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Frequency Dependence of Measured MOSFET Distortion Characteristic

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1. Introduction

Applications of CMOS devices for RF circuits are increasing, and thus complex analog functions with increasing performances are highly required. For realizing these requirements, one important feature of MOSFETs to be considered and predicted for circuit design, is the harmonic distortion (HD) [1]. It is known that HDs are higher-order derivatives of the drain current caused by the nonlinearity of the MOSFET characteristics. It is also known that the inter modulation (IM) of two different HDs, which is caused by two different input frequencies, one in the vicinity of the other, have to be accurately predicted [2].

The objective of the reported work is to investigate the distortions on MOSFETs experimentally. Our focus is given on the relationship between the HDs and the IM distortions under several GHz frequencies. It is demonstrated that the carrier transit delay causes a frequency dependence of the distortions, which results in different characteristics of HDs and IMs.

2. Origin of Distortions in MOSFET's

In a device with linear input-output characteristics such as a resistance, the output signal has the same frequency to as a sinusoidal input signal. However, a nonlinear system like a MOSFET includes output signals not only at the input frequency f_0 but also its multiples, $2f_0$, $3f_0$, and so on as shown in Fig. 1. This is called the HD determined as

$$\begin{cases} \text{HD1:} \dfrac{dI_\mathrm{d}}{dV_\mathrm{g}} V_\mathrm{p} \cos(2\pi f_0 t) \\ \text{HD2:} \ \dfrac{1}{4}\dfrac{d^2 I_\mathrm{d}}{dV_\mathrm{g}^2} V_\mathrm{P}^2 \cos(2\pi 2 f_0 t) \\ \text{HD3:} \ \dfrac{1}{24}\dfrac{d^3 I_\mathrm{d}}{dV_\mathrm{g}^3} V_\mathrm{P}^3 \cos(2\pi 3 f_0 t) \end{cases} \quad (1)$$

where I_d and V_g are the drain current and the DC gate voltage, respectively, and V_p is the amplitude of the input signal.

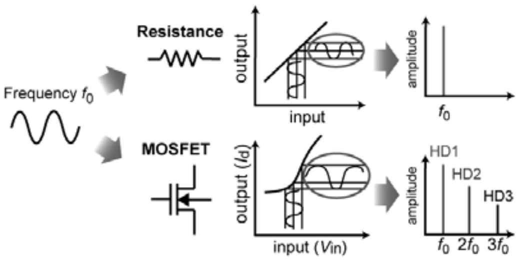

Fig. 1: Origin of harmonic distortions.

When two sinusoidal input signals with two frequencies f_1 and f_2 are applied to a MOSFET, the output signals are observed at combinations of these two frequencies, as shown Fig. 2. This is called the IM, and determined as

$$\begin{cases} \text{IM1:} \ \dfrac{dI_\mathrm{d}}{dV_\mathrm{g}} V_\mathrm{p} \cos(2\pi f_1 t) \\ \text{IM2}\pm\text{:} \ \dfrac{2}{4}\dfrac{d^2 I_\mathrm{d}}{dV_\mathrm{g}^2} V_\mathrm{p}^2 \cos\{2\pi(f_1 \pm f_2)t\} \\ \text{IM3}\pm\text{:} \ \dfrac{3}{24}\dfrac{d^3 I_\mathrm{d}}{dV_\mathrm{g}^3} V_\mathrm{p}^3 \cos\{2\pi(2 f_1 \pm f_2)t\} \end{cases} \quad (2)$$

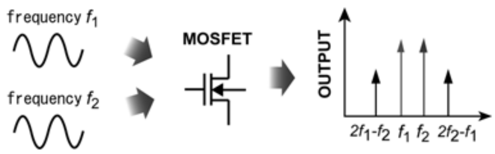

Fig. 2: Origin of inter-modulation (IM) distortions.

If f_1 and f_2 are in vicinity of each other, frequencies of IM3 are also close to f_1 and f_2. This may cause serious problems for circuit reliability.

It is seen from Eqs. (1) and (2) that the frequencies of HD3 and the IM3+ are approximately equal, if f_1 and f_2 are close to f_0 but that IM3+ has a 3 times larger amplitude. It is also obvious that IM3+ and IM3- have different frequencies of about $3f_0$ and f_0 with the same amplitude. This concludes that the bias dependency of HD3 can be characterized by IM3- with 1/3 of the HD3 frequency. Therefore, the measurements of the HD3 characteristics, which are not easy, can be simplified by looking at IM3- at a 3 times lowers frequency. Fig. 3 proves that this hypothesis is correct.

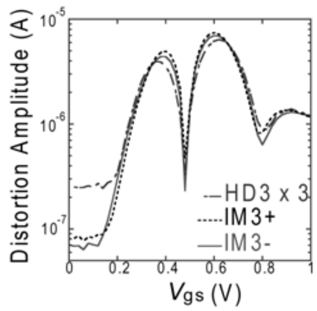

Fig.3:Comparison of measure a distortions for $L_\mathrm{g}/W_\mathrm{g}$=0.5μm/50μm. The measurement conditions. center frequency=1GHz, tone spacing=10MHz, signal amplitude=50mV

3. Measurement Setup

Shown in Fig. 4 is the setup used to perform the distortion measurements. On the gate electrode V_{gs} with small input sinusoidal frequencies is applied, where *V*in is equal to V_{gs} + V_p sin2π(f_1+f_2)t. V_{gs} is the DC offset, and V_p is the amplitude of the sinusoidal input fixed to 50mV. In the measurement circuit, high frequency noise introduced by the voltage source is filtered before entering the MOSFET. The output AC current and its associated IMs are detected by a spectrum analyzer [3].

