SPICE Simulation of tunnel FET aiming at 32 kHz crystal-oscillator operation

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Abstract: We numerically investigate the possibility of using Tunnel field-effect transistor (TFET) in a 32 kHz crystal oscillator circuit to reduce power consumption. A simulation using SPICE (Simulation Program with Integrated Circuit Emphasis) is carried out based on a CMOS transistor model. It is shown that the power consumption of TFET is one-tenth that of conventional low-power CMOS.

Keywords: Tunnel field-effect transistor (TFET), Crystal oscillation, CMOS, IoT

Classification: Electron devices, circuits and modules (silicon, compound semiconductor, organic and novel materials)

References


1 Introduction

In the coming era of the Internet of Thing (IoT), low-power operation is a key factor in device development. Moreover, it is considered that the end of transistor scaling is inevitable in the near future. Given this background, the development of the tunnel field-effect transistor (TFET) has been attracting great interest [1-9]. TFET’s steep subthreshold-slope (SS) current-voltage characteristics would enable low-power operation in many applications.

Fig. 1. (a) Crystal-oscillator circuit. (b) Equivalent circuit of quartz crystal using four elements. (c) Simulation parameters used in the oscillating circuits.

A crystal oscillator is implemented in most digital circuits to generate clock frequency. Crystal oscillators convert a direct current from a power supply to a periodically oscillating current signal. A frequency of 32 kHz is commonly used in many applications to generate a real time clock. This is because 32 kHz is a power of 2 ($32768 = 2^{15}$) value, and a precise 1 second period (1 Hz frequency) is obtained by using a 15 stage binary counter. Because real-time clocks are always working in IoT devices such as a smart phone or a smart watch, the power reduction of the 32 kHz crystal oscillator circuits leads directly to longer device usage. Here, we show
SPICE (Simulation Program with Integrated Circuit Emphasis) simulation results of oscillator circuit using TFET based on a compact model [10,11]. We applied TFET in a 32 kHz crystal oscillator circuit.

In real applications, crystal oscillator circuits have various forms including such as amplification circuits depending on their target devices. Here, we simulate the basic crystal oscillator circuits shown in Fig.1. Although this circuit is very simple, fundamental performance can be investigated by this circuit. The crystal part that determines the frequency of the circuit is represented by its equivalent circuit (Fig.1 (b)). There are four transistors in the NAND gate that works as an amplifier of the resonant signal. We numerically compare the circuit performance in which the NAND gate consists of four TFETs with that of conventional CMOSs. We use HSPICE simulator and transistor model based on 65 nm CMOS parameter set. Even a small difference of transistors in the NAND gate can induce a large difference in circuit performance, because the crystal-oscillation repeats the charging and discharging of transistors. We show that the replacement of four conventional transistors by TFETs in the NAND gate results in a large reduction in power consumption.

![Fig. 2. (a) The schematic device structure of n-type TFET. (b) The schematic device structure of p-type TFET. (c) Equivalent circuit model of TFET in this study (Ref.[10]). The drain current of TFET is a sum of the drain current of the tunneling model and MOSFET model.](image)

<table>
<thead>
<tr>
<th></th>
<th>TFET1</th>
<th>TFET2</th>
<th>CMOS1</th>
<th>CMOS2</th>
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<tbody>
<tr>
<td>$I_{on}/I_{off}$</td>
<td>1.0E+7</td>
<td>8.0E+6</td>
<td>1.0E+8</td>
<td>5.0E+6</td>
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<tr>
<td>$I_{off}[A]$</td>
<td>8.95E-14</td>
<td>1.02E-13</td>
<td>1.09E-12</td>
<td>2.54E-11</td>
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<tr>
<td>$V_{th}[V]$</td>
<td>0.287</td>
<td>0.342</td>
<td>0.285</td>
<td>0.331</td>
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</table>

Table 1. Four type of transistors that are simulated in this paper. CMOS1 and CMOS2 are two types of low-powered CMOSs. The model parameters of TFET2 are abstracted from Ref. [8]. TFET1 is improved version of TFET2.
We apply the same compact model for a TFET as that of Ref.[10]. The steep-slope of TFETs comes from the band-to-band (BTB) tunneling between the source region and the channel region. Because this BTB tunneling cannot be described by the conventional model such as BSIM, we combined the BTB tunneling model to BSIM and applied the equivalent circuit model depicted in Fig.2 (Ref.[10]).

The “on current” and “off current” are determined by BTB tunneling model and the leakage current derived from BSIM model. In this model, $V_{th}$, SS, and $I_{on}$ can be independently changed. Parameters are determined to obtain targeted $I-V$ curve. The capacitances are determined by the BSIM model.

