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Impact of Subthreshold Slope on Sensitivity of Square Law Detector for Radio Wave Imaging

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Abstract

An impact of the subthreshold slope of FET switching on the sensitivity of the square law detector composed of an FET to detect rf signals has been investigated. Theoretical consideration starting from the unified charge control model of FET channel carriers comes down to formulae which indicate that the subthreshold slope significantly affects the output voltage and the sensitivity of the square law detector. Experiments carried out using a MOSFET which has a body terminal isolated from other terminals and, therefore, is able to operate as the dynamic threshold voltage MOSFET proves the theoretical conclusion.

1. Introduction

In recent years, there has been an increasing interest in radio frequency (rf) signal detection in an integrated circuit to develop high-speed wireless communication such as 5G networks and imaging with radio waves such as terahertz imaging. Among various rf signal detectors, the square law detector (see Fig. 1) composed of an FET is attractive because it can easily be implemented in CMOS and other FET circuits. In fact, there have been several reports on development of terahertz-wave imaging devices using square law detector. Detection of 0.65 THz waves using the square law detector has been demonstrated [1]. Recently, we together with collaborators have developed a square law detector using high electron mobility transistor (HEMT) on glass substrate, which is able to detect 1 THz waves with high sensitivity [2]. However, the sensitivity of the detector is still needed to be improved to realize video imaging.

The previous research results suggest that the maximum output voltage, the maximum voltage-sensitivity, and the minimum noise-equivalent-power (NEP) are obtained near the threshold voltage of the FET. However, most of the theoretical studies have concerned with over-threshold operation [1], where the importance of device parameters such as the transconductance was indicated. A few works have taken the subthreshold into account [3], but an impact of the subthreshold slope has not explicitly been shown.

In this study, we investigate the operation of square law detectors in the subthreshold regime. We derive formulae which explicitly give the impact of the subthreshold slope on the detection-characteristics of square law detectors. We verify the theoretical results by experiment where a MOSFET is operated as the dynamic threshold voltage MOSFET (DTMOS) to change the subthreshold slope.

2. Theoretical analysis of square law detector

Fig. 1 shows the circuit model of a square law detector. The input signal $v_{RF}(t) = V_{RF}\sin\omega t$ is applied to gate through the dc blocking capacitor C_{block}. The rf signal is also applied to drain through the coupling capacitor C_{gd}. The gate voltage modulates the channel carrier density to $V_{RF}\sin\omega t$. The drain voltage modulates the carrier velocity to $V_{RF}\sin\omega t$. Thus, the drain output signal is proportional to $V_{RF}^2\sin^2\omega t$ which contain a dc component V_d being proportional to V_{RF}^2.

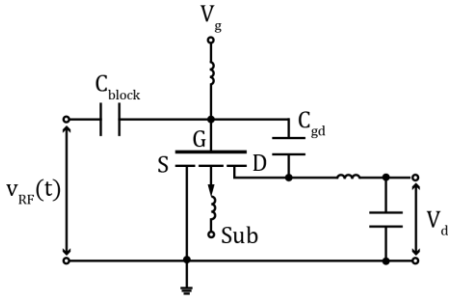

Fig. 1. Circuit model of square law detector

The drain output voltage can be determined from the product of the current flowing through the channel and the internal resistance of an FET. In this paper, we assume that the diffusion current dominates the drain current under the gate bias near or below the threshold voltage. We begin analysis with applying the unified charge control model (UCCM) described by eq. (1) [4], which expresses the channel carrier density in both weak and strong inversion regime of an FET.

$$n = C_{ox}\frac{\eta k_B T}{e^2}\ln\left[1+\exp\left(\frac{e(V_g - V_{th})}{\eta k_B T}\right)\right] \qquad (1)$$

where n is the channel carrier density, C_{ox} is the gate capacitor per unit area, e is the elemental charge, k_B is the Boltzmann constant, T is temperature, V_g is gate voltage, V_{th} is the threshold voltage, and η is the ideality factor. η is related to the subthreshold slope S as $\eta = S\cdot e/kT\ln(10)$.

