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Letter

New Y-function based MOSFET parameter extraction method from weak to strong inversion range

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ABSTRACT

A new Y-function based MOSFET parameter extraction method is proposed. This method relies on explicit expressions of inversion charge and drain current versus $Y_c(=Q_i/\sqrt{C_{gc}})$-function and $Y(=I_d/\sqrt{g_m})$-function, respectively, applicable from weak to strong inversion range. It enables a robust MOSFET parameter extraction even for low gate voltage overdrive, whereas conventional extraction techniques relying on strong inversion approximation fail.

1. Introduction

The accurate extraction of MOSFET electrical parameters is mandatory for a better engineering of CMOS technologies. Several methods have been proposed for the MOSFET parameter extraction but they are restricted to the above or near threshold voltage (V_t) region and assume that the inversion charge Q_i varies linearly with gate voltage overdrive V_{gt} as $Q_i \approx C_{ox} \cdot V_{gt}$, C_{ox} being the gate oxide capacitance [1–11]. For instance, in Refs. [1,6,10] procedures are proposed to extract the threshold voltage value. In Refs. [2–5,7,8], the strong inversion approximation for Q_i is explicitly employed. Among these methods, the Y-function technique, where $Y = I_d/\sqrt{g_m} \approx \sqrt{\beta} \cdot V_{gt}$, ($\beta$ being the transistor gain factor) has proven very efficient for MOSFET parameter extraction as being immune to source–drain series resistance R_{sd} [2,3,9]. However, for reduced supply voltage V_{dd}, this strong inversion approximation becomes less and less valid and renders inaccurate all these extraction methods. Alternatively, in Refs. [11–13], the inversion charge law vs V_g has been somewhat modified to account for the near threshold or below threshold region using exponential or Lambert function.

In this paper, we propose a new Y-function based extraction methodology applicable from weak to strong inversion and not limited to above or near threshold region, thus enabling parameter extraction under low voltage operation. To this end, we first validate the usefulness of the Y-function to describe accurately the inversion charge $Q_i(V_g)$ and inversion capacitance $C_{gc}(V_g)$ characteristics from weak to strong inversion region. Then, we extend this approach to the drain current $I_d(V_g)$ characteristics including conventional mobility expression and apply it for the MOSFET parameter extraction in advanced nMOS devices from a 28 nm FDSOI technology.

2. Experimental details

Electrical measurements were performed on n-MOS transistors issued from a 28 nm FD-SOI CMOS technology. They were fabricated on (100) SOI wafers with 25 nm thin BOX and a Si body thinned down to 7 nm. The metal gate/high k dielectric front gate stack features a 1.5 nm EOT. The channel length (L) is varying from 1 µm down to 28 nm and the channel width (W) is fixed at 1 µm. Both gate-to-channel capacitance and drain current measurements were performed at zero back gate bias with Agilent B1500/1530 Semiconductor Device Analyzer. As usual, the inversion charge $Q_i(V_g)$ is calculated by integration over gate voltage of the $C_{gc}(V_g)$ curve.

3. Parameter extraction methodology

In this section, we establish the equations relating the inversion charge and drain current to their associated Y-function. Based on these equations, we propose a new MOSFET parameter extraction methodology from weak to strong inversion and which avoids the explicit formulation of the inversion charge with gate voltage.

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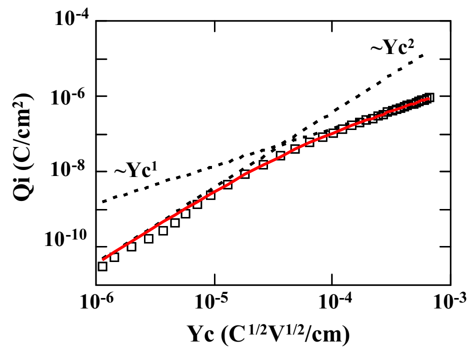

Fig. 1. Experimental (symbols) and modeled (solid line) variations of Q_i with Y_c. The dashed lines show the asymptote limits for weak and strong inversion regions varying respectively as Y_c^2 and Y_c^1 (MOS capacitance $W = 60\ \mu m$, $L = 10\ \mu m$, $V_g = 0$–1 V).

3.1. Y-function dependence of inversion charge and capacitance

By analogy to the Y-function built from the drain current and transconductance, a Y-function can be calculated from the inversion charge Q_i and capacitance $C_{gc} = dQ_i/dV_g$, such as,

$$Y_c = Q_i \Big/ \sqrt{C_{gc}}. \tag{1}$$

In strong inversion, C_{gc} saturates to the gate oxide capacitance C_{ox} and Eq. (1) reduces to:

$$Y_c \approx Q_i/\sqrt{C_{ox}} = \frac{C_{ox}(V_g - V_t))}{\sqrt{C_{ox}}} = \sqrt{C_{ox}}(V_g - V_t), \tag{2}$$

so that $Q_i \approx Y_c\sqrt{C_{ox}}$.

