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Subthreshold Characteristics of a Metal-Oxide–Semiconductor Field-Effect Transistor with External PVDF Gate Capacitance

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Abstract: An organic ferroelectric capacitor, using polyvinylidene difluoride (PVDF) as the dielectric, was fabricated. By connecting the PVDF capacitor in series to the gate of a commercially purchased metal-oxide–semiconductor field-effect transistor (MOSFET), drain current ($I_D$)–drain voltage ($V_D$) characteristics and drain current ($I_D$)–gate voltage ($V_G$) characteristics were measured. In addition, the subthreshold slopes of the MOSFET were determined from the $I_D$–$V_G$ curves. It was found that the subthreshold slope could be effectively reduced by 23% of its original value when the PVDF capacitor was added to the gate of the MOSFET.

Keywords: negative capacitance; organic ferroelectric material; PVDF; subthreshold slope

1. Introduction

When under a subthreshold condition, modern metal-oxide–semiconductor field-effect transistors (MOSFETs) face a fundamental limit, termed the Boltzmann tyranny, which is a direct result of the Boltzmann distribution of electrons at the source/channel interface. Consequently, a gate-source voltage of at least 60 mV/decade at room temperature is required to switch the transistor between ON state and OFF state [1,2]. This subthreshold slope (SS) limit restricts the power consumption of MOSFETs from being reduced any further [2]. As portable electronic devices are gradually becoming indispensable in our daily life, it is crucial to overcome this power consumption barrier, that is, to reduce the SS. Therefore, determining precisely how to remove the Boltzmann tyranny has recently constituted a popular topic of research [3–10]. At least two different approaches have been proposed: (1) to use the tunnel junction at the source/channel end of the MOSFET (called the tunnel field-effect transistor or tunnel FET) [11–14]; and (2) to use the negative gate capacitance of the MOSFET. Negative capacitance has been observed in many different materials and device structures including ferroelastic switches, oxidesuperlattices, supercrystals, and light-emitting diodes [15–21]. It can be practically achieved by utilizing ferroelectric dielectric materials such as AlInN [8], BiFeO$_3$ [9], and HfZrO$_2$ [14], due to the lag of the polarization charge inside the ferroelectric materials with respect to the change of applied voltage. It has also been reported that connecting a negative capacitance externally in series with the gate of the MOSFET can effectively alleviate this 60 mV/decade SS constraint [6,9,22]. It is important to note that some organic materials also possess ferroelectricity. Among them, however, only polyvinylidene fluoride trifluoroethylene [P(VDF-TrFE)], and no other organic ferroelectric material, has been identified in the literature for the SS reduction of MOSFETs [9,10,23]. Since PVDF itself constitutes an organic ferroelectric material and is easily accessible, we attempted to fabricate a capacitor with
PVDF as the dielectric material and tested its effect on the SS characteristics of MOSFETs. Since negative capacitance is challenging to measure directly using conventional measurement techniques, we externally connected the PVDF capacitor in series with the gate of the MOSFET and determined its subthreshold characteristics.

2. Materials and Methods

PVDF capacitors with a metal–dielectric–metal structure were fabricated. A high-quality PVDF film with a thickness of 1 μm was purchased directly from the vendor (Dongguan Haozheng Trading Co. Ltd., Dongguan, China) and aluminum (Al) films were deposited on both sides of the PVDF films through a metal mask to form the top and bottom electrodes. The area of the top electrode was approximately 100 mm², and the electrode area was controlled by the metal mask. Copper wires were then attached to both electrodes using conductive silver paste. Figure 1 shows the device structure of the PVDF capacitor used in this work. The MOSFETs (HCF4007UBE, STMicroelectronics, Inc. Geneva, Switzerland) used in this work were purchased and used without modification. The \( I_D-V_D \) and subthreshold \( I_D-V_G \) characteristics of the n-channel MOSFETs, with and without PVDF capacitors connected in series with the gate, were measured by an Agilent 4156B semiconductor parameter analyzer (Agilent Technologies (Taiwan), Taipei, Taiwan). The subthreshold slopes of the MOSFETs were then identified from the subthreshold \( I_D-V_G \) characteristics. Figure 2a,b illustrate, respectively, the measurement circuits for \( I_D-V_D \) and \( I_D-V_G \) characteristics with and without connection of the PVDF capacitor.

