a) are obtained. The most remarkable fact is that *on*-current is boosted over the whole operation range, reaching a factor of 500x at maximum gate voltage (Fig. 8b), depending on the value of β. As discussed before, this is fundamentally reflected into a body factor reduction below 1 (here we achieve m<0.3 for the PZT of our experiment, better than simulation predictions), acting as a performance booster exactly in the region where the *on*-current of the TFET would otherwise start to have sloppy dependence on the gate voltage. It follows that the gate voltage (and V_{dd}) can be reduced by 65% while maintaining the same level of the output current. Another major limitation of TFET performance is about their poor trans-conductance. Fig. 8c shows the obtained boosting of trans-conductance, ranging from ~10x to 5×10^3x in case of the NC-TFET compared to the base TFET. It is worth noting that from many (>50) tested devices, only for the ones that are non-hysteretic and closely verifying the NC matching conditions, such performance boosting is observed. Otherwise, a ferroelectric gate (with PZT thickness out of the range of NC condition) in-series with the gate of a TFET produces a hysteretic characteristic and rather limited performance boosting, as compared elsewhere.

Conclusion

We have reported the first experimental study, pointing out that the negative capacitance can be used to simultaneously boost the most limiting factors of TFETs: *on*-current, trans-conductance, and overdrive. It was demonstrated for the first time that by a proper NC matching, the transconductance can be improved by many orders of magnitude due to internal voltage amplification.

References

[1] Ionescu, A. M., Riel, H., Nature 479.7373 (2011): 329-337.
[2] Salahuddin, S., and Datta S., Nano letters 8.2 (2008): 405-410.
[3] Khan, A. I., et al. Nature materials 14.2 (2015): 182-186.
[4] Saeidi, A., et al. IEEE TED, 2016.
[5] Zhao, Q.T., et al. IEEE JEDS 3.3 (2015): 103-114.
[6] Rusu, A., et al. Electron Devices Meeting (IEDM), 2010.
[7] Khan, A. I., et al. IEEE EDL 37.1 (2016): 111-114.
[8] Rusu, A., et al. Nanotechnology 27.11(2016): 115201.

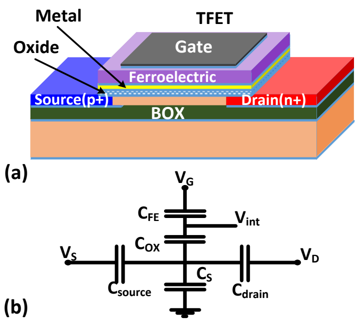

Fig. 1. The device schematic (a) and the capacitance model (b) of the ferroelectric TFET where the gate stack of a conventional TFET is replaced with a series combination of a ferroelectric and linear dielectric.

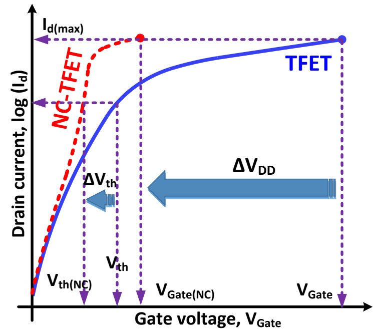

Fig. 2. Transfer characteristic of an NC-TFET versus the conventional TFET, highlighting the gain in terms of overdrive and reduction of threshold voltage, V_{th}, and supply voltage.

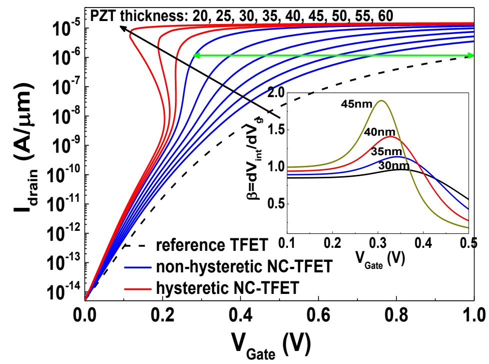

Fig. 3. Transfer characteristic of an NC-TFET (L_{ch}=20 nm, N_{ch}=10^{15}cm^{-3}, EOT=0.9nm, t_{BOX}=25nm, V_{dd}=1V, and sweeping the PZT thickness as the gate ferroelectric). The inset figure represents the body factor regarding the PZT thickness.