In weak inversion, Q_i varies exponentially with V_g, implying that $C_{gc} \approx Q_i/(nkT/q)$, which yields for Y_c,

$$Y_c \approx Q_i \Bigg/ \sqrt{Q_i \Big/ \left(n\frac{kT}{q}\right)} = \sqrt{n\frac{kT}{q}Q_i}, \tag{3}$$

such that $Q_i \approx Y_c^2/(nkT/q)$, kT/q being the thermal voltage.

Therefore, the MOS inversion charge varies as Y_c^2 in weak inversion and as Y_c in strong inversion. As a result, combining both asymptotic laws allows to obtain for the inversion charge a general expression as a function of Y_c valid from weak to strong inversion and given by,

$$Q_i = Y_c^2 \Big/ \left(n\frac{kT}{q} + \frac{Y_c}{\sqrt{C_{ox}}}\right). \tag{4}$$

Combining Eqs. (1) and (4) yields for the inversion capacitance C_{gc}:

$$C_{gc} = Y_c^2 \Big/ \left(n\frac{kT}{q} + \frac{Y_c}{\sqrt{C_{ox}}}\right)^2. \tag{5}$$

Fig. 1 shows that the asymptotic laws of Eqs. (2) and (3) are well verified experimentally, and, that Eq. (4) does provide a continuous description of Q_i versus Y_c from weak to strong inversion. As suggested from (4), Fig. 2a confirms that the plot of Y_c^2/Q_i (=Q_i/C_{gc}) versus Y_c is well linear with slope providing C_{ox} value and y-axis intercept nkT/q value (better perceived in log-lin plot of Fig. 2b). As can be seen from Fig 2c and d, the model of Eqs (4) and (5) also enables a very good fit of $Q_i(V_g)$ and $C_{gc}(V_g)$ characteristics with only two fitting parameters i.e. C_{ox} and n.

3.2. Y-function dependence of drain current

The drain current of a MOSFET in linear operation reads:

$$I_d = \frac{W}{L}\mu_{eff} Q_i V_d \tag{6}$$

where μ_{eff} is the effective mobility and V_d is the drain voltage.

If μ_{eff} is constant with V_g(=μ_0), following the derivation of Eq. (4), then one gets,

$$\frac{Y^2}{I_d} = \frac{I_d}{g_m} = n\frac{kT}{q} + \frac{Y}{\sqrt{\beta}} \tag{7}$$

with $\beta = W \cdot C_{ox} \cdot \mu_0 \cdot V_d/L$ being the gain factor.

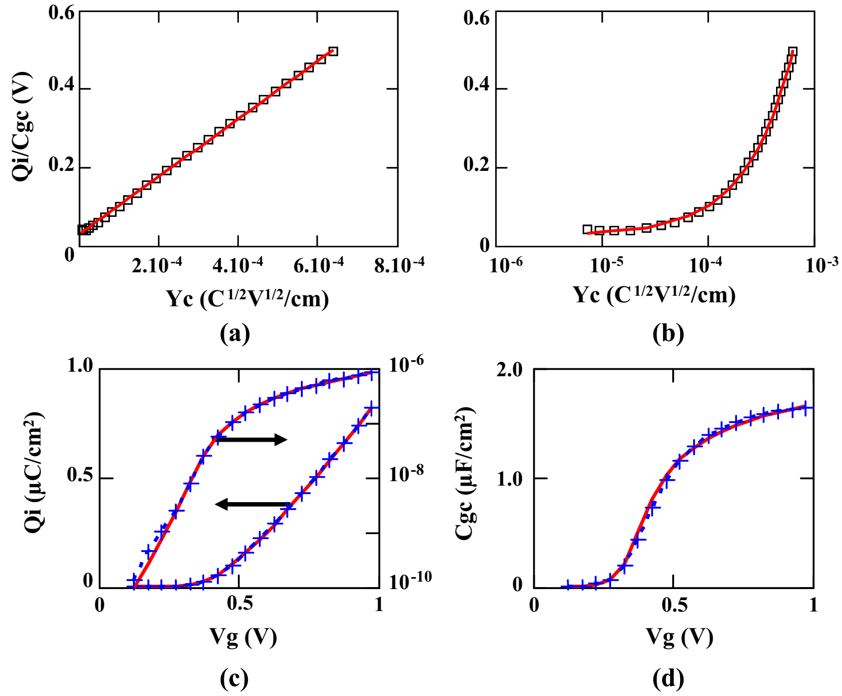

Fig. 2. Variation of Q_i/C_{gc} with Y_c in linear (a) and log (b) scale. Experimental (solid lines) and modeled (symbols) (c) $Q_i(V_g)$ and (d) $C_{gc}(V_g)$ characteristics. Parameters: $C_{ox} = 1.83 \times 10^{-6}$ F/cm^2 and $n = 1.1$.