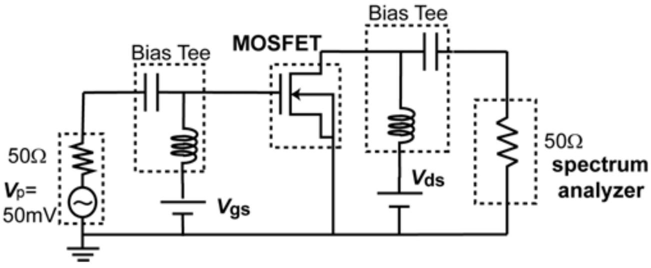

Fig. 4: Circuit used for measuring distortions.

4. Measured Results and Discussions

According to the theory, the amplitude of IM3 is equal to that of HD3 multiplied by three. As shown in Fig. 5, this is true for a short gate length of L_g=0.5μm. However, a clear discrepancy is observed for a long length L_g=5.0μm, namely the amplitude of IM3- differs from those of HD3 and IM3+ for large V_{gs} values. Measurements are repeated for several different chips, and identical results are always reproduced.

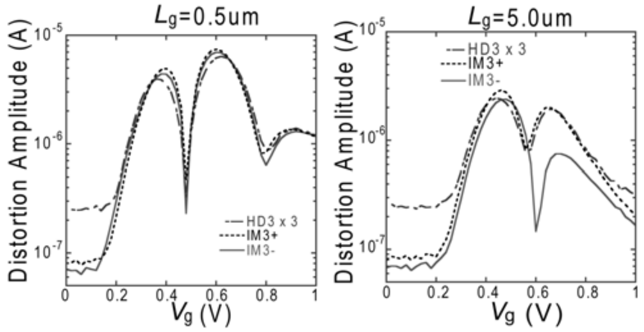

Fig. 5: Comparison of measured distortions for two gate Lengths.

Several reasons for the discrepancy can be considered. Experimental investigations undertaken are summarized in Table 1. They conclude that the discrepancy is not due to the measurement condition.

Table 1: Summary of Experimental Investigations.

changed parameter	Original	changed	Result
tone spacing, f_1 - f_2	10MHz	20MHz	no change
signal amplitude, V_p	50mV	100mV	no change
central a frequency, f_0	1GHz	2GHz	no change

We investigate the reason why a discrepancy occurs only for L_g=5.0μm, but not for L_g=0.5μm. Fig. 6 shows a comparison of extracted cut-off frequency f_T as a function of V_{gs} for the studies gate lengths. The extraction is done with the simulated C_{gg} dependence on frequency as shown in Fig. 6b.

Beyond f_T it is expected that the carriers cannot follow the switching speed causing reduction of C_{gg} as seen in Fig. 6b. The frequencies investigated for the present measurements are 1GHz and 3GHz. f_T of L_g=0.5μm is much higher than the frequencies applied for the measurement (see Fig. 6a). Thus no carrier transit delay affects on the distortion measurements. However, 3GHz is much higher than f_T for L_g=5.0μm, which results in a strong non-quasi-static (NQS) effect on the distortion. Whereas 1GHz is higher than f_T only for V_{gs} smaller than 0.6V. Under the NQS condition the distortion becomes frequency dependent, and the changing delay increases the magnitude of the distortions [4]. For V_{gs} larger than 0.6V the frequency of 1GHz provides normal condition, where the quasi-static approximation is valid. Therefore the enhancement of the distortion magnitude does not occur for V_{gs} larger than 0.6V. This is the reason for the suppressed IM3-. Thus it has to be noticed that IM3 properties at frequencies beyond f_T are not simply predictable.

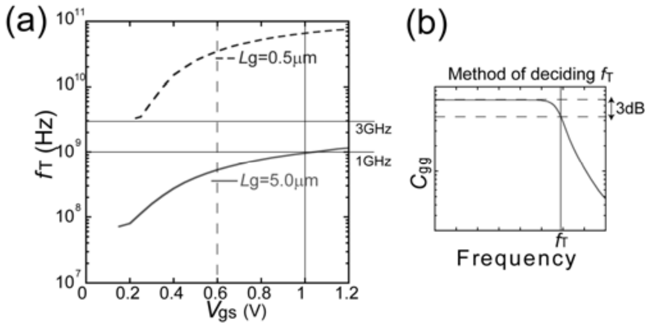

Fig.6: (a) Extracted cut-off frequency f_T for two gate length; L_g=0.5μm (dotted line) and L_g=5.0μm (solid line). The horizontal line with 3GHz is applied for HD3 and IM3+ measurements, and that with 1GHz is applied for IM3- measurements.

5. Conclusion

We have investigated the harmonic distortions and the inter modulations of MOSFETs experimentally. It has been found that the third harmonic distortion HD3 multiplied by three is no more equal to the third inter modulation distortion IM3-, it to the carrier transit delay causes frequency dependence of the distortions.

6. References

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