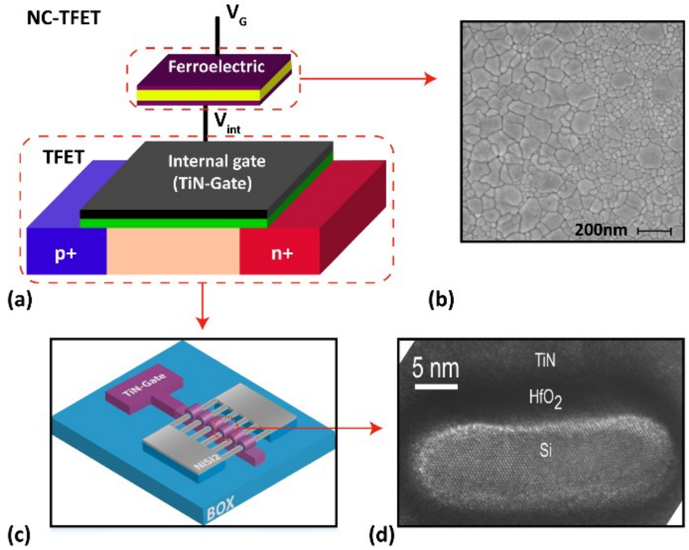

Fig. 4. (a) Experimental configuration used in this work: the gate stack of a strained Silicon nanowire array TFET is loaded with a PZT capacitor to provide negative capacitance operation (NC-TFET). (b) 46nm of polycrystalline PZT with 43/57 (*Zr*/*Ti*) ratio is deposited on a $TiO_2/Pt/TiO_2/SiO_2/Si$ substrate. SEM analysis of the PZT indicates the polycrystalline nature of the film. (c) The nanowire array TFETs are fabricated with a top-down approach and have a cross section of 30×5nm^2, a gate length of 350µm, and ~1:4Gpa tensile strain booster. (d) The transmission electron microscopy (TEM) of the Si-NW TFETs.

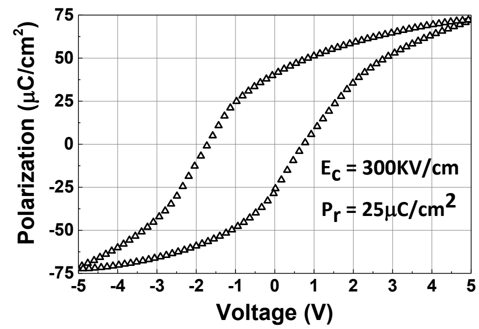

Fig. 5. The P-V characteristic of the PZT capacitor. The relative permittivity, coercive field, and remanent polarization of the PZT thin film are 220-240, 300KV/cm, and 25µC/cm2 respectively.

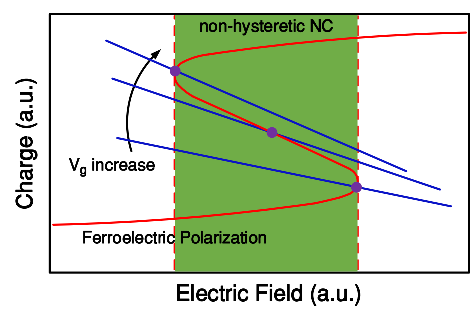

Fig. 6. The intersection of the charge line with the ferroelectric S-shape polarization. The slope of the charge lines changes with the bias, but the stability condition remains fulfilled on the entire range of the gate voltage. When the slope of the load line is sufficiently low, non-hysteretic negative capacitance is obtained over the whole region.

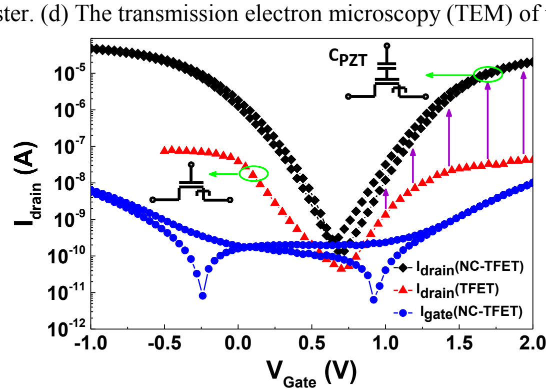

Fig. 7. Transfer characteristic of a non-hysteretic n-type NC-TFET versus its base TFET when the ferroelectric and MOS capacitances are matched in the whole range of the operation. An outstanding performance boosting is simultaneously obtained for *on-current* and *overdrive* (see details in Fig. 8) together with an improvement of the swing, when the ferroelectric NC and the gate capacitance of the transistor are matched in the large range of the gate voltage. The recorded gate leakage is negligible in all regimes of operation.

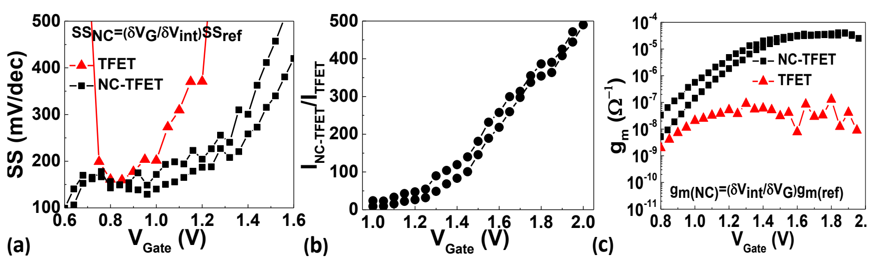

Fig. 8. Outstanding performance boosting of non-hysteretic n-type NC-TFET switch compared with TFET (corresponds to the presented device in Fig. 6). (a) While the subthreshold slope of the NC-TFET shows a relatively modest improvement due to the negative capacitance effect, in Fig. (b), *On*-current ratio between NC-TFET and TFET ($I_{ON\text{-}NCTFET}/I_{ON\text{-}TFET}$) shows exceptional boosting (up to 500x) as a result of the NC effect. (c) Transconductance improvement of more than 2 to 3 orders of magnitude is obtained.