![Device structure of the polyvinylidene fluoride (PVDF) capacitor used in this work.](image1)

**Figure 1.** Device structure of the polyvinylidene fluoride (PVDF) capacitor used in this work.

![Measurement circuits for (a) \( I_D-V_D \) and (b) \( I_D-V_G \) characteristics of the metal-oxide–semiconductor field-effect transistors (MOSFETs) connected or not to a PVDF capacitor at the gate of the transistor.](image2)

**Figure 2.** Measurement circuits for (a) \( I_D-V_D \) and (b) \( I_D-V_G \) characteristics of the metal-oxide–semiconductor field-effect transistors (MOSFETs) connected or not to a PVDF capacitor at the gate of the transistor.
3. Results and Discussion

Figure 3a presents the $I_D$--$V_D$ curves of the n-channel MOSFET (HCF4007UBE, STMicroelectronics, Inc.) without connecting a PVDF capacitor at the gate, under $V_G = 1, 2,$ and $3$ V, respectively. Since the HCF4007UBE MOSFET was originally designed for digital circuit applications, the $I_D$s between different $V_{GS}$ are not evenly spaced. Figure 3b depicts the $I_D$--$V_D$ curves of the n-channel MOSFET (HCF4007UBE) with a PVDF capacitor connected at the gate under $V_G = 1, 2,$ and $3$ V, respectively. By comparing the $I_D$--$V_D$ curves shown in Figure 3a,b, it can be seen that the drain current $I_D$ was apparently lower after the transistor connected a PVDF capacitor in series with the gate. This is because an additional voltage drop across the PVDF capacitor made the effective gate voltage $V_G$ smaller. In addition, a sunken current in $I_D$s was observed when the MOSFET was connected with a PVDF capacitor, as shown in Figure 3b. This sunken drain current behavior indicates that the charges in the channel of the MOSFET were reduced when the gate voltage $V_G$ increased, implying an effective negative gate capacitance. To further examine the negative capacitance effect of the PVDF capacitor, we measured the $I_D$--$V_G$ characteristics of the MOSFET connected or not to a PVDF capacitor at the gate of the transistor and then compared their subthreshold slopes. Figure 4 compares the $I_D$--$V_G$ characteristics of the MOSFET connected or not to a PVDF capacitor at the gate of the transistor for $V_D = 0.3$ V, in which the subthreshold slope of each $I_D$--$V_G$ characteristic is specified. It was found that the subthreshold slope for the original HCF4007UBE MOSFET was $SS = 130$ mV/decade, while the SS for the transistor connected with a PVDF capacitor was $SS = 100$ mV/decade.

![Figure 3a](image1.png) ![Figure 3b](image2.png)

**Figure 3.** $I_D$--$V_D$ curves of the n-channel MOSFET (HCF4007UBE, STMicroelectronics, Inc.) connected (a) without and (b) with a PVDF capacitor at $V_G = 1, 2,$ and $3$ V, respectively.
4. Conclusions

The extant literature has not yet addressed the negative capacitance of PVDF, even though it is an organic ferroelectric material. In this work, we investigated the effect of connecting an organic PVDF capacitor in series with the gate of an n-channel MOSFET. A sunken drain current behavior was found in the $I_D$–$V_D$ curves of the transistor when it was connected with a PVDF capacitor at its gate, indicating the existence of an effective negative gate capacitance. It was also found that the subthreshold slope of the transistor decreased from 130 mV/decade to 100 mV/decade, which constitutes a reduction of 23% of its original value. This result confirms the negative capacitance effect of the PVDF and proves that connecting a PVDF capacitor in series to the gate of a MOSFET can effectively decrease the subthreshold slope of the transistor. Although the MOSFET used in this work was not a state-of-the-art one and had a high SS, it is believed that by connecting a PVDF capacitor in series to the gate, the SS could be reduced to below 60 mV/decade if a scaled MOSFET was used instead.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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