**2 TFET model**

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**3 Basic characteristics of simulated TFET devices**

We compare the two types of TFET models ($L=120\text{nm}$) with two types low-power CMOS models ($L=120\text{nm}$) shown in Table 1. TFET1 is the ideal version model of experimentally fabricated TFET2 of Ref.[8]. Because TFET2 has not yet achieved the low SS ($\sim 79\text{mV/Dec}$), the SPICE model parameters of TFET1 are adjusted to achieve lower SS($\sim 48\text{mV/Dec}$). The CMOS1 and CMOS2 are based on the 65 nm CMOS transistor models aiming at low power operations, and CMOS2 has relatively higher $V_{th}$ than CMOS1 aiming at less low-power operation. The $I_{d}-V_g$ and $g_m$ characteristics at room temperature are shown in Fig.3 (a-b). The $g_m$ is a transconductance of the transistor and contributes to the gain of the amplification circuits.
4 Simulation results

4.1 Voltage overshoot and undershoot

The disadvantage of TFET is that the Miller effect of TFET is about twice that of conventional MOSFET \[12\], which is undesirable in conventional digital circuits. The source side tunneling barrier in the TFET structure enhances the Miller capacitance, resulting in large voltage overshoot/undershoot in its switching performance. Figure 4 shows a simulated waveform of an inverter to a 32 kHz input pulse. We can see a large overshoot and undershoot. It can be also seen that the widths of overshoot and undershoot terminate within 40 ps. Although it is considered the overshoot/undershoot restrict the performance of TFETs, in the next section, we will show that the overshoot and undershoot help to enhance the amplitude of periodic oscillations in the present application.

4.2 Results of crystal oscillator circuits

Although the present circuit (Fig. 1) has only four transistors in its NAND gate, the oscillation leads to repetitions of charging and discharging, resulting in clarifying the difference between TFET and conventional CMOS. The resistances R1, R2 and R3 determine the oscillation performance. R1 is a large resistance to prevent the short of input and output of NAND gate. R2 is a feedback resistor of the amplification. R3 contributes to the oscillation margin, and should be five times larger than that of Rs in Fig. 3 (b). Because Rs=5 kΩ, the oscillation for R3>25 kΩ is desirable.

Figures 5 (a-b) show the gain and the phase of the circuits using TFET1, respectively. Figure 6 shows a typical 32 kHz oscillation waveform. It can be seen that the amplitude of TFET1 is larger than that of CMOS1. This enhancement of the waveform is considered to come from the overshoot and undershoot shown in Fig.4. Figure 7 shows the oscillation waveforms of the circuit using four models. Both of the circuits using TFET1 and CMOS1 oscillate until \( V_{DD} = 0.4[V] \) due to lower \( V_{th} \) than that of TFET2 and CMOS2. Figure 8 shows a power consumption of the circuit, where the power consumption is estimated by the current multiplied by \( V_{DD} \). The currents of the circuits using TFET1 and TFET2 are one-tenth those of CMOSs. This will be related to the low \( I_{off} \) and relatively suppressed current (Fig.3 and table 1). Although it is observed that the oscillation margin of circuit using
CMOS is larger than that of TFET (Fig. 9), the power consumptions of the circuits using TFETs are one-tenth those of conventional low-power CMOSs as shown in Table 2.

Fig. 5. (a) Gain of the crystal oscillator circuit when $V_{DD}$ is changed. (b) Phase of the crystal oscillator circuit when $V_{DD}$ is changed.

Fig. 6. Part of the output of 32 kHz crystal-oscillator of TFET1 for $V_{DD}$=0.6[V]. We can see the effect of overshoot and undershoot, which help to enhance the amplitude of the periodic oscillations.
Fig. 7. Output of 32 kHz Oscillation when $V_{DD}$ is changed. (a) TFET1, (b) TFET2, (c) CMOS1, (d) CMOS2. TFET1 and CMOS1 show clear oscillation at $V_{DD}=0.4$ [V] while TFET2 and CMOS2 show no clear oscillation at $V_{DD}=0.4$ [V].

Fig. 8. Current of 32 kHz Oscillation when $V_{DD}$ is changed. (a) TFET1, (b) TFET2, (c) CMOS1, (d) CMOS2. The power consumption is calculated from these currents. Thus, it can be seen that the power consumptions of TFETs are much smaller than those of CMOSs.
Conclusions
SPICE simulation of a 32 kHz crystal oscillator circuit is carried out using a TFET compact model. It is shown that the power consumption of the circuit using TFET is much smaller than that of conventional CMOS. It is also shown that the steep SS current-voltage characteristics, which have lower $I_{off}$ and relatively suppressed current compared with those of CMOS, contributes to the low power consumption. In this paper, the transistor parameters are adjusted to obtain the targeted $I$-$V$ curve. The parameter adjustment of $C$-$V$ curve in addition to the $I$-$V$ curve is a future problem. In any event, because the 32 kHz crystal oscillator circuit is widely used in IoT devices, TFET is proven to be an important candidate for the 32 kHz crystal oscillator circuit.

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<th>$V_{DD}$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>0.4[V]</td>
<td>4.274e-11[W]</td>
<td>NG</td>
<td>1.959e-10[W]</td>
<td>NG</td>
</tr>
</tbody>
</table>

Table. 2. Simulated power consumption of four types of crystal oscillators during 10ms.

Acknowledgments
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