We solved differential equations about the diffusion current by using eq. (1). The Taylor series expansion was applied to approximate under the small signal condition. The output voltage thus obtained is

$$V_d = \frac{V_{RF}^2}{4\left\{1+\exp\left(\frac{\ln(10)}{S}\left(V_g - V_{th}\right)\right)\right\}^2}\left(\frac{\ln(10)}{S}\right). \quad (2)$$

Eq. (2) indicates that the output voltage is inversely proportional to the subthreshold slope.

Using the above result and thermal noise, $4k_BTR_{ch}$, due to the channel resistance R_{ch}, NEP is given by

$$\mathrm{NEP} = \frac{S}{\ln(10)}\sqrt{\frac{64e}{R_{in}^2\mu C_{ox}\frac{W}{L}}\frac{\left\{1+\exp\left(\frac{\ln(10)}{S}\left(V_g - V_{th}\right)\right)\right\}^3}{\exp\left(\frac{\ln(10)}{S}\left(V_g - V_{th}\right)\right)}}, \quad (3)$$

where μ is the mobility, and R_{in} is the real part of the detector input impedance. Thus, the subthreshold slope is a significant device parameter to develop highly sensitive square law detectors.

3. Experimental

A square law detector has been fabricated on a printed circuit board to verify the above analysis by using commercially available components. Fig. 2 shows the photo of the fabricated detector. Microwave at 1 GHz frequency was supplied to the detector through an SMA connector.

The MOSFET was a p-type 4 terminal transistor, which was supplied from Microchip Technology. The MOSFET was operated in two modes to investigate the impact of the subthreshold slope; the normal MOSFET mode where the body terminal was grounded and the DTMOS mode where body potential was varied and set at the same voltage as the gate voltage V_g. In the DTMOS mode, the subthreshold slope becomes the ideal value owing to the body bias effect [5].

Fig. 3 shows switching characteristics of the MOSFET operated in the normal MOSFET mode and the DTMOS mode. When the detector was operated as the normal MOSFET mode, the threshold voltage and subthreshold slope were -1.09 V and 79 mV/dec, respectively. On the other hand, these values were -0.84 V and 59 mV/dec, respectively, when the MOSFET was operated in the DTMOS mode.

Fig. 4 shows the output voltage V_d as a function of gate voltage measured with the normal MOSFET mode and the DTMOS mode. The results clearly indicate that the use of DTMOS mode which has smaller subthreshold slope than normal MOSFET mode gives higher output voltage.

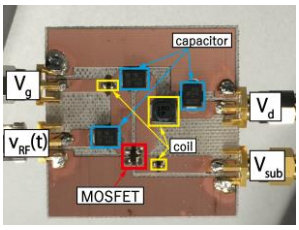

Fig. 2. Square law detector fabricated by using 4 terminal MOSFET.

NEP was evaluated by taking the input power of microwaves and the reflection coefficient S_{11} into consideration. The minimum NEPs were 2.3×10^{-9} W/Hz$^{1/2}$ and 7.0×10^{-9} W/Hz$^{1/2}$ for DTMOS mode and normal MOSFET mode, respectively, which also proves the benefit of the use of a steep slope MOSFET.

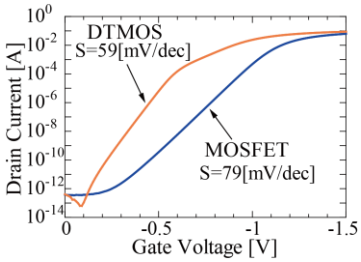

Fig. 3. Switching characteristics of MOSFET mode and DTMOS mode.

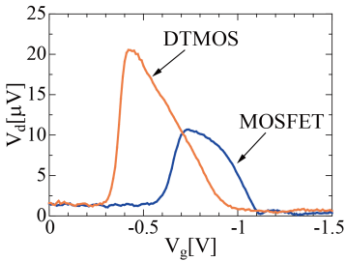

Fig. 4. Output voltage of square law detector in MOSFET mode and DTMOS mode.

4. Conclusion

We have derived analytical formulae which explicitly indicate the impact of the subthreshold slope of FET on the detection sensitivity of square law detector. The analytical results were experimentally validated by using a MOSFET which was able to operate as DTMOS. In conclusion, the use of steep slope FET improves the sensitivity of square law detector for radio wave imaging.

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